Directions in Strong Motion Instrumentation

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STRUCTURAL MONITORING ARRAYS – PAST, PRESENT AND FUTURE

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Abstract : This paper presents a summary of the seismic monitoring issues as practiced in the past, as well as current applications and new developments to meet the needs of the engineering and user community. A number of examples exhibit the most recent applications that can be used for verification of design and construction practices, real-time applications for the functionality of built environment and assessment of damage conditions of structures.

Key Words : Seismic monitoring, structural response, global positioning system, real-time, acceleration, displacement, drift ratio, performance

1. INTRODUCTION

Seismic monitoring of structural systems constitutes an integral part of the National Earthquake Hazard Reduction Program in the United States. Recordings of the acceleration response of structures have served the scientific and engineering community well and have been useful in assessing design/analysis procedures, improving code provisions and in correlating the system response with damage. Unfortunately, there are only a few records from damaged instrumented structures to facilitate studies of the initation and progression of damage during strong shaking (e.g. Imperial County Services Building during the 1979 Imperial Valley earthquake, [Rojahn and Mork, 1981]). In the future, instrumentation programs should consider this deficiency. Jennings (1997) summarizes this view as follows: "As more records become available and understood, it seems inevitable that the process of earthquake resistant design will be increasingly, and quite appropriately,

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based more and more upon records and measured properties of materials, and less and less upon empiricism and qualitative assessments of earthquake performance. This process is well along now in the design of special structures".

An instrumented structure should provide enough information to (a) reconstruct the response of the structure in sufficient detail to compare with the response predicted by mathematical models and those observed in laboratories, the goal being to improve the models, (b) make it possible to explain the reasons for any damage to the structure, and (c) to facilitate decisions to retrofit/strengthen the structural systems when warranted. In addition, a structural array should include, if physically possible, an associated free-field tri-axial accelerograph so that the interaction between soil and structure can be quantified.

Recent trends in development of performance based earthquake resistant design methods and related needs of the engineering community, as well as advances in computation, communication and data transmission capabilities, have prompted development of new approaches for structural monitoring issues and applications. In particular, (a) verification of performance based design methods and (b) needs of owners to rapidly and informedly assess functionality of a building following an event require measurement of displacement rather than or in addition to accelerations as is commonly done. Thus, new avenues in recording or computing displacement in real or near-real time are evolving. Thus, to meet the requirements for timely evaluation of damage condition of a building following an earthquake are leading the development of acquisition systems with special software that can deliver real-time or near real-time acceleration and displacement measurements.

This paper describes the past and current status of the structural instrumentation applications and new developments. The scope of the paper includes the following issues: (a) types of current building arrays and responses to be captured, (b) recent developments in instrument technology and implications, and (d) issues for the future. The scope does not include cost considerations.

2. HISTORICAL PERSPECTIVE

2.1 General Statistical Summary

In the United States, the California Division of Mines and Geology (CDMG) of the California Geologic Survey and the United States Geological Survey (USGS), manage the largest two structural instrumentation programs. Until recently, these programs have aimed to facilitate response studies in order to improve our understanding of the behavior and potential for damage to structures under the dynamic loads of earthquakes. The principal objective

has been the quantitative measurement of structural response to strong and possibly damaging ground motions for purposes of improving seismic design codes and construction practices. However, to date, it has not been the objective of either instrumentation program to create a health monitoring environment for structures.

To date, the USGS has conducted a cooperative strong ground motion and structural instrumentation program with other federal and state agencies and private owners. Tables 1 and 2 summarize the current inventory and cooperative affiliations of the USGS Cooperative National Strong-Motion Program (NSMP). Within the USGS program, and unless other factors are considered and/or specific organizational choices are made apriori, the following general parameters have been considered for selecting and ranking structures for instrumentation:

1. Structural parameters: the construction material, structural system, geometry, discontinuity, and
2. Site-related parameters : severity-of-shaking on the basis of closeness to one or more of the main faults within the boundaries of the area considered (e.g. for the San Francisco Bay area, the San Andreas, Hayward, and Calaveras faults are considered).

Detailed procedures and overall description used by the USGS structural instrumentation program are described by Çelebi (2000, and 2001).

Table 1. Nationwide Distribution of USGS Cooperative Structural Instrumentation Arrays (updated 4/10/2004)

Extensively Instrumented Buildings [>6 channels]		Extensively Instrumented Bridges [>6 channels]		Extensively Instrumented Dams, Reservoirs, Pumping Plants and Power Generating Facilities [>6 channels]	
Alaska	4	California	2	Arizona	1
California	37	Oregon	10	California	[illegible]
Hawaii	1	Utah	1	Colorado	1
Missouri	2			Idaho	2
Puerto Rico	1			Montana	1
South Carolina	1			New Mexico	1
Tennessee	1			Oregon	13
Utah	2			Utah	1
Washington	2			Washington	7

Table 2. Cooperative National Strong-Motion Network of USGS [Extensively Instrumented Bldgs (> 6 channels)] (updated 4/10/2004)

Owner Agency [* Federal funds]	Stations	Recorders
Department of Veterans Affairs [*]	3	6
General Services Administration [*]	3	5
Los Angeles County	1	2
NASA-JPL [*]	8	9
University of Puerto Rico [**NSF funds]	1	5
U.S. Geological Survey [*]	31	66
Washington Dept of Natural Resources	1	1
USGS-ANSS [*]	3	8
TOTALS	51	102

On the other hand, the State of California CDMG program, which now has over 170 buildings instrumented in accordance to a predefined matrix, aims to cover a wide variety of structural systems (Huang and Shakal, 2001, and Shakal, Huang, Rojahn and Poland, 2001).

2.2 General Instrumentation Issues

2.2.1 Data Utilization

Ultimately, the types and extent of instrumentation must be tailored to how the data acquired during future earthquakes will be utilized, even though there may be more than one objective for instrumentation of a structure. Table 3 summarizes some data utilization objectives with sample references. As a recent example of data utilization, Jennings (1997) analyzed data from two buildings within close proximity (<20 km) to the epicenter of the 1994 Northridge, CA earthquake. He calculated the base shear from the records as 8 and 17 % of the weights of the buildings and the drift ratios as 0.8 and 1.6 % (exceeding code limitations). Jennings (1997) concluded: "A difference between code design values and measured earthquake responses of this magnitude – approaching a factor of ten – is not a tenable situation." Thus, recorded responses allowed the assessment of excessive drift ratios while shear forces remained reasonable.

Table 3. Sample List of Data Utilization Objectives & Sample References

GENERIC UTILIZATION
Verification of mathematical models (usually routinely performed) (*e.g.*Boroschek et al, 1990)
Comparison of design criteria vs. actual response (usually routinely performed)
Verification of new guidelines and code provisions (*e.g.*Hamburger, 1997)
Identification of structural characteristics (Period, Damping, Mode Shapes)
Verification of maximum drift ratio (*e.g.* Astaneh, 1991, Çelebi, 1993)
Torsional response/Accidental torsional response (*e.g.* Chopra, 1991, De La Llera, 1995)
Identification of repair & retrofit needs & techniques (Crosby, 1994)
SPECIFIC UTILIZATION
Identification of damage and/or inelastic behavior (*e.g.* Rojahn & Mork, 1981)
Soil-Structure Interaction Including Rocking and Radiation Damping (Çelebi, 1996, 1997)
Response of Unsymmetric Structures to Directivity of Ground Motions (*e.g.* Porter, 1996)
Responses of Structures with Emerging Technologies (base-isolation, visco-elastic dampers, and combination (Kelly and Aiken, 1991, Kelly, 1993, Çelebi, 1995)
Structure specific behavior (*e.g.* diaphragm effects, Boroschek and Mahin,1991, Çelebi, 1994)
Development of new methods of instrumentation/hardware (e.g. GPS: Çelebi et. al., 1997, 1999, 2001; wireless: Straser, 1997)
Improvement of site-specific design response spectra and attenuation curves (Boore, et. al. 1997, Campbell, 1997, Sadigh *et. al.*, 1997, Abrahamson and Silva, 1997
Associated free-field records (if available) to assess site amplification, SSI and attenuation curves(Borcherdt, 1993, 1994, 200a, 2002b, Crouse and MacGuire, 1996)
Verification of Repair/Retrofit Methods (Crosby et al, 1994, Çelebi and Liu, 1996)
Identification of Site Frequency from Building Records (Çelebi, 2003)
RECENT TRENDS TO ADVANCE UTILIZATION
Studies of response of structures to long period motions (e.g. Hall et al, 1996)
Need for new techniques to acquire/disseminate data (Straser, 1997, Çelebi, 1998, Çelebi and Sanli, 2002, Celebi and others, 2004)
Verification of Performance Based Design Criteria (future essential instrumentation work)
Near Fault Factor (more free-field stations associated with structures needed)
Comparison of strong vs weak response (Marshall, Phan and Çelebi, 1992, Çelebi, 1998)
Functionality Çelebi, 2004, Needs additional specific instrumentation planning)
Health Monitoring and other Special Purpose Verification (Heo et al, 1997)

2.2.2 Code versus Extensive Instrumentation

The most widely used code in the United States, the Uniform Building Code (UBC-1997 and prior editions), recommends, for seismic zones 3 and 4, a minimum of three accelerographs be placed in every building over six stories with an aggregate floor area of 60,000 square feet or more, and in every building over ten stories regardless of the floor area. The purpose of this requirement by the UBC was to monitor rather than to analyze the complete response modes and characteristics. UBC-code type recommended instrumentation is illustrated in Figure 1a. Following 1971 San Fernando earthquake, in 1982, in Los Angeles, the code-type requirement was reduced to one tri-axial accelerometer at the roof (or top floor) of a building meeting the aforementioned size requirements (Darragh and others, 1994). In general, code-type instrumentation is naturally being de-emphasized as a result of strong desire by the structural engineering community to gather more data from instrumented structures to perform more detailed structural response studies. Experiences from past earthquakes show that the minimum guidelines established by UBC for three tri-axial accelerographs in a building are not sufficient to perform meaningful model verifications. For example, three horizontal accelerometers are required to define the (two orthogonal translational and a torsional) horizontal motions of a floor. Rojahn and Mathiesen (1977) concluded that the predominant response of a high-rise building can be described by the participation of the first four modes of each of the three sets of modes (two translations and torsion); therefore, a minimum of 12 horizontal accelerometers would be necessary to record these modes. Instrumentation needed to provide acceptable documentation of the dominant response of a structure is addressed by Hart and Rojahn (1979) and Çelebi and others (1987). This type of instrumentation scheme is called the ideal extensive instrumentation scheme as illustrated in Figure 1b.

Specially designed instrumentation arrays are needed to understand and resolve specific response problems. For example, thorough measurements of in-plane diaphragm response require sensors in the center of the diaphragm (Figures 1c) as well as at boundary locations. Performance of base-isolated systems and effectiveness of the isolators are best captured by measuring tri-axial motions at the top and bottom of the isolators as well as the rest of the superstructure (Figure 1d). In case of base-isolated buildings, the main objective usually is to assess and quantify the effectiveness of isolators. If there is no budgetary constraint, additional sensors can be deployed between the levels above the isolator and roof to capture the behavior of intermediate floors.

2.2.3 Associated Free-Field Instrumentation

More information is required to interpret the motion of the foundation substructure relative to the ground on which it rests. This requires free-field instrumentation associated with a structure (Figure 1b). However, this is not always possible in an urban environment[1]. Engineers use free-field motions as input at the foundation level, or they obtain the motion at foundation level by convoluting the motion through assumed or determined layers of strata to base rock and deconvoluting the motion back to foundation level. Confirmation of

these processes requires downhole instrumentation near or directly beneath a structure. These downhole arrays will yield data on:

(1) the characteristics of ground motion at bedrock (or acceptably stiff media) at a defined distance from a source and
(2) the amplification of seismic waves in layered strata.

Downhole data from sites in the vicinity of instrumented building or other structures are especially scarce. Two new building monitoring arrays in the United States that include downhole sub-arrays are described later in the paper.

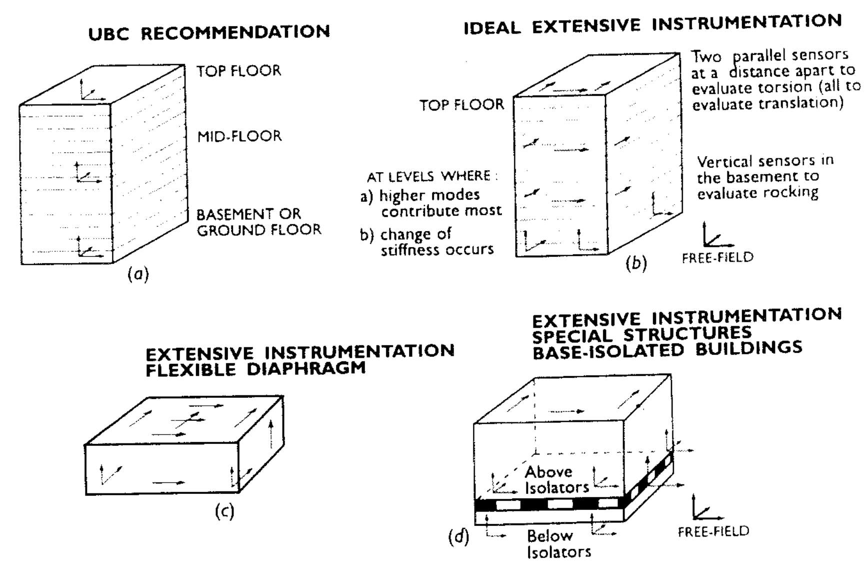

Figure 1. Typical Instrumentation Schemes

2.2.4 Record Synchronization Requirement

High-precision record synchronization must be available within a structure (and with the free-field, if applicable) if the response time histories are to be used together to reconstruct the overall behavior of the structure. Such synchronization has been achieved through extensive cabling from each of the individual sensor to the recorder. Recent technological developments enable decreasing or minimizing, and in certain cases eliminating, the use of extensive cabling. For example, the global positioning systems (GPS) is now widely used to synchronize a building instrumentation with that of a separate recorder system for the free-field; thus, eliminating cable connection between the free-field recorder and recorder within a structure. The issue here is that synchronization must be an integral part of any structure monitoring scheme whether cable or wireless transmission is the means to realize it.

2.2.5. Recording Systems, Constraints and New Developments

Until recently, commercially available recording systems have been limited to a maximum of 12-18 channels (*e.g.* analog recorder CRA-1[2], 13 channels; the digital K-2[2], 12 channels; digital Mt. Whitney[2], 18 channels). Although multiple numbers of recording units may be used to accommodate requisite multiple-channel instrumentation systems for a structure, cost restrictions usually limit the number of channels to 12 or 18 (or multiples thereof), unless more channels are needed or special financing is available. Recently, however, with the development of PC-based data acquisition systems that utilize multiple A/D converters, several dozen channels of data can be accommodated. In such systems, the only constraints are the cost of the sensors and data transmission media required. One such system is described later in the paper.

3. SPECIAL ARRAYS – LOOKING TO THE FUTURE

3.1 Special Arrays in Los Angeles

Figure 2 shows the nine-story Millikan Library at Caltech Campus in Pasadena and the 15-story UCLA Factor Building in Los Angeles. In each building, the general objective is to thoroughly document the response of a building including the propagation of seismic waves. Another multi-story building including the special-purpose instrumentation scheme for the twin towers at Century City, Los Angeles is shown in Figure 3. The objective of the recently-upgraded instrumentation of these two buildings is to better facilitate studies of the inter-story drift problem by means of recording the responses at several pairs of consecutive floors.

3.2 Displacement Measurement Needs and Arrays

... does not imply endorsement of these

Two important reasons are driving the recent push for developing technologies for measuring displacements in real-time or near real-time: (a) the evolution of performance-based design methods and procedures which rely on displacement as the main parameter and (b) the needs of local and state officials and prudent property owners, to establish procedures to assess the functionality of buildings and other important structures, such as lifelines, following a significant seismic event. As a result, structural engineers increasingly want the measurement of displacements during strong shaking events in order to assess drift ratios that in turn are related to performance of the structure, as schematically shown in Figure 4. On the other hand, dynamically measuring relative displacements between floors directly is very difficult and, except for tests conducted in a laboratory (e.g., using displacement transducers), has yet to be readily and feasibly achieved for a variety of real-life structures. However, recent technological developments have already made it possible to successfully develop and implement two approaches to dynamically measure real-time displacements from which drift ratios or average drift ratios can be computed. Both approaches can be used for performance evaluation of structures and can be considered as building health-monitoring applications.

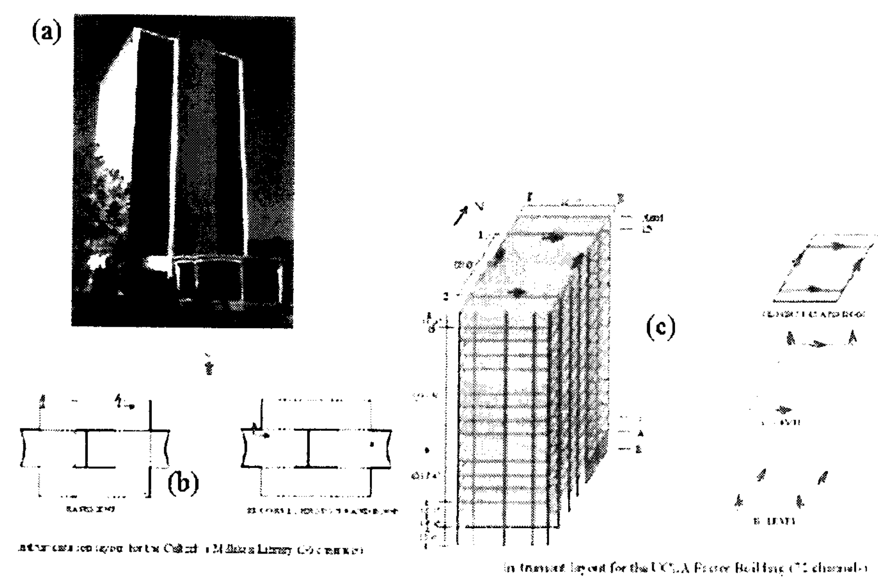

Figure 2. (a) Millikan Library (Pasadena, CA) and *(b)* its instrumentation scheme, and *(c)* Factor Building at UCLA (Los Angeles, CA) campus and its instrumentation scheme (Safak, *pers. comm. 2001*).

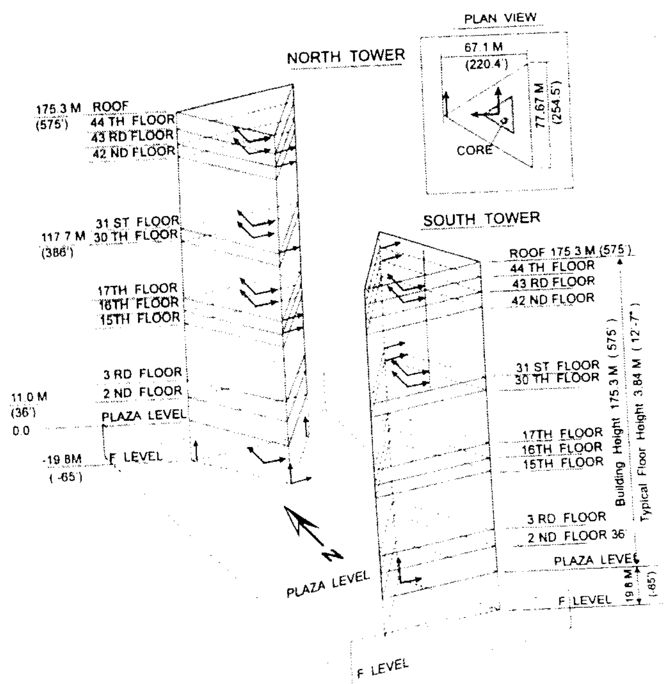

Figure 3. Twin Towers of Century City (extensively instrumented for drift studies)

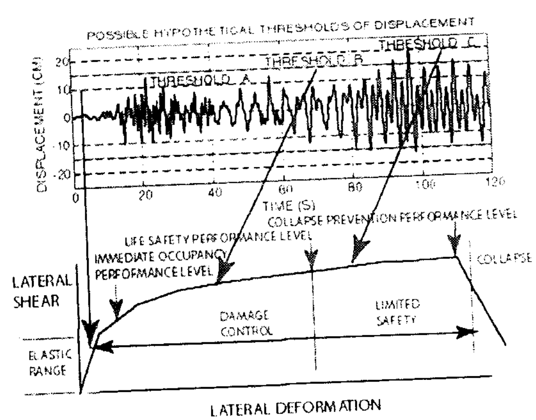

Figure 4. Hypothetical displacement time-history as related to FEMA- 274.

3.2.1. Use of GPS for Direct Measurements of Displacements

For long-period structures such as tall buildings and long-span bridges, dynamic displacement measurements using differential Global Positioning Systems (GPS) are now possible (Çelebi and Sanli 2002). However, GPS technology is limited to sampling rates of 10-20 Hz and, for buildings, measurement of displacement is possible only at the roof. The accuracy of GPS measurements is ± 1 cm horizontal and ± 2cm vertical. A schematic and photos of an application in the use of GPS to directly measure displacements is shown in Figure 5. In this particular case, two GPS units are used in order to capture both the translational and torsional response of the 34-story building in San Francisco, Ca. Furthermore, at the same locations as the GPS antennas, tri-axial accelerometers are deployed to verify the displacements measured by GPS with those obtained by double-integration of the accelerometer records. Real-time acceleration and displacement data streaming in the PC based monitoring system is shown also in Figure 5.

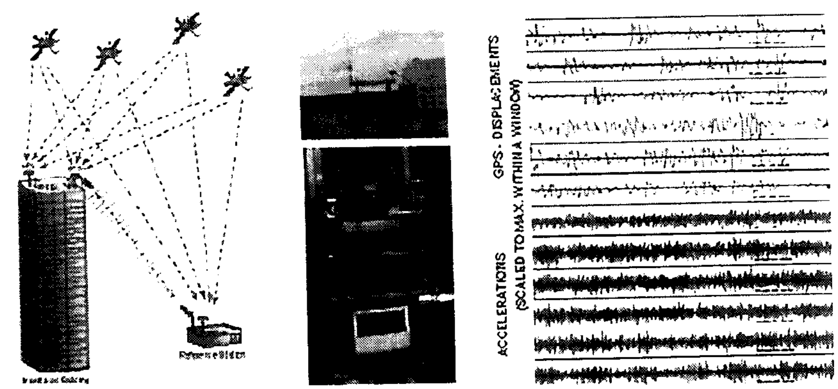

Figure 5. Special Instrumentation Using GPS and Accelerometers (San Francisco, CA.): (Left)- Schematic of thev overall system, (Center)- GPS and Radio modem antenna and the recorders connected to PC, (Right)- streaming of acceleration and displacement data in real-time.

In absence of strong shaking data from the deployed system, ambient data obtained are analyzed to infer the validity of the recorded vibration signals even though the amplitudes of both the acceleration and displacement data are very small and the data is noisy (Figure 6). The GPS displacement data is within the margin of error specified by the manufacturer (< 1 cm. horizontal).

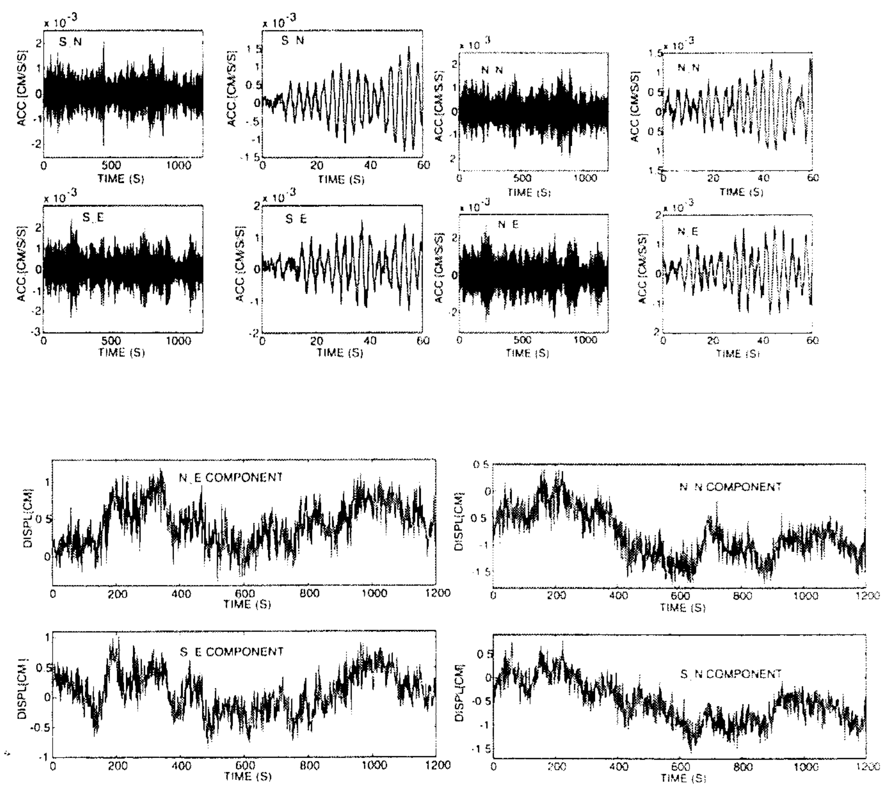

Figure 6. (Top)Remotely triggered and recorded accelerations at N (North) and S(South) locations. The figure shows pairs of 1200 second long (and 60 second window from the same) record. (Bottom) Remotely triggered and recorded displacements at N (North) and S (South) Locations.

In Figure 7, cross-spectra (Sxy) of pairs of parallel records (north-south component of north deployment [N_N] vs. north-south component of south deployment [S_N], and east-west component of north deployment [N_E] vs east-west component of south deployment [S_E]) from accelerometers are calculated. The same is repeated for the differential displacement records from GPS units. The cross-spectra (Sxy) clearly indicate a dominant frequency of 0.24-.25 Hz from both acceleration and displacement data. This frequency is within the band of expected frequency for a 34-story building. The lower peak in frequency (near ~ 0.1 Hz) seen in the cross-spectra of displacement records is due to noise, which is probably microseisms. It is expected that during larger amplitude motions with higher signal to noise ratios, such low frequency amplitudes due to noise will not be noticeable. In the acceleration data, a second frequency at 0.31 Hz is apparent. We will accept the 0.24-0.25 Hz as the fundamental translational frequency (in both

directions). This is confirmed by the fact that at this frequency, the cross spectra of parallel acceleration records have a coherency of approximately unity (~ 1) and they are in-phase (0°). On the other hand, the Sxy of parallel acceleration records at 0.31 Hz also show coherency of approximately unity but they are out of phase (180°). Therefore, this frequency corresponds to a torsional mode.

For the fundamental frequency at 0.24 Hz, the displacement data exhibits a 0° phase angle; however, the coherencies are lower (~0.6-0.7) . The fact that the fundamental frequency (0.24 Hz) can be identified from the GPS displacement data, amplitudes of which are within the manufacturer specified error range, and that it can be confirmed by the acceleration data, is an indication of promise of better results when larger displacements can be recorded during strong shaking caused by earthquakes or strong winds.

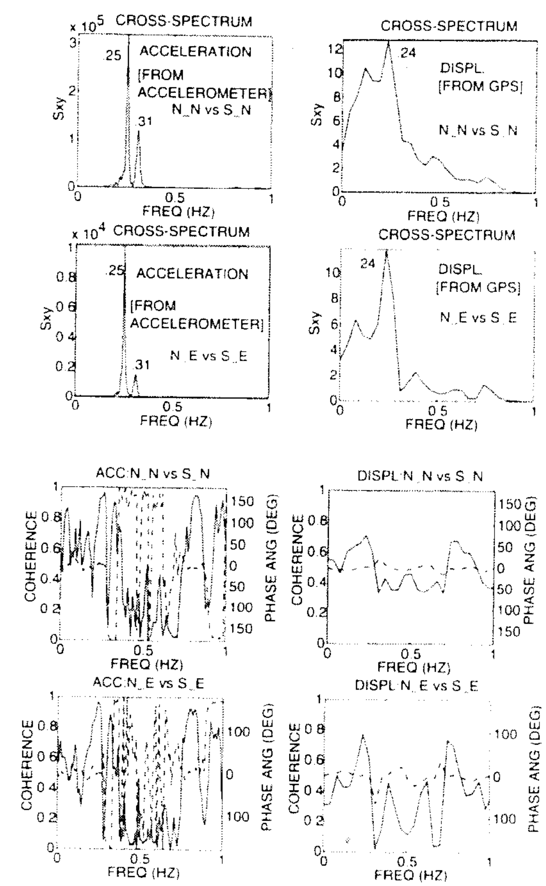

Figure 7. Cross-spectra (Sxy) and associated coherency and phase angle plots of horizontal, and parallel accelerations and displacements. [Note: In the coherency-phase angle plots, solid lines are coherency and dashed lines are phase-angle].

Since the deployment of the pioneering GPS units in San Francisco, CA, multiple other such arrays have been developed. An important array for monitoring the wind response of tall buildings in Chicago, IL have been developed by Kijewski-Correa and Kareem (2004).

3.2.2 Displacement via Real-time Double Integration

As mentioned, GPS applications are limited to sampling at ≤ 20 Hz, and for building monitoring, displacements measurements are possible on at the roof. This limits the application to long period structures rather than wide variety of structural systems. Therefore, the challenge is to compute displacements from recorded acceleration responses in real-time or near real-time.

A new approach in obtaining displacements in real-time is depicted in Figure 8 which also shows the distribution of accelerometers in the building - designed to provide data from several pairs of neighboring floors to facilitate drift computations. The system has a server that (a) digitizes continuous analog acceleration data, (b) pre-processes the 1000 sps digitized data with low-pass filters (herein called as the preliminarily filtered uncorrected data), (c) decimates the data to 200 sps and streams it locally (d) monitors and applies server triggering threshold criteria and locally records (with a pre-event memory) when prescribed thresholds are exceeded and (e) broadcasts the data continuously to remote users by high-speed internet.

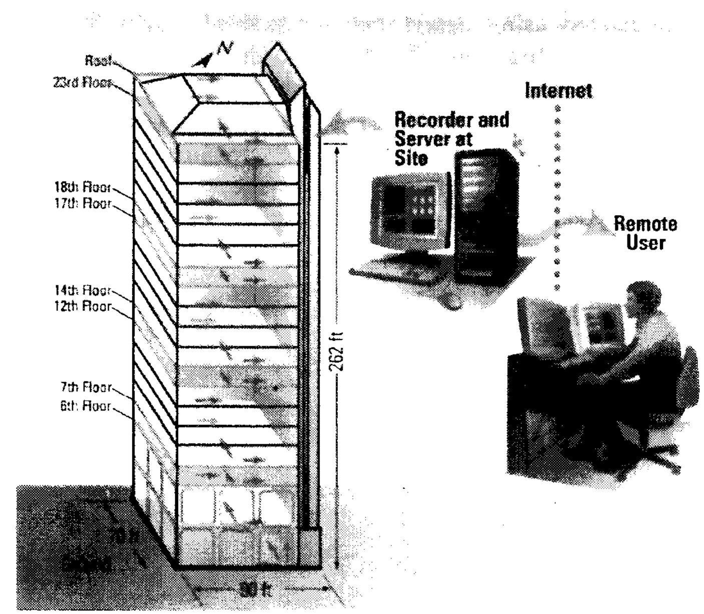

Figure 8. General schematic of data acquisition and transmittal for seismic monitoring of the building.

The broadcast streamed real-time acceleration data are acquired remotely using a "Client Software" configured to compute velocity, displacement and select number of drift ratios. Figures 9 show two PC screen snapshots of the client software display configured for 12 channels of streaming acceleration or velocity or displacement or drift ratio 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 6 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 9 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 4 stages of colored indicators. 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.

ratios are calculated using data from any pair of accelerometer channels oriented in the same direction. 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 4 (Figure C2-3 of *FEMA-274* [ATC 1997]) and summarized in Table 4 for this particular building. Figure 9 hypothetically shows that the first level of threshold is exceeded, and the client software is recording data as indicated by the illuminated red button.

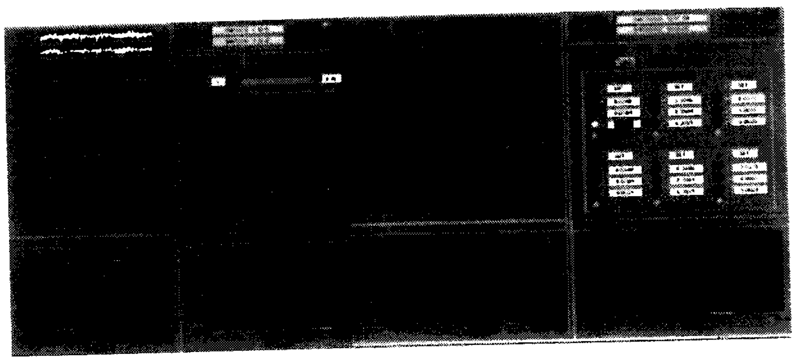

Figure 9. (Left) Screen snapshot of client software display showing acceleration streams and computed amplitude and response spectra. (Right) Screen snapshot of client software display showing 12-channel (six pairs with each pair a different color) displacement and corresponding six-drift ratio (each 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.

Table 4. Summary of Threshold Stages and Corresponding Drift Ratios

Threshold Stage	1	2	3
Adopted Drift Ratio	0.2%	0.8%	1.4-.2%

Thus the system can (a) be used to facilitate rapid assessment of the building integrity following an earthquake, (b) 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 (c) deliver the data within a relatively short time (few minutes if not in seconds), to facilitate informed decision making regarding post-earthquake building occupancy.

3.2.4 Soil-Structure Interaction Array(s)

State-of-the-art practice and analytical approaches require, when warranted, the structure-foundation system to be represented by mathematical models that include the influence of the sub-foundation media. In many cases, under a specific geotechnical environment, certain structures will respond differently than if that structure was built as a fixed based structure on a very stiff (e.g rock) site condition. This alteration of vibrational characteristics of structures due to soil-structure interaction (SSI) can be both beneficial and detrimental for their performances. To date, the engineering community is not clear about the pros and cons of SSI.

Adverse effects of SSI during the 1985 Michoacan (Mexico) earthquake were addressed by Tarquis and Roesset (1988), who showed that, in the lakebed zone of Mexico City, 400 km away from the epicenter, fundamental periods of mid-rise buildings (5-15 stories) lengthened due to SSI. Thus, such buildings were negatively affected due to SSI because the lengthening of their fundamental periods placed them in a resonating environment close to the approximately 2-second resonant period of Mexico City lakebed.
On the other hand, under different circumstances, SSI may be beneficial because it produces an environment whereby the structure escapes the severity of shaking due to shifting of its fundamental frequency. Certainly, in a basin such as that of the Los Angeles area, SSI may cause both beneficial and detrimental effects in the response of structures.

Thus, the identification of the circumstances under which SSI is beneficial or detrimental and the relevant controlling parameters is a necessity. Therefore, measurement of soil-structure interaction effects is required to fully understand the response of a major structure. This is easily accommodated along with the instrumentation schemes of the superstructure. Sensors at critical locations of the foundation are required to capture its relevant motions. Additional sensors may be needed to record the motions of the surrounding geological materials. For example, if vertical motion and rocking are expected to be significant and need to be recorded, at least three vertical accelerometers are required at the basement level (Figure 1b). In some cases; additional instrumentation (e.g. free-field accelerographs on the surface and in boreholes [downhole accelerographs]) may be required. Horizontal and vertical spatial downhole sensors will provide information on how the motions change while traveling through the media and how much it is affected by the building response. Detailed proposals for soil-structure interaction experiments resulting from a workshop are presented in USGS OFR-92-295 (Çelebi and others, 1992).

Specialized arrays that will capture SSI effects will further advance the verification of SSI effects that are currently very much limited to theoretical studies.

Two existing SSI arrays are shown in Figures 10a and b. Each of these arrays has the necessary components of sub-arrays (e.g. superstructure, foundation, surface and downhole free-field sub-arrays). Figure 10a depicts Pacific Park Plaza Building array in Emeryville, CA and Figure 10b depicts the Atwood Building in Anchorage, AK. Both building monitoring schemes are designed to capture SSI effects in addition to the traditional translational and torsional responses.

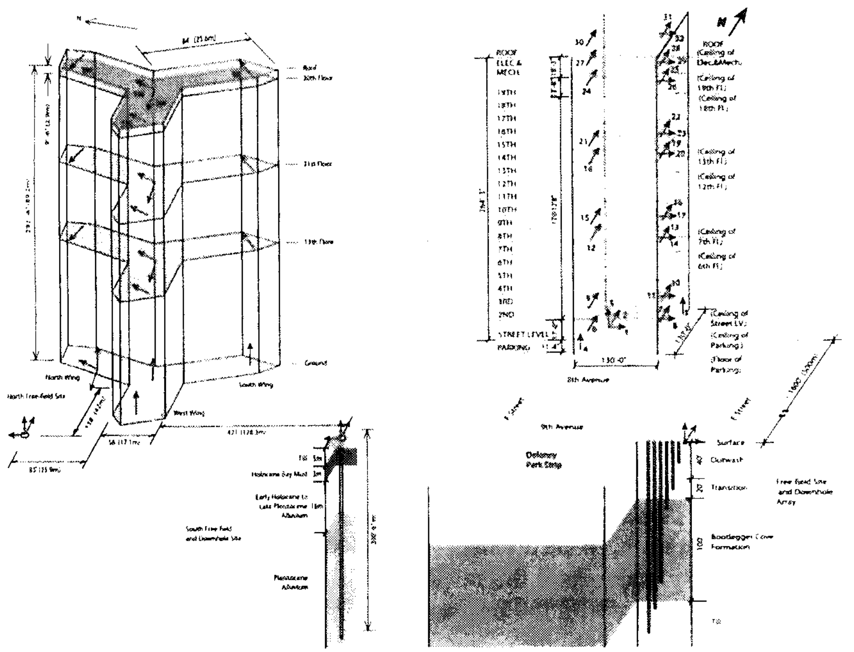

Figure 10. (Left) A three-dimensional schematic of the Pacific Park Plaza Building (Emeryville, CA) showing with integrated structure, surface and downhole sub-arrays (Note: The tri-axial downhole accelerograph was added after the 1989 Loma Prieta earthquake). (Right) A General three-dimensional schematic of the Atwood Building (Anchorage, AK) showing the general dimensions and locations of accelerometers deployed within the structure and tri-axial downhole accelerometers at free field site.

4. OUTSTANDING ISSUES AND ANSS

The following outstanding issues need to be considered in future instrumentation efforts but are not discussed in detail in this paper:

- How to better instrument to validate performance-based design procedures,
- Health monitoring needs and related cost issues for both installation and maintenance.
- Drift assessment related instrumentation needs. USGS already has 4 buildings with multiple sensors on consecutive floors that are configured to record data to assess drift ratios.
- Wireless instrumentation – is it here?
- Monitoring capability in large urban areas such as New York – in light of the September 11, 2001 event.
- Verification of specific emerging technological applications (e.g. unbonded braced system, damper systems used in new and retrofit design and construction).

There are new challenges but also new opportunities in the development of state-of-the-art seismic instrumentation projects to help better understand existing and outstanding engineering and scientific issues related to mitigation strategies in urban environs. A new initiative, the Advanced National Seismic System (ANSS), authorized by U.S. Congress and managed by the USGS, specifically aims to address such outstanding issues for seismic monitoring of structures. Development of procedures for deploying arrays related to seismic monitoring projects are currently underway while some projects are already completed (e.g. Atwood Building in Anchorage, AK).

5. CONCLUSIONS

This paper presents the current status of and methods used for the structural instrumentation program mainly by the U.S. Geological Survey but also generally in the United States. Both historical and current trends and methods used for seismic monitoring of structures are discussed in terms of utilization of data acquired by seismic monitoring. New approaches in monitoring (using GPS technology and real-time double-integration) and related data acquisition systems to meet special needs are introduced. The extent to which a structure should be instrumented to meet the code recommendations versus special needs are discussed without consideration of cost issues. Several examples of instrumented buildings are shown.

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