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Seismic Structural Health Monitoring

From Theory to Successful Applications

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Maria Pina Limongelli ·
Mehmet Çelebi
Editors

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Editors
Maria Pina Limongelli
Department of Architecture
Built Environment and Construction
Engineering
Politecnico di Milano
Milan, Italy

Mehmet Çelebi
United States Geological Survey
Menlo Park, CA, USA

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Preface

During the last three decades, Seismic Structural Health Monitoring (herein S^{2}HM) has grown due to the needs of owners, managers, occupants and users as well as great interest by both researchers and professionals. The maturity of this important discipline is also well evidenced by the development of sensing systems that—when deployed, configured and installed properly—enable retrieval of requisite data during significant seismic events. Such data then are post-processed using damage identification algorithms—implemented in structure-specific configured software—to assess serviceability, functionality and/or occupiability of the structure.

One of the main reasons for increased adoption of S^{2}HM is that it is a superior and significant alternative to other traditional observational and/or intrusive methods which are costly, time-consuming and, due to dependency on the operator, may be subjective and thus associated with large uncertainties.

Several research efforts have been dedicated to these topics, as shown by the ever-increasing number of related journal and conference publications. However, there is a requisite need in the literature for a focused collection of works dedicated to S^{2}HM.

The primary motivation for this book is to fill this gap by presenting a unified state of the art on theoretical developments and successful applications of S^{2}HM around the world, compiled by leading researchers and academicians.

The volume is organized in four topical parts. Each part comprises several chapters by authors experienced in different aspects of S^{2}HM. Part I collects six chapters devoted to the description of the specific requirements of S^{2}HM systems for different types of civil structures and infrastructures (buildings, bridges, cultural heritage, dams, structures with base isolation devices) and different phenomena to monitor (e.g. soil–structure interaction and excessive drift). Four chapters covering the methods and the computational tools available for the data processing—needed to retrieve information about the structural health from the signals provided by the sensor network—are grouped in Part II. In Part III, hardware and software tools for

S^2HM are described in two chapters. Finally, in Part IV, five chapters report on several state-of-the-art applications of S^2HM around the world.

The book is aimed to be useful to researchers, practicing engineers and students and to benefit owners and managers from potential applications of S^2HM in their properties.

Milan, Italy — Maria Pina Limongelli
Menlo Park, USA — Mehmet Çelebi

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Part I
S^2HM for Civil Structures

Chapter 1
S²HM of Buildings in USA

Mehmet Çelebi

Abstract The evolution of seismic structural-health monitoring (S²HM) of buildings in the USA is described in this chapter, emphasizing real-time monitoring. Rapid and accurate assessment of post-earthquake building damage is of paramount importance to stakeholders (including owners, occupants, city officials, and rescue teams). Relying merely on rapid visual inspection could result in serious damage being missed because it is hidden by building finishes and fireproofing. Absent visible damage to a building's frame, most steel or reinforced-concrete moment-frame buildings will be green-tagged based on limited visual indications of deformation, such as damage to partitions or glazing. Contrary, uncertainty in judging extent of structural damage may lead an inspector toward a relatively conservative tag, such as a red tag. In such cases, expensive, intrusive, and time-consuming inspections may be recommended to building owners (e.g., following the M_w 6.7 1994 Northridge, Calif., earthquake, approximately 300 buildings were subjected to costly inspection of connections (FEMA 352)). Using real-time data-driven computation of drift ratios as the parametric indicator of structural deformation and damage to a structure could be of great value to minimize potential judgmental errors in such assessments. Recorded sensor data are an indication of performance, and performance-based design standards stipulate that the amplitude of relative displacement of a building's roof (with respect to its base) indicates performance. Establishing sound criteria for performance is the most important issue for S²HM process, and since 2000 (in the USA), using real-time computed drift ratios and acceptable threshold criteria form the basis for almost all applications in S²HM.

Keywords Seismic response · Health monitoring · Drift · Threshold displacements · Performance

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M. Çelebi (✉)
U.S. Geological Survey, Earthquake Science Center, 345 Middlefield Rd. (MS977), Menlo Park, CA 94025, USA
e-mail: celebi@usgs.gov

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1.1 Introduction and Rationale

Following an earthquake, rapid and accurate assessment of the damage condition and seismic performance of a building is of paramount importance to stakeholders (owners, leasers, permanent and/or temporary occupants, and city officials and rescue teams that are concerned with safety of those in the building and those that may be affected in nearby buildings and infrastructure). Until recently, assessments of damage to buildings following an earthquake were essentially carried out by inspections conducted by city-designated engineers following procedures similar to ATC-20 tagging requirements [1]. Tagging usually involves visual inspection only and is implemented by assigning the colored tags corresponding to the extent of damage the building experienced or absence thereof, indicative of potential hazard to occupants—green tag indicates the building can be occupied (that is the building does not pose a threat to life safety), yellow indicates Restricted Use (that is, hazardous to life safety but not to prevent limited entrance to retrieve possessions), and red indicates entrance prohibited (that is, hazardous to life). However, one of the impediments to accurately assessing the damage level of structures by visual inspection is that some serious damage may not be visible due to the presence of existing building finishes and fireproofing material. In the absence of visible damage to a building's frame, most steel or reinforced concrete moment-frame buildings will be tagged based on visual indications of building deformation, such as damage to partitions or glazing. Lack of certainty regarding the actual deformation that the building experienced may typically lead an inspector toward a relatively conservative tag. In such cases, expensive and time-consuming intrusive detailed structural inspections may be recommended to building owners (e.g., it is known that, following the M_w 6.7 1994 Northridge, Calif., earthquake, approximately 300 buildings ranging in height from 1 to 26 stories were subjected to costly intrusive inspection of connections [2]).

As stated above, much of the discussion presented here related to structural health monitoring is focused on "rapid and accurate assessment of damage of a building" following an earthquake. I distinguish this aspect from those other studies and assessments made months and years after events using recorded data from instrumented buildings. A vast number of other such studies that are performed weeks, months, and years after events have occurred do exist in the literature. See for example, Rojahn and Mork [3], Ventura and Ding [4], Boroschek and Mahin [5], Rahmani and Todorovska [6, 7], Safak and Çelebi [8, 9], Jennings [10], Çelebi and Safak [11, 12], Çelebi et al. [13–22], Çelebi [23–34], and Rodgers and Çelebi [35]. Thus, because of the rapid (and in reality, near real-time) process of obtaining performance indicators, the pioneering developments in early 2000 are distinguished as "near real-time" seismic structural-health monitoring—thus the acronym S^2HM.

Over the past few decades, the majority of post-earthquake safety evaluations of buildings have been made through the process of ATC-20 safety-tagging. In this chapter, a new method to evaluate buildings through real-time response of a structure as a health monitoring tool is presented. This alternative advanced method has become established and is also commercially available to owners and their designated engineers. The rationale is that building owners and their designated engineers are expected to use the response data acquired by a real-time structural-health monitoring system to justify a reduced inspection program, compared to that which would otherwise be required by a city government for a similar non-instrumented building in the same area. It is possible that depending on the deformation pattern and associated damage indicators observed in a building, the initial inspections could be directed toward specific locations in the building that experienced large and potentially damage-inducing drifts during an earthquake. A notable program based on this flexibility to use near real-time monitoring in lieu of tagging has been enacted by the City of San Francisco (see the Building Occupancy Resumption Program, BORP)[1] [36], which will be elaborated further in this chapter.

It is important to iterate the reasons why we need real time or near real-time structural health monitoring of a building. These include:

1. Safety of occupants following an earthquake. If there is damage, this information can be used to decide if evacuations are necessary.
2. Deliberations and decision making for occupancy or reoccupancy after evacuations—immediately after an earthquake.
3. Economical aspects: (1) What would be the financial impact of a lengthy shut-down of a building for further inspection and assessment? (2) Should the structure be permanently shut down and/or replaced?
4. If damage is predicted, how severe is it? What is its impact on occupancy, repair, and/or future retrofit?

1.2 Historical Background and Requisites

Almost two decades ago, when it became possible to reliably and quickly transmit digital structural response time-history signal data, programs were developed to acquire near-real time data from instrumented structures. The initial objective of these programs was to develop a method that would enable informed decisions on the performance and occupation resumption of a building within a reasonably short lapse of time (~1 day) following a strong shaking caused by an earthquake (irrespective of near or distant earthquake).

About the year 2000, the recording of streaming data from sensors in an instrumented building became possible, with the most reliable transmittal of data to a remote computer system for studies and/or applications accomplished using telephone lines. The streaming data were then correlated to the performance of each building. Then as now, a key variable to performance studies for reaching perfor-

[1]The City of San Francisco, California, has developed a “Building Occupancy Resumption Program” (BORP) [36] whereby a prequalified occupancy decision making process as described in this paper may be proposed to the city as a reduced inspection program but in lieu of detailed inspections by city engineers following a serious earthquake.

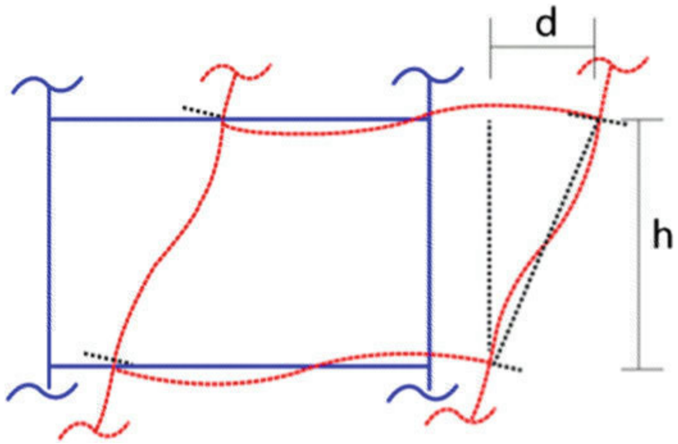

Fig. 1.1 Schematic describing drift ratio computation for a building (d = relative displacement between two consecutive floors, h = floor height)

mance decisions was displacement and, in turn, the drift ratios[2] of the building. Figure 1.1 displays a schematic of how drift ratios (DR = d/h) are computed regardless of whether or not data was sensor based or from mathematical modeling and analyses of the structural system of a building. It is important to note that due to the cost and or logistical difficulties in deploying sensors on every floor of a building, in most cases, this is not done, thus average drift ratios between a number of floors are also widely used.

About the year 2000, there were two challenges to performing this method: (1) how best to accurately measure or compute displacements in near real-time environment with minimal errors and compute drift ratios and (2) how displacements and/or drift ratios could be related to performance of buildings subjected to earthquake shaking. It was envisioned at the time that once these variables could be reliably acquired using sensors, rational performance-related structural dependent strategies could be developed.

Measuring physical deformation/displacement of a structure subjected to an excitation is very difficult and quite challenging exercise, except for cases of experimental lab-tests conducted in a controlled environment (e.g., using displacement transducers). Real-time measurements of displacement were acquired either directly using GPS or by double integration of accelerometer time-series data. Naturally, both approaches had pros and cons.

For structures with long-period responses, such as tall buildings, displacement measurements using GPS are measured directly only at the roof, so drift ratios are thus an average value for the building. On the other hand, for accelerometer-based systems, the accelerometers must be strategically deployed at specific locations on

[2]Drift ratio (DR) is defined as relative displacement between any two floors divided by the difference in elevation of the two floors. Usually, this ratio is computed for two consecutive floors.

several floors of a building to facilitate real-time measurement of the actual structural response used to compute displacements and drift ratios.

As stated earlier, GPS technology became the favored method because displacements could be measured without double-integration. It is important to stress that, during about the same period, it was not possible to perform speedy (near real time) retrieval and transmittal and then reliably double-integrate acceleration response data to arrive at displacements [37, 38]. However, the limitations of using GPS were (and mostly still are) (1) the GPS units have to be able to send/receive signals from a minimum number of satellites to minimize the error; (2) because GPS units could only be deployed at the roof of a building, the original computation of drift ratios computed with GPS data are therefore only average drift ratios over the total height of a building; (3) a technically acceptable nearby reference station on either the ground or roof of a 1–2 story stiff building (without interference from taller buildings in an urban setting) is required to compute relative displacements between the roof and the ground level (see the schematic of a typical GPS deployment at a building in Fig. 1.2); and (4) the highest sampling rate of the then commercially available GPS units was 10 Hz,[3] which limited the application to buildings of 20 stories or higher due to the corresponding Nyquist frequency ($f_n = 1/(2 \times \Delta t)$) [40] at 5 Hz ($0.5 \times$ sample rate), or to periods greater than 2 s.

Thus, if average drift ratios were considered acceptable, then the former approach is preferable and advantageous for taller buildings because direct measurement of displacements is easily converted into drift ratios.

In this schematic, accelerometers (force-balanced accelerometers, FBAs) are also included to facilitate verification of displacements recorded by GPS and vice versa. It is well known that accelerometers have been widely used over decades for seismic monitoring of buildings. Recorded accelerations from accelerometers strategically deployed throughout a building allow double-integration to get displacements. One could deploy as many accelerometers as was economically and physically feasible to improve the computation of drift ratios between two consecutive floors as shown in Fig. 1.1, or the average drift ratios between any two instrumented floors. Furthermore, if configured properly, an exact drift ratio between two consecutive floors of a building can be computed. There remains the possibility of processing errors—from raw data to double integrated displacements. However, with extensive experience in processing raw acceleration data by carefully selecting filters and baseline correction, such errors are minimized. Therefore, with advances in internet-based data transmittal or near real-time remote acquisition of streaming data, it became possible to use classical accelerometer data from deployed structures. As stated earlier, this led to the configuration of accelerometer data based on the establishment of the seismic health monitoring of structures [37, 38, 41].

Whether displacements are acquired using GPS or accelerometers, one must determine what levels of drift ratios are acceptable—to relate the displacement (and there-

[3] By 2006, as many as 50–100 samples per second (sps) differential GPS systems have been available on the market and have been successfully used [39]. Currently, GPS units with sampling rate of 100 Hz are commercially available.

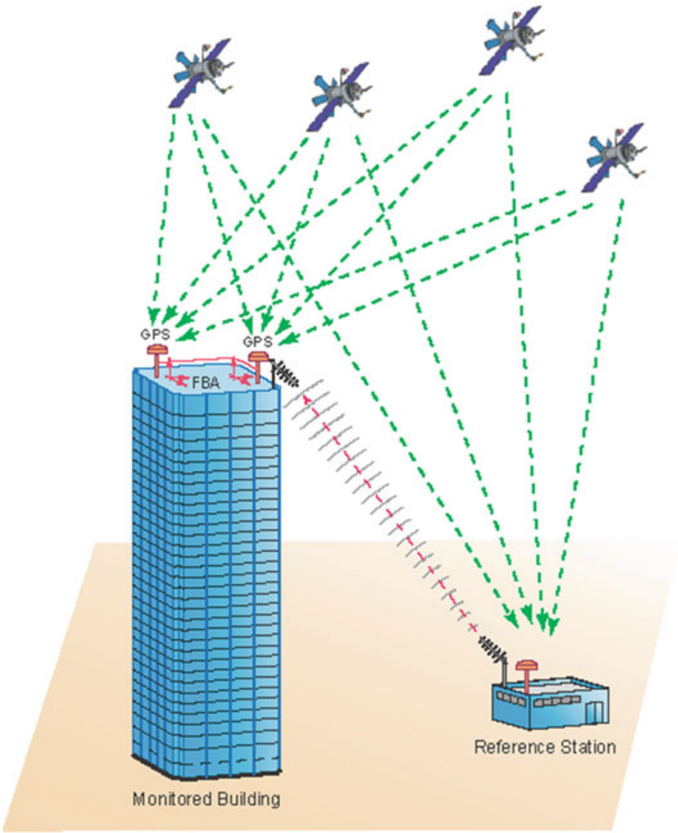

Fig. 1.2 General configuration for GPS acquisition of displacements in 35-story building in San Francisco, Calif. [37]

fore drift ratio data) to the seismic performance of a building. The most relevant parameter to assess performance of a building is the measurement or computation of actual or average story drift ratios. We have not found evidence of reliable applications using other parameters (e.g., mode shape variation, frequency variation). As hypothetically shown in Fig. 1.3 (modified from Figure C2-3 of FEMA 274 [42]), drift ratios are related to the performance-based force-deformation curve [37, 38, 41]. When drift ratios, as computed from relative displacements between consecutive floors, are determined from measured responses of the building, the performance and/or "damage state" of the building can be estimated as in Fig. 1.3. A reasonable number (3–5) of thresholds of levels of relative displacements (or drift ratios) can be established in relation to the desired level of performance. Therefore, structural engineers often determine the requisite level of thresholds in relation to the desired building performance in advance of a seismic event.

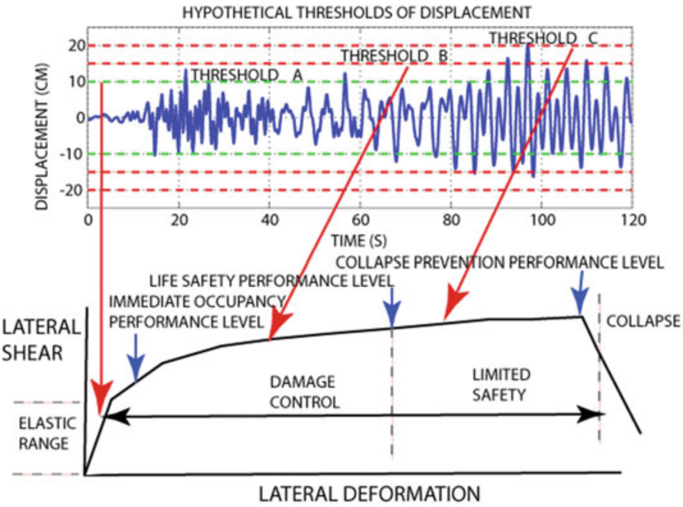

Fig. 1.3 Schematic of hypothetical thresholds of level of displacements related to performance curve as illustrated in FEMA 273 [43] and modified in Çelebi et al. [38]

Table 1.1 Typical threshold stages and ranges of drift ratios

Threshold stage	1	2	3
Suggested typical drift ratios (in percent)	0.2–0.3	0.6–0.8	0.4–2.2

In the final step, recorded sensor data are related to the performance level of a building and therefore to the performance-based design that stipulates the maximum amplitude of relative displacement of the roof of a building (with respect to its base) as an indication of its performance. Establishing sound criteria for performance is the most important step of the S^{2}HM process. As an example, Table 1.1 shows typical drift ratios for steel moment-resisting framed buildings. The table is developed from FEMA 352 [2]. For reinforced-concrete buildings, the lower figures may be more appropriate to adopt.

It is important to state that, as an alternative to FEMA 273 [43] or FEMA 352 [2] suggested values, structural engineers can compute drift ratios through analyses to establish limits related to acceptable performance levels according to Fig. 1.3.

Before these developments in early 2000, there were no other sensor (GPS or accelerometer) data-based performance assessments. As stated by Porter et al. [44, 45]:

> [Until now,] sensor information has played little role in PBEE (Performance Based Earthquake Engineering). A notable exception is Çelebi et al. [38] who recently combined sensor information with FEMA 273 (FEMA 1997) [43]. They illustrate the methodology with a 24-story steel-frame building that has been instrumented to compute interstory drift ratios at a few story levels with sensors at adjacent floors. These interstory drift ratios are then compared with drift limits associated with the FEMA-273 performance levels: operational,

immediately occupiable, life-safety, and collapse-prevention. When a drift limit is exceeded, the associated performance level is assumed to be exceeded.

Experience with both types of sensor deployments indicate that they are reliable enough (with acceptable levels of errors) and provide pragmatic alternatives to alert building owners and other authorized parties to make informed decisions and to select choices for predefined actions following significant events. Furthermore, the recent adoption of such methods by financial and industrial enterprises is testimony to their viability.

Thus, the processes advocated in Çelebi and Sanli [37] and Çelebi et al. [38] and Çelebi [41] and based on sensor-based data related to performance-based earthquake engineering (PBEE) are the first near real-time seismic structural-health monitoring (S^2HM) developments being used around the world.

1.3 Early Applications

1.3.1 Using GPS for Direct Measurements of Displacements

As stated before, before the year 2000, use of GPS was limited to long-period structures ($T > 1$ s) because differential GPS systems readily available were limited to 10–20 samples per second (sps) capability[4] with an error of ± 1 cm horizontal and ± 2 cm vertical. Furthermore, with GPS deployed on buildings, measurement of displacement is possible only at the roof [37]. Technology has not yet advanced to detect signals from GPS antennas placed on various floors within a building, as the antennas need to "see" the satellites.

1.3.1.1 Early Testing with GPS

Before going forward with actual utilization of GPS for S^2HM of a tall building, we tested GPS capability and reliability with a rather primitive model (Fig. 1.4). Also, prior research provided confidence in the technical feasibility of using GPS technology to measure displacements of civil structures. Aerospace (atmospheric) researchers have accomplished most of the initial work. Studies related to the application of GPS for static or dynamic measurements of displacements of structural systems include but are not limited to those by Hyzak et al. [46], Teague et al. [47], Guo and Ge [48], Kondo and Cannon [49], Lovse et al. [50], Hudnut and Behr [51], Behr et al. [52], and Stein et al. [53]. Temporary deployments to dynamically monitor excessive deflections due to wind, in the decimeter range, of the 1410-m-long Humber Bridge on the east coast of England were successfully carried out [54]. In Japan,

[4] Recently, up to 50 samples per second (sps) differential GPS systems are available on the market and have been successfully used Panagitou et al. [39].

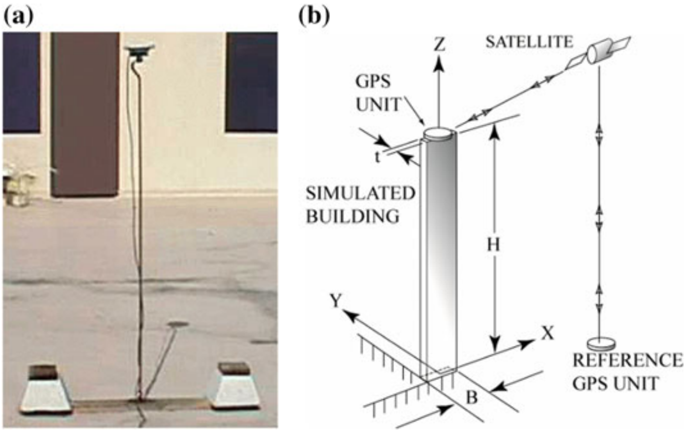

Fig. 1.4 **a** Photograph and **b** schematic of test set-up to simulate using GPS for dynamic monitoring of tall buildings (from [57])

Nakamura [55] cited semistatic displacement measurements (sampling at 1 Hz) of a suspension bridge using temporarily deployed GPS units. Although it is not directly mentioned as to whether permanent and continuous measurements were made, Toriumi et al. [56] depict several meter-level dynamic GPS displacement measurements at the Akashi Bridge, the world's longest span suspension bridge. In the current application, the aim has been actual permanent deployment of GPS units to dynamically obtain displacements during strong-motion events in real or near-real time. More recently, as many as 50 sps differential GPS systems readily available were successfully used on a shaking-table test of a shear-wall building ([39], Jose Restrepo, Univ Calif. San Diego, written communication, 2007)—thus enabling future application of GPS to all types of structures.

To confirm technical feasibility of such an application, before investing a lot of time and fiscal resources on an actual deployment on a building, Çelebi et al. [57] performed tests using a primitive model structure using two bars 1.82 m (6 ft) in length with small thicknesses (0.32 cm [1/8 in.]) and widths of 1.5 in. (3.8 cm) and 2 in. (5 cm), respectively. Figure 1.4 depicts a photo and the overall setup for a simple and inexpensive experiment designed by selecting a standard stock steel bar to simulate a 30- to 40-story flexible building. The authors selected the length, thickness, and width of the two bars to yield a fundamental period of approximately 4 s in the weak direction. For simplicity, the authors purposefully selected the width and thickness of each of the two bars with an extremely weaker axis in one direction. The width was varied to show the sensitivity of measurements during vibration and at a 10-Hz sampling rate. Each bar was fixed at the base, and the GPS unit was attached at its tip. By providing an initial displacement (simply by pulling the top of the bar and releasing), each bar was set into free vibration and its motion was recorded. Results are summarized in Table 1.2. Figure 1.5 shows the particle motion and time-history of one of the tests performed. The axes of the bar were at an angle to

Table 1.2 Results of tests with GPS units (f = frequency, T = period; see Fig. 1.4b for explanation of H, B, and t) (from [57])

Specimen	Length [H] (m (ft))	Width [B] (in. (cm))	Thickness [t] (in. (cm))	Measured [f] (Hz)	Measured [T] (s)	Damping [ξ] (%)
Bar A	1.82 (6)	3.8 (1.5)	0.32 (1/8)	0.245	4.08	~2.0
Bar B	1.82 (6)	5.0 (2.0)	0.32 (1/8)	0.296	3.38	~2.0

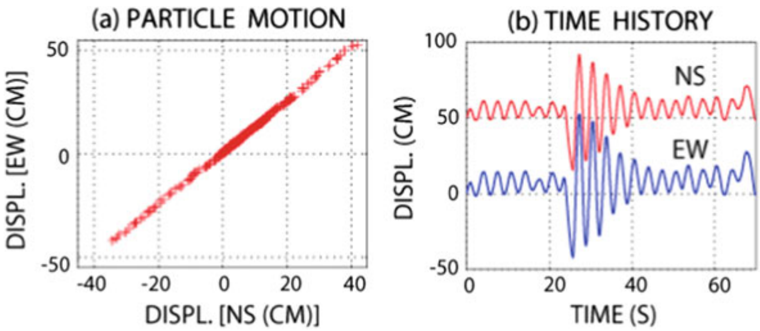

Fig. 1.5 **a** Particle motion and **b** time-history of relative displacements (north-south and east-west components) of simulated test specimen (from [57])

the north-south (N-S) and east-west (E-W) directions. Therefore, the N-S and E-W components of displacements are identical in phase and proportional in amplitude. Also, because the GPS unit is not symmetrically and concentrically mounted in the weak direction (Fig. 1.4a), the amplitudes of positive and negative displacements measured are not the same. The detection of the effect of the eccentric mass adds to the assurance that the measurements are accurate and sensitive. The simple tests and results of Çelebi et al. [57] can be validated easily elsewhere.

Figure 1.6 is a plot of NS components of measured relative displacements and corresponding amplitude spectra of bars A and B. The figure shows the accuracy and sensitivity of GPS monitoring technology at 10 sps. The measurements differentiate between the frequency of the free-vibration response of the two bars with different dynamic characteristics. From the data, the fundamental frequency (period) of the two bars are identified to be 0.245 Hz (4.08 s) and 0.296 Hz (3.38 s), respectively. Also, a damping percentage of approximately 2% is determined. This simple test shows that sampling at 10 Hz with GPS units provides a clear and accurate displacement response history (with high signal-to-noise ratio) from which drift ratios and dynamic characteristics of the specimen can be derived [57].

The tests clearly demonstrate the reliability of GPS measurements from forced vibration. Later Tamura et al. [58] performed similar successful tests before using GPS in larger tall building monitoring projects in Japan.

A schematic of a real-life application using GPS to directly measure displacements was shown earlier in Fig. 1.2, where two GPS units are used to capture both

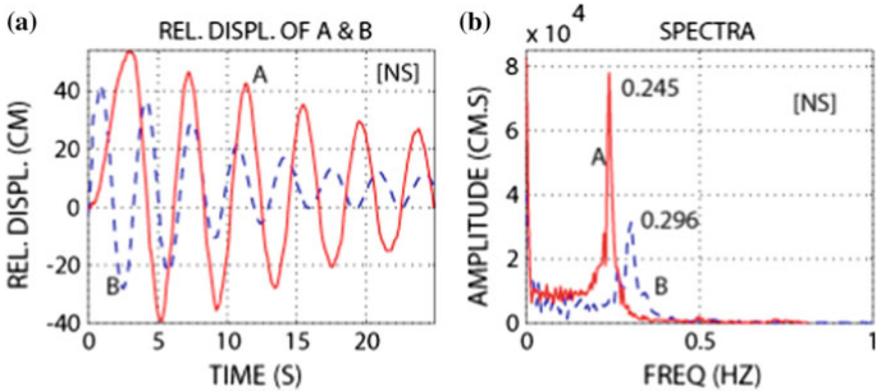

Fig. 1.6 **a** Relative displacements of two test specimens (north-south components only) in free-vibration (**a**) and **b** corresponding amplitude spectra identifying the fundamental frequencies of the test specimens (from [57])

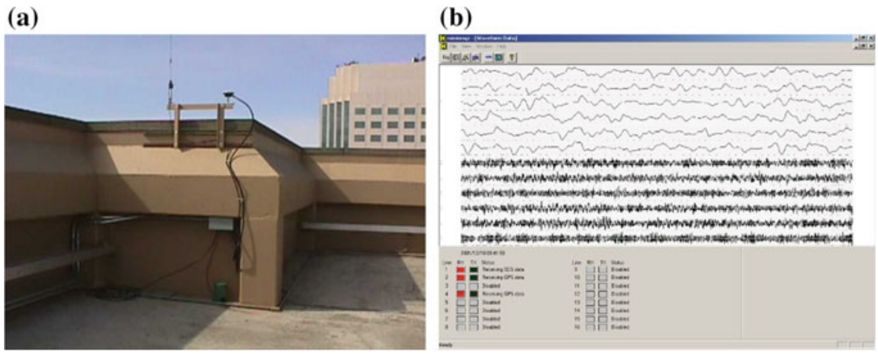

Fig. 1.7 **a** Picture of deployment of GPS antenna at the roof of a 35-story building in San Francisco, Calif. Schematic of the overall system using GPS and accelerometers is shown in Fig. 1.2. **b** Screen capture of streaming acceleration and displacement data in real time (from [57])

the translational and torsional response of the 35-story building in San Francisco, California. Figure 1.7a shows one of the GPS antennas, as well as a triaxial accelerometer deployed to compare the displacements measured by GPS with those obtained by double-integration of the accelerometer records. Figure 1.7b shows screen captured acceleration and displacement data streaming into the monitoring system.

To date, strong shaking data from the deployed system has not been recorded. However, ambient data (Fig. 1.8a–d) obtained from both accelerometers and GPS units are analyzed (Fig. 1.9). Sample cross-spectra (Sxy) (Fig. 1.9a–d) and coherency and phase angle plots (Fig. 1.9e–h) of pairs of parallel records N-S component of north deployment [N_N] versus N-S component of south deployment [S_N], from accelerometers are shown in Fig. 1.9e–f. The same is repeated for the differential displacement records from GPS units (Fig. 1.9g–h). Frequency of 0.24–0.25 Hz seen

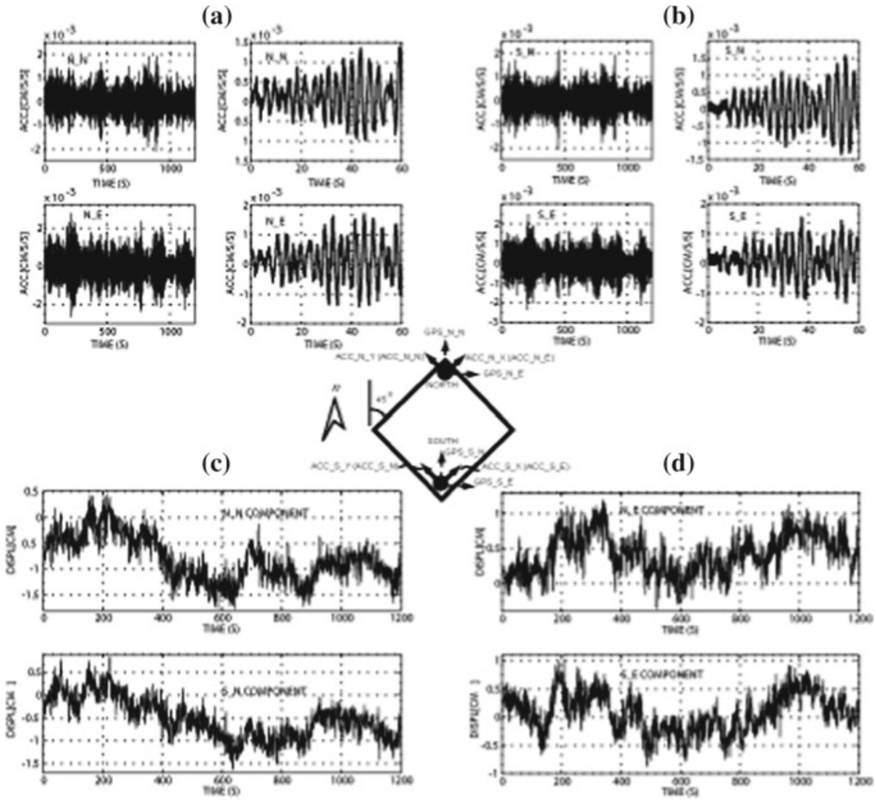

Fig. 1.8 **a**, **b** Remotely triggered and recorded (1200 and 60-second windows) accelerations at N (north) and S (south) locations, respectively, and **c**, **d** remotely triggered and recorded displacements from GPS at N (north) and S (south) locations, respectively, for a 35-story building in San Francisco, Calif. Locations are defined in the central schematic (from [57])

in Sxy plots from both acceleration and displacement data belong to the expected fundamental frequency for a 35-story building. A second frequency at 0.31 Hz (from acceleration data) Hz is belongs to the torsional mode. Background information on coherency and related spectral relations are found in Bendat and Piersol [59].

At 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.

One comment on this is that using GPS monitoring of tall buildings should be a proven option but with the caveat that decision-making on performance is based on average drift ratio.

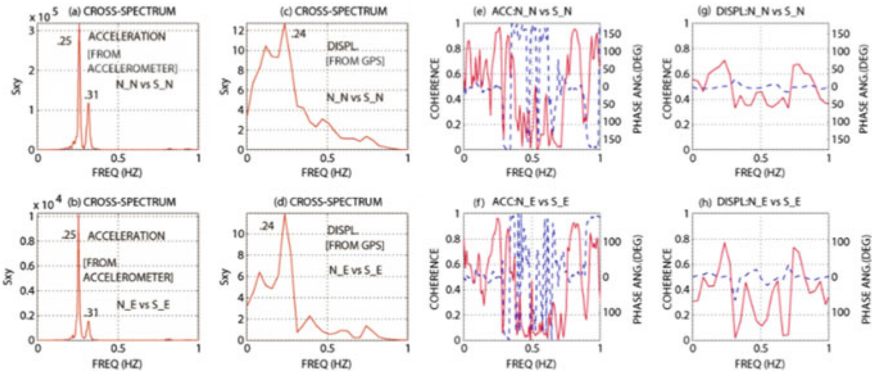

Fig. 1.9 Cross-spectra (Sxy) (**a**, **b**) of accelerations from accelerometers and (**c**, **d**) displacements from GPS and associated coherency and phase angle plots of horizontal and parallel (**e**, **f**) accelerations [**e**, **f**] and (**g**, **h**) from GPS displacements for a 35-story building in San Francisco, Calif. [*Note* In the coherency-phase angle plots, solid lines are coherency and dashed lines are phase-angle] (from [57])

1.3.2 Early Development—S²HM Use of Displacement Via Real-Time Double Integration of Accelerations

For S²HM purposes, a proven alternative to using GPS technology to acquire displacements is through a strategical configuration of accelerometer-based monitoring of buildings. As mentioned before, about the year 2000, with the advent of real-time streaming of acceleration responses which are double-integrated in near real-time to obtain displacements opened opportunities for an accelerometer-based S²HM capability.

A general flowchart for an alternative strategy based on computing displacements in real-time from signals of accelerometers strategically deployed throughout a building is depicted in Fig. 1.10 and described by Çelebi [41]. Although ideal, generally, deploying multiple accelerometers in every direction on every floor level is not a feasible approach. This is due to installation costs and also being able to robustly (1) stream n number of accelerations from *n* number of channels, (2) compute and stream displacements and drift ratios after double integration of accelerations, and (3) visually display threshold exceedences, thus fulfilling the objective of timely assessment of performance level and damage conditions.

A schematic of the very first deployed structural-health monitoring system that uses these principles is shown in Fig. 1.11 [38, 41]. The distribution of accelerometers provides data from several pairs of neighboring floors to facilitate drift computations.[5] The system server at the site (1) digitizes continuous analog data, (2)

[5]The locations of sensors are generally dictated by the desire to obtain optimum response data from different floors and within strategic locations of those floors to compute reliable drift ratios for assessing near real-time performance of a building during an earthquake. Cost also becomes

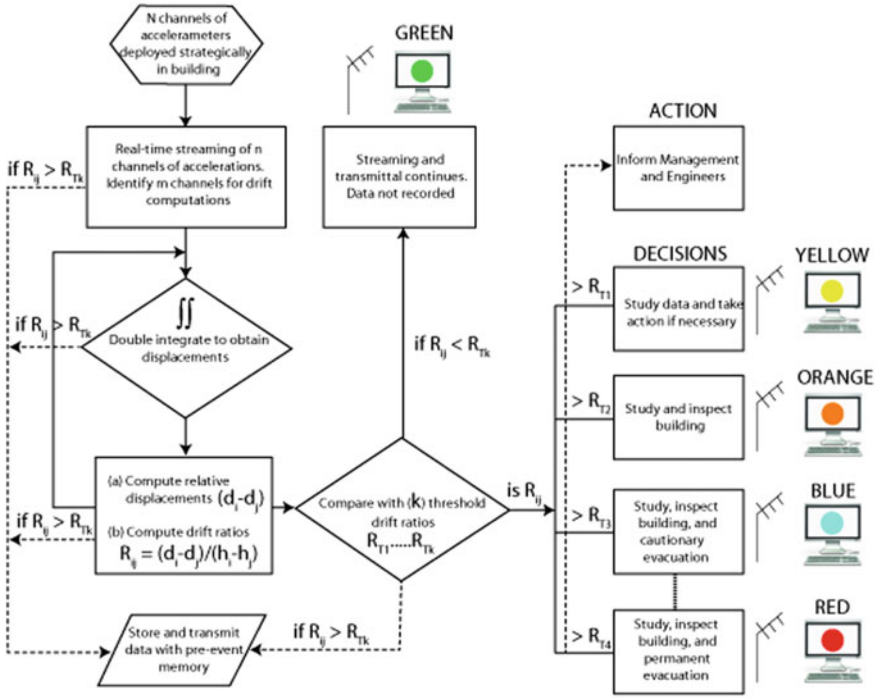

Fig. 1.10 Flow-chart for observation of structural damage levels based on threshold drift ratios as described in Fig. 1.3 (flowchart from [41])

preprocesses the 1000 sps digitized data with low-pass filters, (3) decimates the data to 200 sps and streams it locally, (4) monitors and applies server triggering threshold criteria and locally records the shaking of the building (with a pre-event memory) when prescribed thresholds are exceeded, and (5) broadcasts the data continuously to remote users by high-speed internet. Data can also be recorded on demand to facilitate studies while waiting for strong shaking events.

Whereas Fig. 1.10 depicts the logical process to configure acceleration to displacement dependent S^2HM software, Fig. 1.11a depicts, in general, all elements of this new approach in obtaining structural displacements in near real-time, transmittal of data using the internet, and configuration of performance computations in an onsite or offsite remote server. Figure 1.11b depicts the numbering system and orientations of accelerometers. This schematic actually is representative of the system installed

a consideration. In general, on each instrumented floor, a minimum of three accelerometers are deployed—two parallel at a distance apart to facilitate computation of torsion and the third orthogonal to the other two. A minimum of three verticals are deployed at the basement in ground-level corners to compute rocking, if any [29]. The Los Angeles Tall Buildings Structural Design Council [60] provides guidance also for number of accelerometers according to number of floors of a building (e.g., they recommend 36 channels for buildings taller than 50 stories). However, for S^2HM purposes, the number of accelerometers should be greater.

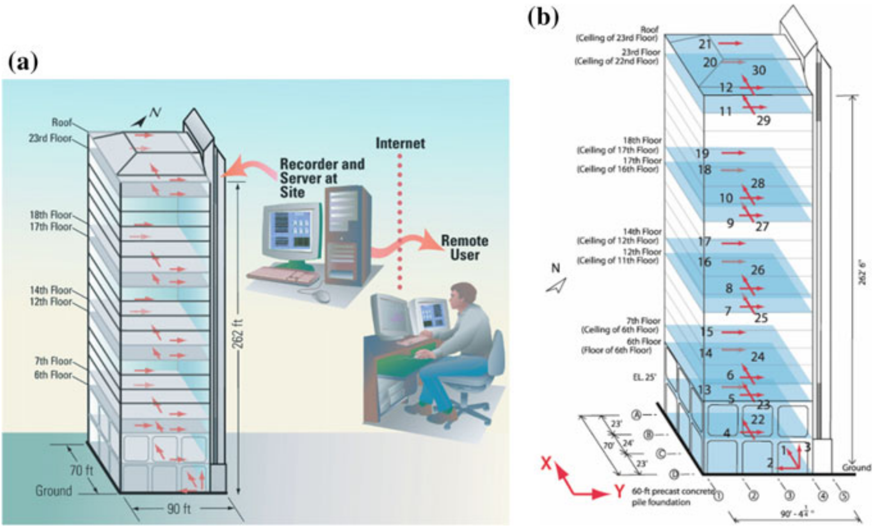

Fig. 1.11 **a** General schematic of data acquisition and transmittal for seismic monitoring of a 24 story building using accelerometers as sensors. **b** Numbering system and orientations (from [38])

in a 24-story building in San Francisco shown in Fig. 1.2. As mentioned earlier, to the best of our knowledge, this actual development is based on the initial project that led to the earliest S^{2}HM development (between 1999 and 2002) in the USA, as well as the world. It is relevant here to state that the project and resulting development was initiated because the building owner and their consultants needed a monitoring system that could be used to make informed decisions about performance and functionality after an earthquake and how soon the building could be re-occupied. By using this technology, the objective of the owners and the consultants was to meet the requirements of San Francisco's BORP [36], in lieu of tagging as described in the Introduction section of this chapter. Thus, in consideration of financing but without sacrificing reliability, the accelerometer-based array used in the building was designed to provide data from several pairs of neighboring floors to facilitate drift ratio computations.

The broadcast streamed real-time acceleration data were acquired remotely using building-specific S^{2}HM software that was configured to compute velocity, displacement, and drift ratios or average drift ratios as needed. Figure 1.12 shows two computer screenshots of the client software display configured for 12 channels of streaming acceleration, velocity, displacement, or drift-ratio time series. Around the year 2000, at the time of this development, this was the limit of number of channels could be displayed as streaming on a screen. However, computations were made for all combinations to arrive at drift ratios. Each paired set of acceleration response streams was displayed with a different color. The amplitude spectrum for one of the selected channels was periodically recomputed and clearly displayed several identifiable frequencies. In the lower left of Fig. 1.12a, b, time series of drift ratios are

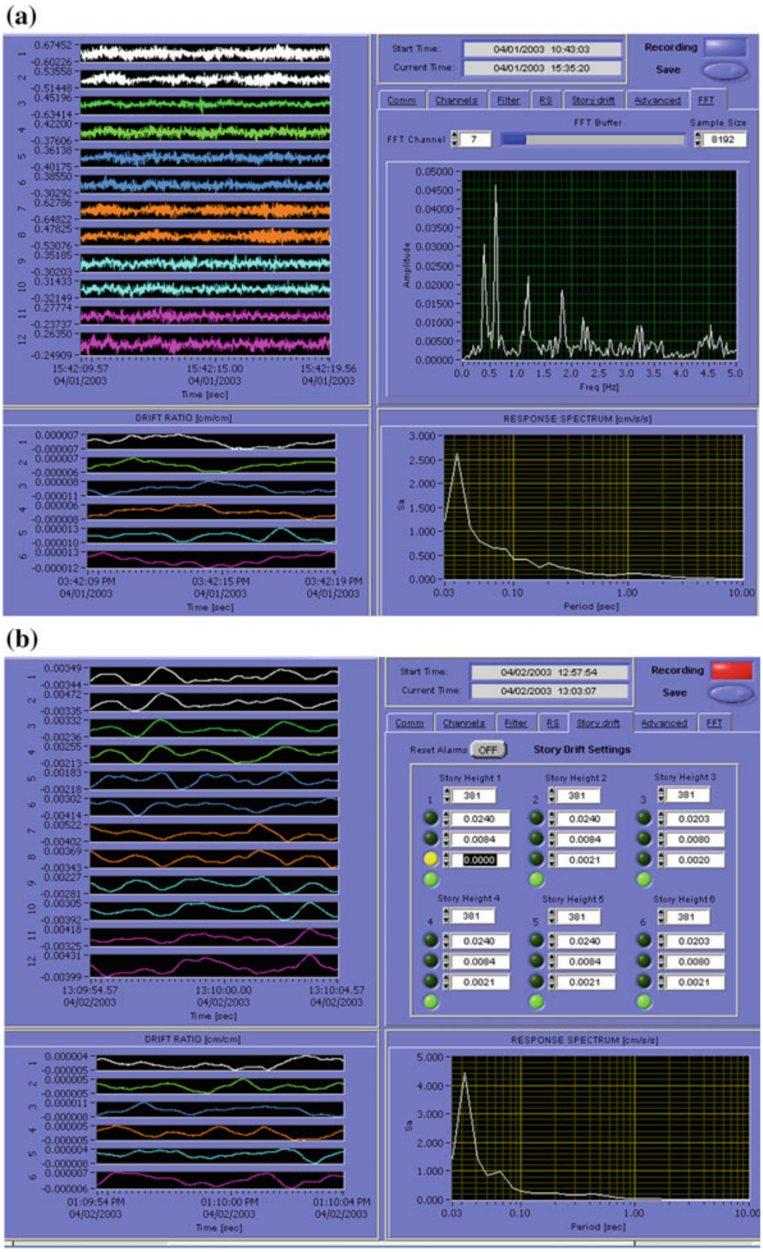

Fig. 1.12 **a** Screenshot of S^{2}HM client software display showing acceleration streams and computed amplitude and response spectra. **b** Screenshot of S^{2}HM client software display showing 12-channel (six pairs with each pair a different color) displacement and corresponding six drift-ratio (each with the same color as the parent 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 (from [38])