REAL-TIME MONITORING OF DRIFT FOR OCCUPANCY RESUMPTION

M. Çelebi[1]

[1] **Research Civil Engineer and Manager of Structural Monitoring, USGS,
345 Middlefield Road, Menlo Park, CA., USA
Email: celebi@usgs.gov**

ABSTRACT :

At selected locations of instrumented structures, real-time displacements are acquired by either double integration of accelerometer time-series data, or differential GPS with high sampling ratios deployed at roofs of tall buildings. Thus, sensor data is related to performance level and health of a building. Drift ratios are computed as the parametric indicator of damage condition of a structure. Several levels of threshold drift ratios can be postulated in order to make decisions for inspections and/or occupancy. Drift ratio is computed using relative displacement between two floors computed from accelerometers strategically deployed at select number of pairs of consecutive floors. However, GPS-measured relative displacements are limited to being acquired only at the roof with respect to its reference base - yielding only average drift ratio for a building. Until recently, GPS systems available were limited to 10-20 samples per seconds (sps) capability – limiting their use only to long-period structures (T>1 s). Most recently, up to 50 sps differential GPS systems readily available are successfully used (Panagitou et al, 2006, Restrepo, *pers. comm*.. 2007) – thus enabling future usefulness of GPS to all types of structures. Experience with data acquired from both accelerometers and GPS deployments indicates that they are reliable and provide pragmatic alternatives to alert the owners and other authorized parties to make informed decisions and select choices for pre-defined actions following significant events. Furthermore, recent adoption of such methods by financial and industrial enterprises is testimony to their viability.

KEYWORDS: Drift ratio, occupancy, damage indicator, accelerometer, displacement, GPS

1. INTRODUCTION

1.1. Background and Rationale

Following an earthquake, rapid and accurate assessment of the damage condition or performance of a building is of paramount importance to stakeholders, including 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 infrastructures. These stakeholders will require answers to key questions such as: (a) is there visible or hidden damage?, (b) if damage occurred, what is the extent?, (c) does the damage threaten other neighboring structures?, (d) can the structure be occupied immediately without compromising life safety or is life safety questionable? As a result, property damage and economic loss due to lack of permit to enter and/or re-occupy a building may be significant.

Until recently, assessments of damage to buildings following an earthquake were essentially carried out through inspections by city-designated engineers following procedures similar to ATC-20 tagging requirements *(ATC* 1989). Tagging usually involves visual inspection only and is implemented by colored tags indicative of potential hazard to occupants: green indicating the building can be occupied - that is, the building does not pose a threat to life safety; yellow indicates limited occupation - that is, hazardous to life safety but not to prevent limited entrance to retrieve possessions; and red indicating 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 building finishes and fireproofing. In the absence of visible damage to the building 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 deformations that the building experienced may typically lead an inspector toward a relatively conservative tag. In such cases, expensive and time-consuming intrusive inspections may be recommended to building owners (e.g., it is known that, following the [M_w=6.7] 1994 Northridge, CA earthquake, approximately 300 buildings ranging in height from 1 to 26 stories were subjected to costly intrusive inspection of connections (FEMA352, SAC 2000)).

This paper describes an alternative to tagging that is now available to owners and their designated engineers by configuring real-time response of a structure instrumented as a health monitoring tool. As Porter and others (2006) state, most new methods do not utilize real-time measurements of deformations of a building for assessments of a building's performance during an event with the exception outlined by Çelebi and Sanli (2002) and Çelebi and others (2004). In these applications, differential GPS (Çelebi and Sanli, 2002) with high sampling ratios and classical accelerometer deployed structures (Çelebi and others, 2004) are configured to obtain data in real-time and compute drift ratios[1] as the main parametric indicator of damage condition of a structure or one or more components of a structure. The rationale here is that a building owner and designated engineers are expected to use the response data acquired by a real-time health monitoring system to justify a reduced inspection program as compared to that which would otherwise be required by a city government for a similar non-instrumented building in the same area[2]. It is possible, depending on the deformation pattern and associated damage indicators observed in a building, to direct the initial inspections toward specific locations in the building that experienced large and potentially damage-inducing drifts during an earthquake.

Examples of and data from either type of sensor deployment (GPS or accelerometers) indicate that these methods are reliable and provide requisite information for owners and other parties to make informed decisions and select choices for pre-defined actions following significant events. Furthermore, recent additional adoptions of such methods by financial and industrial enterprises validate its usefulness.

1.2. Requisites

The most relevant parameter to assess performance is the measurement or computation of actual or average story drift ratios. Specifically, the drift ratios can be related to the performance-based force-deformation curve hypothetically represented in Figure 1 [modified from Figure C2-3 of *FEMA-274* (ATC 1997)]. When drift ratios, as computed from relative displacements between consecutive floors, are determined from measured responses of the building, the performance, and as such "damage state", of the building can be estimated as in Figure 1.

---

[1] Drift ratio 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.

[2] The City of San Francisco, California, has developed a "Building Occupancy Resumption Program" (BORP, 2001) whereby a pre-qualified Occupancy decision-making process, as described in this paper, may be proposed to the City as a reduced inspection program and in lieu of detailed inspections by city engineers following a serious earthquake.

Measuring displacements directly is very difficult and, except for tests conducted in a laboratory (e.g., using displacement transducers), has not yet been feasible for a variety of real-life structures. For structures with long-period responses, such as tall buildings, displacement measurements using GPS are measured directly at the roof only; hence, drift ratio then is an average drift ratio for the whole building. Thus, recorded sensor data is related to performance level of a building and hence to performance-based design, which stipulates that for a building the amplitude of relative displacement of the roof of a building with respect to its base indicates its performance. For accelerometer-based systems, the accelerometers must be strategically deployed at specific locations on several floors of a building to facilitate real-time measurement of the actual structural response, which in turn is used to compute displacements and drift ratios as the indicators of damage.

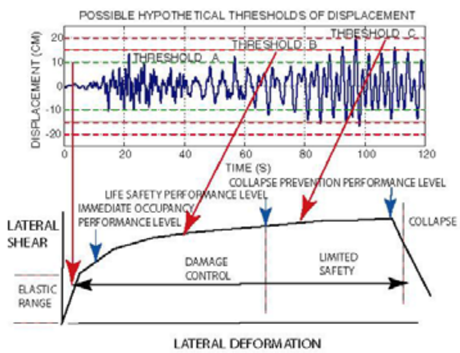

Figure 1. Hypothetical displacement time-history as related to performance [modified from Figure C2-3 of *FEMA-274* (ATC 1997)].

Table 1 shows typical ranges of drift ratios that define threshold stages for steel moment resisting framed buildings. The table is developed from FEMA 352 (also SAC 2000). For reinforced concrete framed buildings, the lower figures may be more appropriate to adopt.

Table 1. Summary of Suggested Typical Threshold Stages and Ranges of Drift Ratios

Threshold Stage	1	2	3
Suggested Typical Drift Ratios	0.2-0.3%	0.6-0.8%	1.4-2.2%

2. TWO APPROACHES FOR MEASURING DISPLACEMENTS

2.1. Use of GPS for Direct Measurements of Displacements

2.1.1. Early Pioneering Application of GPS

Until recently, use of GPS was limited to long-period structures (T>1 s) because differential GPS systems readily available (with the accuracy of 10-20 Hz GPS measurements is ± 1 cm horizontal and ± 2 cm vertical) were limited to 10-20 sps capability. Recently, up to 50 sps differential GPS systems are available on the market and have been successfully used (Panagitou et al, 2006, and J. I. Restrepo, *personal correspondence*, 2007). It is stressed herein that, with GPS deployed on buildings, measurement of displacement is possible only at the roof.

A schematic and photos of a pioneering application using GPS to directly measure displacements is shown in Figure 2. 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 (Çelebi and Sanli, 2002). At the same locations as the GPS antennas, tri-axial accelerometers are deployed in order to compare the displacements measured by GPS with those obtained by double-integration of the accelerometer records. Both acceleration and displacement data stream into the monitoring system as shown also in Figure 2.

To date, strong shaking data from the deployed system has not been recorded. However, ambient data obtained from both accelerometers and GPS units (Figures 3a-d) have been analyzed. Sample cross-spectra (Sxy) and coherency and phase angle plots of pairs of parallel records (N-S component of north deployment [N_N] vs. N-S component of south deployment [S_N], from accelerometers are shown in Figures 3e-f. The same is repeated for the differential displacement records from GPS units (Figures 3g-h). The dominant peak in frequency at 0.24-.25 Hz seen in cross-spectra (Sxy) plots from both acceleration and displacement data are compatible with expected fundamental frequency for a 34-story building. A second peak in frequency at 0.31 Hz in the acceleration data belongs to the torsional mode.

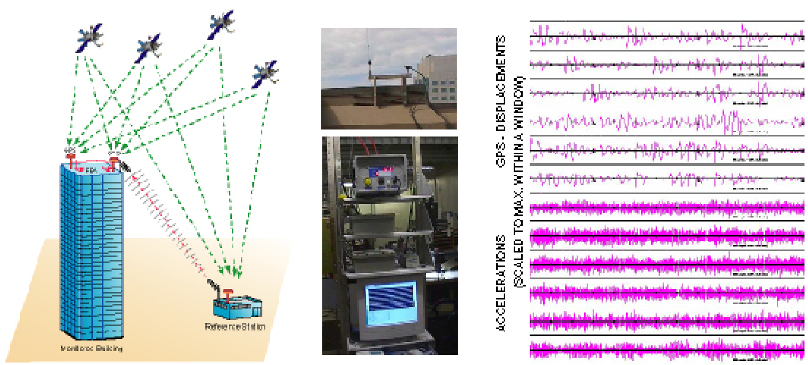

Figure 2. (Left)- Schematic of the overall system using GPS and accelerometers (San Francisco, CA.): (Center)- GPS and radio modem antenna and the recorders connected to PC, (Right)- streaming acceleration and displacement data in real-time.

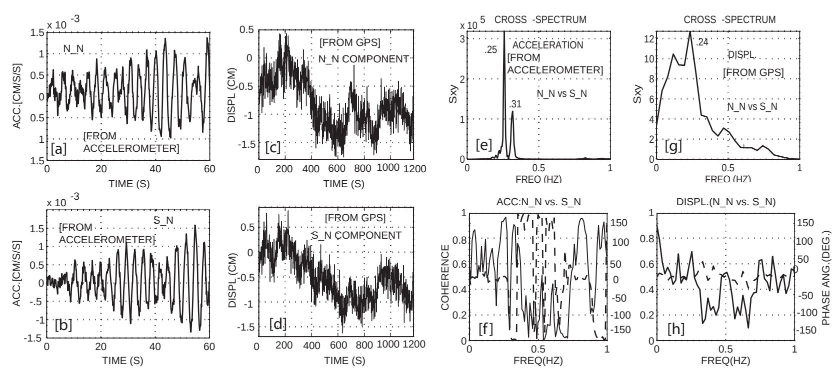

Figure 3. [a,b] 60-second windowed accelerations and [c,d] 1200 second windowed GPS displacement data in the north-south orientation and at N (North) and S (South) locations (acceleration data sampled at 200 sps and GPS at 10 sps). Cross-spectra (Sxy) and associated coherency and phase angle plots of horizontal, and parallel accelerations [e,f] and GPS displacements [g,h]. [Note: In the coherency-phase angle plots, solid lines are coherency and dashed lines are phase-angle].

At the fundamental frequency at 0.24 Hz, the displacement data exhibits a 0^o phase angle; however, the coherencies are low (~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.

2.2. Displacement via Real-time Double Integration

A general flowchart for an alternative strategy based on computing displacements and drift ratios in real-time from signals of accelerometers strategically deployed throughout a building is depicted in Figure 4 and described by Çelebi and others (2004). Although ideal, deploying multiple accelerometers in every direction on every floor level is not a feasible approach, not only because of the installation cost, but also from the point of view of being able to robustly, and in near real-time, (a) stream accelerations, (b) compute and stream displacements and drift ratios after double-integration of accelerations, and (c) visually display threshold exceedences, thus fulfilling the objective of timely assessment of performance level and damage conditions.

A schematic of a recently deployed health monitoring system which utilizes these principles is shown in Figure 5 (Çelebi and others, 2004). The distribution of accelerometers provides data from several pairs of neighboring floors to facilitate drift computations. The system server at the site (a) digitizes continuous analog data, (b) pre-processes the 1000 sps digitized data with low-pass, anti-alias filters (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. Data can also be recorded locally on demand to facilitate studies while waiting for strong shaking events.

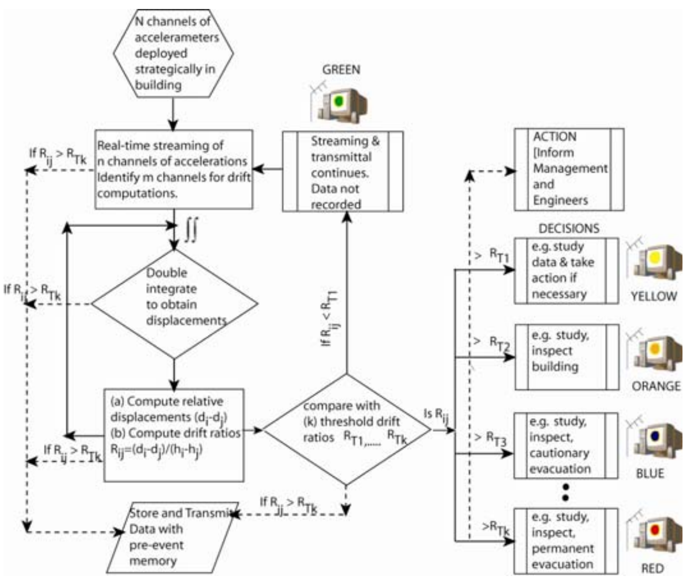

Figure 4. Flow-chart for observation of damage levels based on threshold drift ratios.

A "Client Software" remotely acquires acceleration data that can then be used to compute velocity, displacement and drift ratios. Figure 6 shows two PC screen snapshots of the client software display configured to stream acceleration or velocity or displacement or drift ratio time series. The amplitude spectrum for one of the selected channels is periodically recomputed and clearly displays several identifiable and distinct frequency peaks. In the lower left, time series of drift ratios are shown.

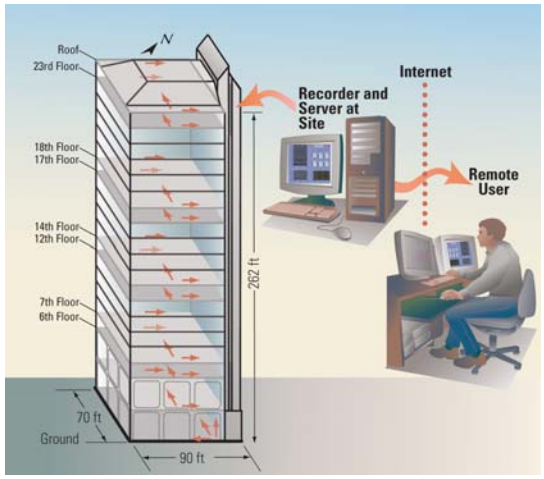

Figure 5. Schematic of real-time seismic monitoring of the building.

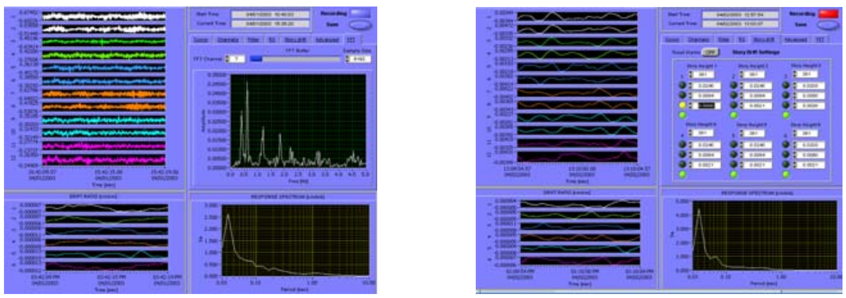

Figure 6. Screen snapshots of sample client software displays: (left) acceleration streams and computed amplitude and response spectra, and (right) displacement and corresponding drift ratios and alarm systems corresponding to thresholds.

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, additional indicators are activated, each with a different color (see Figure 4). The drift ratios are calculated using data from any pair of accelerometer channels oriented in the same direction. The threshold drift ratios for alarming and recording are computed and determined by structural engineers using structural information and are compatible with the performance-based theme, as previously illustrated in Figure 1.

A set of low-amplitude accelerations (largest peak acceleration ~ 1 % g) recorded in the building during the December 22, 2003 San Simeon, CA. earthquake (Mw=6.4, epicentral distance 258 km) are exhibited in Figure 7 for one side of the building. Figure 7 (center) also shows accelerations at the roof and corresponding amplitude spectra for the (a) two parallel channels (Ch12 and Ch21), (b) their differences (Ch12-Ch21), and (c) orthogonal channel (Ch30). The amplitude spectra depicts the first mode translational and torsional frequencies as 0.38 Hz and 0.60Hz respectively. The frequency at 1.08 Hz belongs to the second translational mode. At the right of Figure 7, a 20 s window of computed displacements starting 20 s into the record reveals the propagation of waves from the ground floor to the roof. The travel time is about 0.5 seconds. Since the height of the building is known (262.5 ft [80m]), travel velocity is computed as 160 m/s. One of the possible approaches for detection of possible damage to structures is by keeping track of significant changes in the travel time, since such travel of waves will be delayed if there are cracks in the structural system (Safak, 1999).

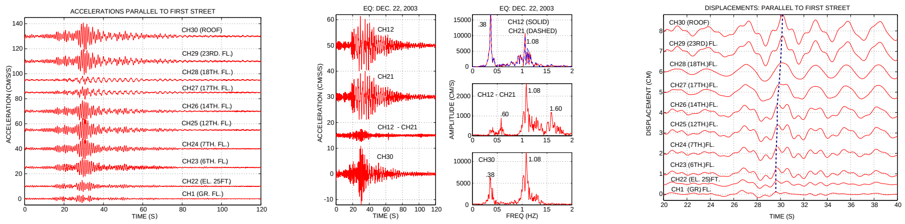

Figure 7. Accelerations for the 12/22/2003 San Simeon, CA earthquake [(left) at instrumented floors on one side of the building, (center) from parallel roof channels (CH12, CH21), their difference (CH12-CH21), and orthogonal CH30, and corresponding amplitude spectra indicate fundamental frequency at 0.38 Hz. (right) A 20-s window of computed displacements shows propagating waves [travel time of ~ 0.5 s - indicated by dashed line] from the ground floor to the roof.

3. MONITORING SINGLE STRUCTURE VS. CAMPUS STRUCTURES

Rather than having only one building monitored, there may be situations where some owners desire to monitor several buildings simultaneously, such as on industrial campus. Figure 8 schematically shows a campus-oriented monitoring configuration. Depending on the choice of the owner and consultants, a campus system may have building-specific or central-monitoring systems and as such is highly flexible in configuration. As can be stipulated, potential variations and combinations of alternatives for a campus-wide monitoring system are tremendous. There can be central-controlled monitoring as well as building-specific monitoring or both. A wide variety of data communication methods can be configured to meet the needs (Figure 8).

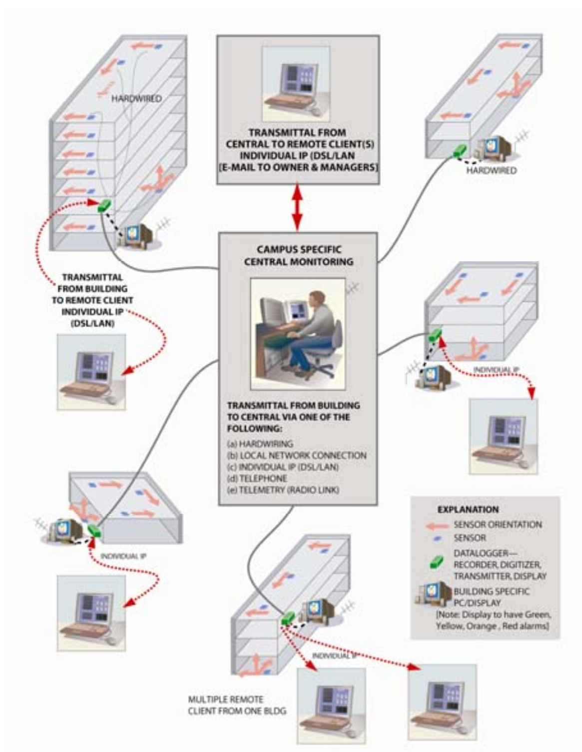

Figure 8. A schematic of campus-oriented monitoring system. Each building within a campus may have its own monitoring system or there may a central monitoring unit.

4. CONCLUSIONS

Capitalizing on advances in global positioning systems (GPS), in computational capabilities and methods, and in data transmission technology, it is now possible to configure and implement a seismic monitoring system for a specific building with the objective of rapidly obtaining and evaluating response data during a strong shaking event in order to help make informed decisions regarding the health and occupancy of that specific building. Displacements, and in turn, drift ratios, can be obtained in real-time or near real-time through use of GPS technology and/or double-integrated acceleration. Drift ratios can be related to damage condition of the structural system by using relevant parameters of the type of connections and story structural characteristics including its geometry. Thus, once observed drift ratios are computed in near real-time, technical assessment of the damage condition of a building can be made by comparing the observed with pre-determined threshold stages. Both GPS and double-integrated acceleration applications can be used for performance evaluation of structures and can be considered as building health-monitoring applications. Although, to date, these systems were not tested during strong shaking events, analyses of data recorded during smaller events or low-amplitude shaking are promising.

REFERENCES

Applied Technology Council (ATC), 1989. Procedures for Post-Earthquake Safety Evaluation of Buildings, ATC-20, Redwood City, CA.

Applied Technology Council (ATC). (1997). NEHRP Commentary on the Guidelines for the Seismic Rehabilitation of Buildings, prepared for the Building Seismic Safety Council, published by the Federal Emergency Management Agency, FEMA 274, Washington, D.C.

Building Occupancy Resumption Program (BORP), 2001. City and County of San Francisco, Department of Building Inspection, Emergency Operation Plan, (Rev. 2001). [www.seaonc.org/member/committees/des_build.html).

Çelebi, M., and Sanli, A. (2002). GPS in Pioneering Dynamic Monitoring of Long-Period Structures, ***Earthquake Spectra,*** Journal of EERI,. Volume 18, No. 1, pages 47–61, February 2002.

Çelebi, M., Sanli, A., Sinclair, M., Gallant, S., and Radulescu, D. (2004). Real-Time Seismic Monitoring Needs of a Building Owner and the solution – A Cooperative Effort, Journal of EERI, ***Earthquake Spectra***, v.19, Issue 1, pp.1-23.

FEMA-352: Recommended Post-earthquake Evaluation and Repair Criteria for Welded Steel Moment-Frame Buildings (also SAC Joint Venture 2000 prepared for FEMA), Washington, D.C.

Panagitou, M., Restrepo, J.I., Conte, J. P., and Englekirk, R. E., 2006, Seismic Response of Reinforced Concrete Wall Buildings, 8NCEE (paper no. 1494), San Francisco, Ca. April 18-22, 2006.

Porter, K., Mitrani-Reiser, J., Beck, J. L., and Ching, J., 2006, Smarter Structures: Real- time loss estimation for instrumented buildings, 8NCEE (paper no. 1236), San Francisco, Ca. April 18-22, 2006.

Safak, E. (1999). Wave-propagation formulation of seismic response of multistory buildings, ASCE, Journal of Structural Engineering, vol. 125, no. 4, April 1999, pp. 426-437.