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EARTHQUAKE DAMAGE DETECTION IN STRUCTURES AND EARLY WARNING

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ABSTRACT :

The ability to monitor the health of an instrumented structure, detect damage as it occurs, and issue an early warning during or soon after the earthquake (or some other natural or man made disaster), and before physical inspection is possible, has significant potential benefits in reducing loss of life and injuries, in emergency response, and in recovery following the disaster. The timeliness of such information, even when the damage is obvious or there is no structural damage, is very useful to a building owner, of an important business or a critical facility. To be *practically* useful, the structural health monitoring systems must be robust when applied to real data, reliable, and sufficiently sensitive and accurate. This paper reviews briefly the current methods, trends and outstanding issues in practical implementation of such systems, with emphasis on a new method based on detecting changes in wave travel times using impulse response functions. This method can be viewed as an *intermediate scale* method, bridging the gap between the NDT and global vibrational methods. Results are shown as proof of concept studies using data from full scale buildings.

KEYWORDS: Earthquake damage detection, early warning, health monitoring, waves in buildings, impulse response function, Van Nuys hotel, Imperial County Services building.

1. INTRODUCTION

Structural health monitoring aims to determine and track the structural integrity and to assess the nature of damage. The earliest and wide spread methods are those that are based on the use of vibrational data from permanent or temporary arrays of sensors. The ability to monitor remotely the health of an instrumented structure, detect damage as it occurs, and issue an early warning after an extreme event (earthquake, explosion or some other natural or man made disaster), before physical inspection is possible, has immense potential benefits in reducing loss of life and injuries, in emergency response, and in recovery following the disaster. For example, a building owner can make a timely decision on evacuation of an unsafe building, reducing the risk of loss of life and injuries caused by potential collapse of the weakened structure during shaking from aftershocks. Similarly, a bridge operator can make a timely decision to close the bridge, and redirect the traffic. Another important benefit from structural health monitoring would be in detecting hidden damage (its precise location and extent), due to an extreme event or gradual decay in time, without a costly physical inspection of every structural member. The development of such methodology that would work in practical real life applications, however, is a *very difficult task*, and, considering the challenges faced and the potential benefits, has the elements of a *grand challenge* problem in civil engineering (Farrar and Worden 2007).

To be practically useful, the structural health monitoring systems need to be robust, reliable and sufficiently sensitive when applied to actual earthquake data. They should neither miss to detect significant structural damage, nor create false alarms leading to needless and costly service interruptions. This is particularly important for critical facilities, such as hospitals, and nuclear power plants. In addition, they should be able to point out to the location of the damage. *Despite the progress made in this field in more than 30 years of research, currently there are no such systems.*

A review of recent developments in structural health monitoring, as applied to civil and mechanical systems, can be found in Chang et al. (2003) and Liu et al. (2006). The earliest, and still by far the most widely used methods for civil structures are those that use data from vibrational sensors (accelerometers or velocity meters), and detect changes in the vibrational characteristics of the structure (frequencies of vibration and mode shapes, Doebling et al. 1996, Sohn et al. 2003, Carden and Fanning 2004, Farrar and Worden 2007, Todorovska 2009).

Most vibration based methods monitor changes in the *modal* properties of structures (modal frequencies and mode shapes). The difficulties with these methods are: (i) the intrinsic *global nature* of the modal properties (characteristics of the structure as a whole) and their inability to point to the location of the damage; (ii) the presence of other factors than damage that produce similar effects on the damage sensitive features, which are not easy to isolate (the effects of soil-structure interaction on the measured frequencies of vibration, and environmental influences such as temperature; Clinton et al. 2006; Todorovska and Al Rjoub 2006ab, 2008); and (iii) the redundancy of the civil engineering structures, which results in low sensitivity of the method (small change of the overall stiffness and consequently of the measured frequencies) when the damage is localized. Other difficulties of the vibrational methods include: (iv) dependence on detailed prior analytical models and/or prior test data for the detection and location of damage (supervised learning), which may not be readily available for a structure, may be outdated, and even when available are only an idealization of the real structure (Chang et al. 2003). Doebling et al. (1996) conclude that "*while sufficient evidence exists to promote the use of measured vibration data for the detection of damage in structures, using both forced-response testing and long-term monitoring of ambient signals, the research needs to be more focused on the specific applications and industries that would benefit from this technology….Additionally, research should be focused more on testing of real structures in their operating environment, rather than laboratory tests of representative structures*". Regrettably, more than 10 years following this statement, full-scale test data are still rarely used in structural health monitoring research. New methods are mostly tested using numerically simulated response data, and in some cases with experimental data of response of scaled models in the laboratory. While such tests are necessary in the early development stages of a method, they do not guarantee that the method would ever work for real structures and real excitation. Rigorous appraisals of methods using earthquake response data from full-scale damaged structures are rare.

The focus of this paper is on a method based on detecting changes in the structural stiffness based on analysis of *travel times of seismic waves* propagating through the structure, which is being developed at the University of Southern California Strong Motion Laboratory, and calibrated using earthquake response and small amplitude test data recorded in full-scale structures. Proof of concept applications to two buildings damaged by earthquakes (Todorovska and Trifunac 2006, 2007, 2008a,b, Gičev and Trifunac 2008), and to an analytical model of a building-foundation-soil system (Todorovska 2008a,b) showed that the method (i) is robust when applied to damaging levels of earthquake response data, (ii) is not sensitive to the effects of soil-structure interaction, and (iii) is local in nature (gave results consistent with the spatial distribution and degree of the observed damage). The damaged buildings are the former Imperial County Services Building – a 6-story RC structure in El Centro, California, damaged by the 1979 Imperial County earthquake and later demolished (Todorovska and Trifunac 2005a,b, 2007, 2008a,c), and the 7-strory RC building in Van Nuys, damaged by both the 1971 San Fernando and the 1994 Northridge earthquakes (Trifunac et al. 1999, Todorovska and Trifunac 2008b, Gičev and Trifunac 2008). The method was also applied to a building in Banja Luka in former Yugoslavia, using records of 20 earthquakes, one of which lead to levels of response approaching structural damage, but no damage was reported following a detailed inspection (Trifunac et al. 2008).

2. WAVE METHOD FOR STRUCTURAL HEALTH MONITORING

This wave method is based on the D'Alambert's solution of the wave equation. In contrast, the modal methods are based on representation in the frequency domain, as superposition of modes of vibration. The wave travel times are detected by tracing the propagation of an impulse radiated by a virtual source. Such a source can be conveniently created by deconvolution of the recorded response, the result of which is the system impulse response function $h(t)$ (inverse Fourier transform of the system transfer-function). The wave travel time between two pints $\tau = d / V_S$, where d is the distance traveled and V_S is the equivalent shear wave velocity in the part of the building between the two sensors. The latter is related to the rigidity via the relation $V_S = \sqrt{\mu / \rho}$, where μ is the shear modulus and ρ is the density. A reduction of rigidity due to damage will produce a reduction of the equivalent shear wave velocity, which will produce an increase in the pulse travel time, relative to the travel time for the undamaged state. The change in wave travel time will depend *only on changes of the* *physical properties between the sensors*. Hence this *wave* method is *local*, and will be more sensitive to local damage than the *modal* methods, which are *global*.

Global changes can also be detected by monitoring the *total* wave travel time from the base to the roof. Let τ_{tot} be the travel time of seismic waves from the ground level to the roof. Then the building fundamental fixed-base frequency $f_1 = 1/(4\tau_{\text{tot}})$ assuming that the building as a whole deforms like a shear beam. Based on this relation, f_1 can be estimated using data from only two horizontal sensors. While the goodness of this approximation of f_1 may vary from one building to another, the changes in $f_1 = 1/(4\tau_{\text{tot}})$ will still depend *only* on changes in the building itself, and not on changes in the soil, and monitoring of changes in such an estimate of f_1 can be used as a global indicator of damage in a building.

Fig. 1a. ICS building.

Analyses of civil structures using the wave propagation approach are rare. The early work can be traced to Kanai (1965), who represented the seismic response of a building as a superposition of shear waves that propagate upwards and downwards, being reflected each time they hit one of the boundaries (roof or the interface with the soil). There are infinitely many such waves, resulting from different generations of reflections from the boundaries. Kanai used such a model to predict the motion at the base of the building from the motion at the roof, and got a good agreement between the predicted and recorded motions. Todorovska and Trifunac (1989, 1990) and Todorovska and Lee (1989) used continuous 2D models of buildings to study the effects of traveling waves in buildings without major discontinuities, and with a soft first story or with a central core. They showed that the wave motion is dispersed, due to reflections from the lateral boundaries. Safak (1998a; 1999) proposed 1D wave propagation models through *layered* medium to represent the seismic response of buildings, and compared simulated response using the wave propagation model with simulated response using mode superposition. Todorovska et al. (2001a,b) used a 2D anisotropic building model to study the response of the 7-story RC building in Van Nuys, California, to several earthquakes.

Fig. 1b ICS building: damaged columns at the ground floor (Kojić et al 1984).

Only few studies use (global) wave propagation models to detect damage in civil structures. Safak (1998b) proposed a layered continuous building model representation of its seismic response to detect damage, by tracing changes in the model parameters in different layers. He considered a 10-story building with postulated reduction of stiffness at the 5th floor (between 0 and 90%), and simulated its response using both mode superposition, and the wave propagation model, and compared the results. The results showed that the reduction of stiffness resulted in much larger change of the wave model parameter than of the modal parameters (to have 20% change in any of the modal frequencies, reduction of stiffness as high as 50% was needed). Ivanović et al. (2001) estimated time lags by a cross-correlation analysis for the motions recorded in the 7-story RC building in Van Nuys during the 1994 Northridge earthquake. Finally, Ma and Pines (2003) proposed a lumped mass building model and propagation of dereverberated waves to identify the damage. In their model, the reverberations are annihilated by virtual actuators placed at each story. They applied this model to simulated building response data.

Measuring wave travel times using impulse response functions computed by deconvolution, has been applied to buildings by Snieder and Şafak (2006), who studied one-dimensional wave propagation in Millikan Library in Pasadena, California, during small amplitude seismic response. It was also applied to small amplitude response of the Factor building in Los Angeles, California (Kholer et al. 2007). This method was first applied to earthquake damage detection in the Imperial County Services building (Todorovska and Trifunac, 2008a), and in the 7-story RC hotel in Van Nuys (Todorovska and Trifunac, 2006; 2008b), as mentioned earlier. These studies showed that the results from this method were consistent with results from other structural health monitoring methods, and that the method is promising and should be further developed. Wave travel times in buildings (undamaged and damaded) were also measured by the normalized input-output normalization (NIOM) method (Oyunchimeg and Kawakami 2003; Kawakami and Oyunchimeg 2003), which can be reduced to a special case of the impulse response method, but is conceptually more complicated than the impulse response method, without apparent advantages. All of these studies were exploratory in nature, and favorably evaluated the detection of wave travel times as a promising method for analysis of structural response and for structural health monitoring. They all showed that the measured wave travel times were consistent with the distribution of stiffness of the buildings studied, and with their state of damage.

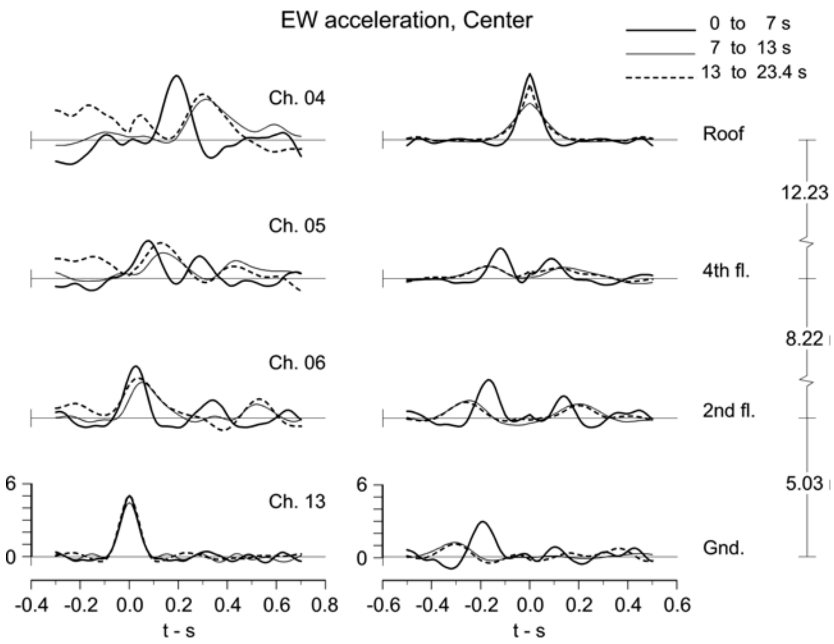

Fig. 2 Imperial County Services building: impulse response functions for EW motions and for impulse at the ground floor (left) and at the roof (right).

This wave propagation method, which uses seismic monitoring data, differs from the wave methods used in non-destructive testing (NDT) of materials in that the latter typically use: (1) ultrasonic waves, which are attenuated quickly along the wave path, (2) need an actuator to create the waves, and (3) detect cracks, or some other defect in a member, using *reflected* waves from the defects. These methods are typically used locally, to detect the location of a defect in a member, but are impractical and too costly for global structural health monitoring (Chang et al. 2003). The method described in this paper uses *seismic waves*, which are long (5-500 m) and are not much attenuated, does not need actuators, and is based on measurements of travel times of waves *transmitted* through the damaged zone.

This method can be viewed as an *intermediate scale* method, bridging the gap between the NDT and global vibrational methods. While the former aim to detect the overall state of damage of the *entire* structure, and the latter aim to detect damage in a particular structural *member*, the seismic wave method aims at detecting the *part* of the structure where damage had occurred. Its spatial resolution depends on the number of sensors. Minimum of two sensors (at the base and at the roof) are required to determine if the structure has been damaged, and additional sensors at the intermediate floors would help point if damage occurred in the upper or lower part of the structure. More sensors can help point out to the stories where damage had occurred, and several vertical arrays (like in the Imperial County Services building) can further increase the precision of localizing the damage. *Global* changes in the structural stiffness can be monitored by detecting changes in the total wave travel time along the building height (equivalent to monitoring changes in the equivalent shear wave velocity, v_{eq}, or f_1), and *local* changes can be monitored by detecting changes in wave travel time between sensors at different floors. Changes can be detected by measuring the travel times in consecutive or moving time windows during the earthquake shaking, and comparing the values with those for the initial time window. Such a scheme does not need baseline data measured before the earthquake, and is not sensitive to permanent or temporary changes in the structure not related to damage.

3. PILOT APPLICATIONS AND CONSLUSIONS

This section illustrates the methodology by selected results for the Imperial County Services (ICS) Building and for the Van Nuys hotel. The ICS building was a 6-story RC structure, with a soft first story, damaged by the Imperial Valley earthquake of 1979 and later demolished.

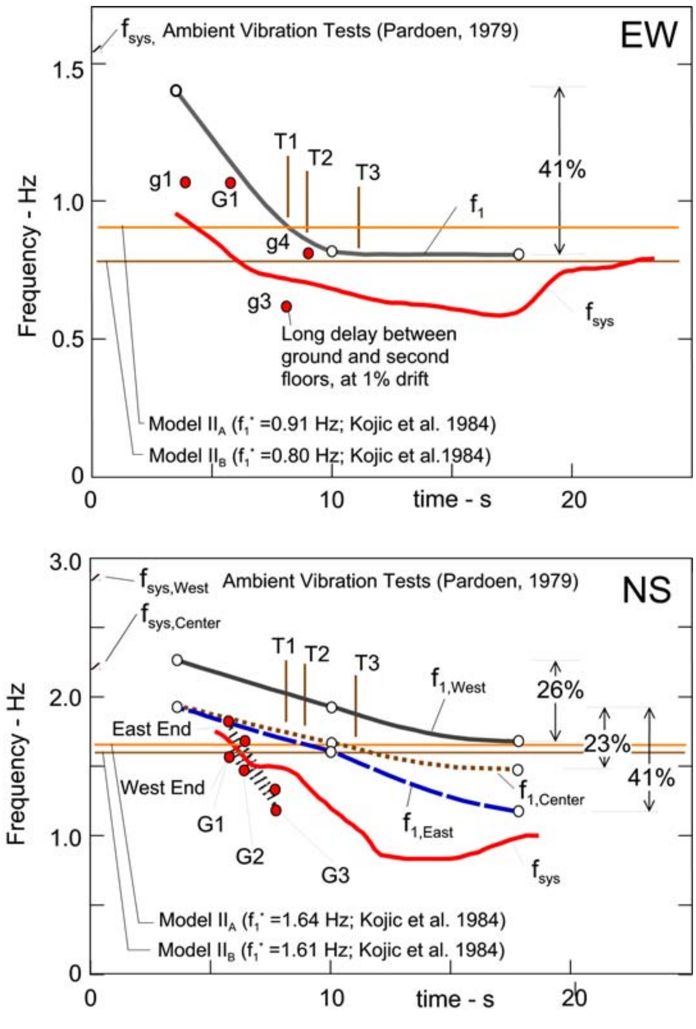

Fig. 3a ICS building: frequency versus time.

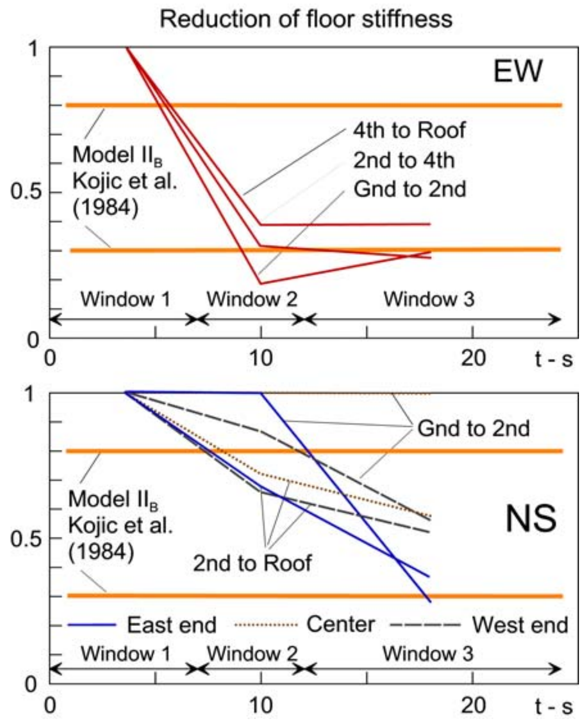

Fig. 3b. Reduction of stiffness versus time.

The damage was most severe at the east side of the building, in the first story columns (Fig. 1a,b). The building transverse response (NS) was recorded by three vertical arrays of sensors (at both sides and at the middle), which enabled us to test the method in predicting both the spatial distribution and severity of damage.

Fig. 2 shows impulse responses for the EW response. Different lines correspond to different time intervals of the recorded motion (before, during and after the strongest shaking). The plots on the left correspond to an input impulse at the ground floor, and those on the right – to an input impulse at the top. The latter plots show two waves propagating downwards, one acausal (in negative time, representing the wave going up) and one causal (in positive time). The delays in the pulse arrival during the second and third time interval are obvious, and are consistent with the occurrence of damage, as determined using other methods. Fig. 3a shows a comparison of different frequencies, including f_1 from wave travel times, system frequency f_{sys} estimated from time-frequency analysis (Todorovska and Trifunac 2007), and f_1 using structural models (Kojić et al. 1984). T1, T2 and T3 mark the times of occurrence of major damage, as indicated by novelties in the response, detected by wavelets; Todorovska and Trifunac 2008b). It can be seen that f_1 from wave travel times is consistent with the results of other independent studies. Fig. 3b shows the inferred reduction of stiffness.

Figure 4 shows results for the Van Nuys building, a 7-story RC structure damaged by both the 1971 San Fernando and 1994 Northridge earthquakes (Todorovska and Trifunac 2006; 2007b). It shows a comparison of fixed-base frequency f_1 during 11 events estimated from wave travel times, and system frequency f_{sys}

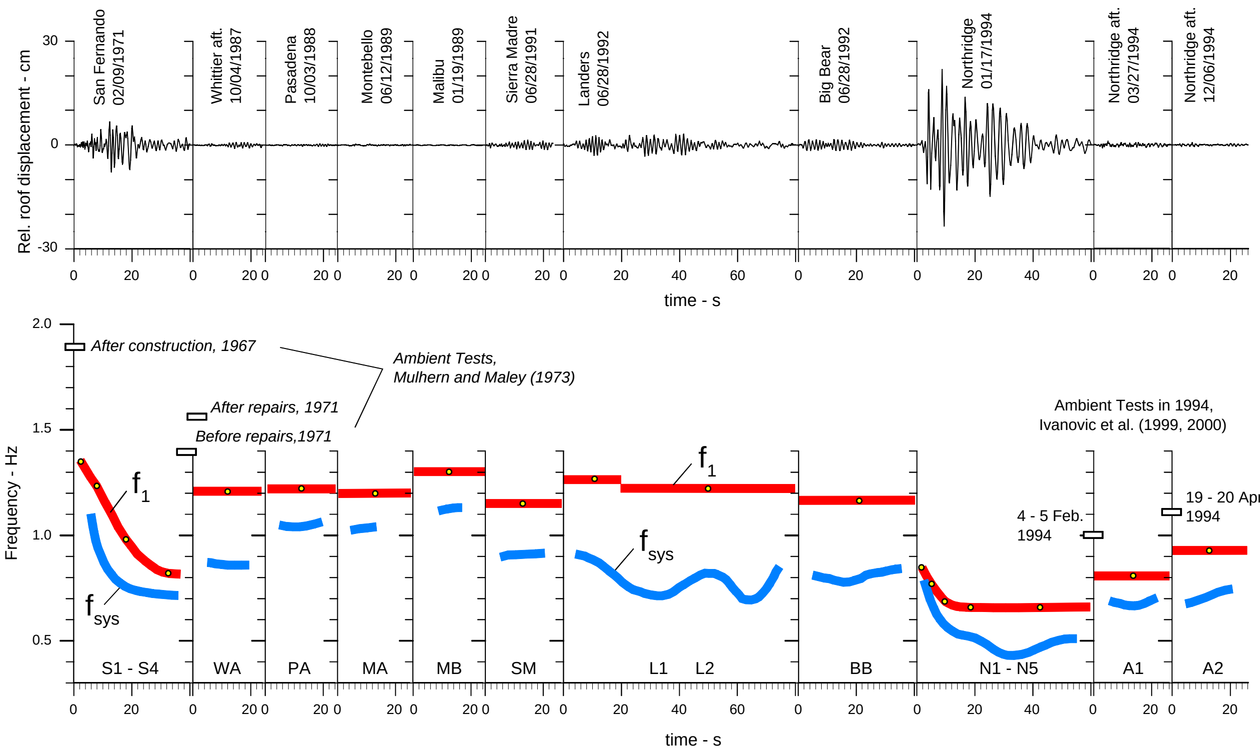

Fig. 4 Variations of f_1 and f_{sys} in the Van Nuys building during the 11 earthquakes, between February of 1971 and December of 1994, for EW response. Measured values of f_{sys} during five ambient vibration tests: (i) in 1967, following construction, (ii) in 1971, after San Fernando earthquake and before repairs, (iii) in 1971 after the repairs, (iv) in January of 1994, eighteen days after the Northridge earthquake, and (v) in April of 1994, after the building was restrained by wooden braces.

during the same earthquakes estimated by time frequency analysis (Gabor transform), as well as estimates of f_{sys} during ambient vibration tests (Ivanović et al. 2000). The analysis shows that, during the San Fernando earthquake, f_1 decreased by about 40% (relative to its value within the first 5 s from trigger), which corresponds to a decrease in the global rigidity of about 63%. During the Northridge earthquake, f_1 decreased by about 22% (relative to is value within the first 3 s from trigger), which corresponds to a decrease in the global rigidity of about 40%. The analysis also showed that, although f_{sys} was always smaller than f_1, their difference varied, contrary to what one could expect from a linear soil-structure interaction model. It also showed that while f_{sys} was significantly lower during the Landers and Big Bear earthquakes, compared to the previous earthquakes, f_1 did not change much, which is consistent with the fact that these earthquakes (which occurred about 200 km away from the building) did not cause any damage. The study concluded that monitoring changes in f_{sys} can lead to false alarms about the occurrence of damage, and that f_1, as estimated from wave travel times by the proposed method, is a much more reliable estimator of damage.

Following the encouraging results from the pilot applications, the earthquake damage detection method based on detecting changes in wave travel times is being further developed and calibrated for future use in a structural health monitoring and early warning system.

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* All USC reports can be viewed at http://www.usc.edu/dept/civil_eng/Earthquake_eng/