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D. B. McCallen
L. J. Hutchings

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Ground Motion Estimation and Nonlinear Seismic Analysis

David B. McCallen[1] (Member ASCE) **Lawrence J. Hutchings[2]**

Abstract

Site specific predictions of the dynamic response of structures to extreme earthquake ground motions are a critical component of seismic design for important structures. With the rapid development of computationally based methodologies and powerful computers over the past few years, engineers and scientists now have the capability to perform numerical simulations of many of the physical processes associated with the generation of earthquake ground motions and dynamic structural response. This paper describes application of a physics based, deterministic, computational approach for estimation of earthquake ground motions which relies on site measurements of frequently occurring small (i.e. $M < 3$) earthquakes. Case studies are presented which illustrate application of this methodology for two different sites, and nonlinear analyses of a typical six story steel frame office building are performed to illustrate the potential sensitivity of nonlinear response to site conditions and proximity to the causative fault.

Introduction

With the refinement of finite element techniques and computer hardware, linear response computations have become a routine component of seismic analysis and design of major structures. However, as a result of existing design philosophies even the most well designed modern structures will enter the inelastic, nonlinear response regime when subjected to extreme earthquake ground motions. Older structures, built prior to the implementation of modern seismic code provisions, often lack robust ductility and are even more susceptible to nonlinear behavior and potential collapse. Ensuring a structure will undergo acceptable nonlinear behavior, and not suffer catastrophic collapse during extreme earthquake motion, is a critical problem facing engineers. Recent trends toward the utilization of nonlinear modeling capabilities in

1. Structural Mechanics Group, Lawrence Livermore National Laboratory, University of California, Livermore, California 94550.

2. Seismology Group, Lawrence Livermore National Laboratory, University of California, Livermore, California, 94550

seismic analyses of important structures has presented a number of challenges. Whereas linear response computations employed in design can often rely primarily on probabalistically based smooth spectra to define earthquake ground motion, nonlinear time history computations require a complete description of ground motion time histories. Meaningful nonlinear time-history computations require realistic definitions of expected ground motion at a specific site.

Over the past few years, the California Division of Mines and Geology has deployed a state-wide array of seismic instrumentation sites throughout California and since 1989 a number of California earthquakes have provided a wealth of new ground motion data. This data has brought to light the difficulties involved in predicting the details of the ground motion which any specific structure will be subjected to during a major earthquake. The potential for generation of very large ground accelerations has been demonstrated, and the significant spatial variation of ground motion due to local soil conditions and seismic wave radiation pattern has been observed (Benuska et. al. 1990, Hall et. al. 1995). In addition, new insight has been gained into the nature of strong ground motions in the near field and the potential for large, long period, fault-normal displacement pulses near the fault (Somerville and Graves 1994). This type of motion may be particularly problematic for long period structures such as high-rise buildings (Heaton et. al. 1995) or long-span bridges.

The physical basis for the complexity of earthquake ground motions is found in both the mechanics of how earthquake faults rupture and the manner in which seismic waves radiate through inhomogeneous geologic material. Wave arrivals from different portions of the fault, sometimes tens of kilometers apart, can destructively or constructively interfere at a given site, and superposition of body waves and surface waves will generally result in an extremely complicated wave field. Ground motions very near the fault may be adversely effected by the ground movement due to actual permanent offset displacement of the fault. A significant amplification of the ground motion shaking can also result from the directivity effect of the fault rupture propagation, i.e. whether the fault rupture propagates towards or away from the site in question.

A seismological, computational approach to synthesizing strong ground motion that attempts to account for all of these complicating factors has recently been developed. The study reported on herein investigated the application of this seismological methodology for the estimation of ground motions suitable for engineering analysis and design purposes. This methodology has the potential of accounting for the source-to-site wave propagation and fault rupture mechanics on site specific ground motions. One potential important application of this methodology is generation of site specific ground motion time histories for use in nonlinear analysis of critical structures. In the current study, ground motion estimates and nonlinear analysis of a steel frame building were performed for two sites which exhibited significantly different ground motions during the 1989 Loma Prieta California earthquake. This analysis provides some insight into the potential utility of the methodology and importance of site specific ground motion estimates for nonlinear analysis.

Empirical Green's Function Based Ground Motion Estimates

The computational approach to ground motion estimation consists of solving the representation relation for earthquake rupture and seismic wave propagation as a summation of point source Green's functions (Heaton 1982). Green's functions represent the point source response of a medium for a particular source and receiver pair (Fig. 1). The Green's functions are convolved with the earthquake fault slip model at each point along a discretized fault and time delayed to account for propagation of the rupture across the fault plane. This process is essentially an appropriate summation of the ground motion for each discrete zone on the fault to generate the ground motion due to rupture of the entire fault plane.

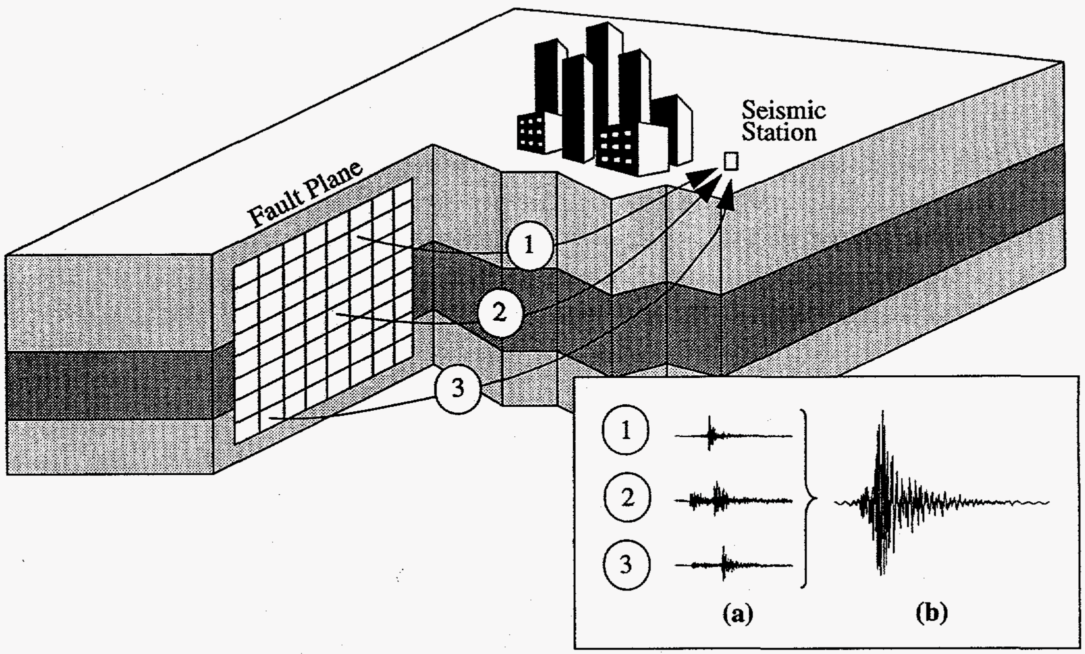

FIGURE 1. Fault zone discretization and measurement of empirical Green's functions for ground motion generation. (a) site measurement of empirical Green's functions from fault zone ruptures; (b) synthesized motion for entire fault plane.

Based on elasticity solutions for a horizontally layered half-space, it is possible to mathematically derive analytical Green's functions. However, for short wave length, high frequency, seismic waves, geologic inhomogeneities have a pronounced influence on wave propagation and the analytic Green's functions generally provide a poor estimate of the source to site propagation. Low frequency, long wavelength seismic waves are significantly less effected by geologic inhomogeneities and can be used directly in the convolution. To augment the low frequency analytic Green's functions, a hybrid procedure has been developed which utilizes measured empirical Green's functions (EGF) to account for higher frequency motion. The method, which is described in detail in Hutchings and Wu 1990, Hutchings 1991, and Jarpe and Kasameyer 1993 requires site measurement of small earthquakes which emanate from the causative fault in order to generate a suite of representative Green's Functions (Fig. 1a shows three actual measured Green's functions). In practical application, there are insufficient empirical Green's functions to provide impulse response for all zones of the fault rupture discretization and the functions must be interpolated across the fault rupture area. For soft soil sites, the generated time histories can be used as input to soils models, for stiff sites the time histories can be used as input directly to the structural model.

The Green function method has been implemented in the EMPSYN computer program (Hutchings, 1988). The parameters input to the program include fault geometry, seismic moment, rupture velocity, rise time or healing velocity, asperity locations and percent roughness. For a given earthquake fault and structure site, these parameters are semi-constrained by existing geologic information. For prediction purposes, it is necessary to vary these parameters to find the worst case scenario within the realm of geologic constraints. For a typical analysis, the fault is discretized on the order of 200,000 zones and the EMPSYN convolution requires approximately 4 hours on a SPARC 20 workstation.

The validity and potential accuracy of this method for ground motion estimation has been demonstrated by detailed comparisons of measured and computed ground motion time histories. Hutchings 1991 and Jarpe and Kasameyer 1993 extensively studied Loma Prieta earthquake ground motions and showed that the EGF based methodology could accurately represent ground motions at many of the measured sites.

The Nonlinear Model for Steel Frame Buildings

Historically, nonlinear finite element models for steel frame structures have been based on beam finite elements which utilize point plasticity idealizations for plastic hinge formation in flexural elements. While computationally efficient, these elements do not allow the model to capture a smoothed transition from the elastic to plastic state as yielding spreads through the depth of the member cross section. The point plasticity model is also incapable of representing the finite length of the yield region in a plastic hinge zone and the interaction between the member stresses generated by bending moment and axial force is accounted for only in a very approximate fashion, or neglected altogether. The influence of finite deformation and the resulting secondary moments due to P-Δ effect is often neglected or accounted for approximately with linearization about some configuration, such as the state of the structure under static dead load.

Recently, more advanced nonlinear, fiber type flexural elements have been developed to provide a more realistic approximation of the nonlinear, plastic behavior of flexural elements (Challa and Hall 1994). For modeling steel building frames in the current study, a fiber type element available in the NIKE3D finite element program was utilized (Maker et. al. 1991). This element employs numerical integration in the beam cross section and has an option for user defined integration points in the beam cross section. The element utilizes one point Gauss integration along the element length. The nonlinear material behavior at each cross section Gauss point is handled with a multidimensional plasticity constitutive law which accounts for interaction of stress components in the yield condition. Finite deformation effects are accounted for with a local element convected coordinate system which translates and rotates with the element.

The performance of this element is illustrated in Fig. 2, in which the elasto-plastic behavior of a deep cantilever beam is determined with the beam element. For sake of comparison, the nonlinear behavior has also been computed with a detailed nonlinear shell element model of the beam. The two models have good concurrence and illustrate the ability of the beam element to capture the plastic behavior of the beam. The

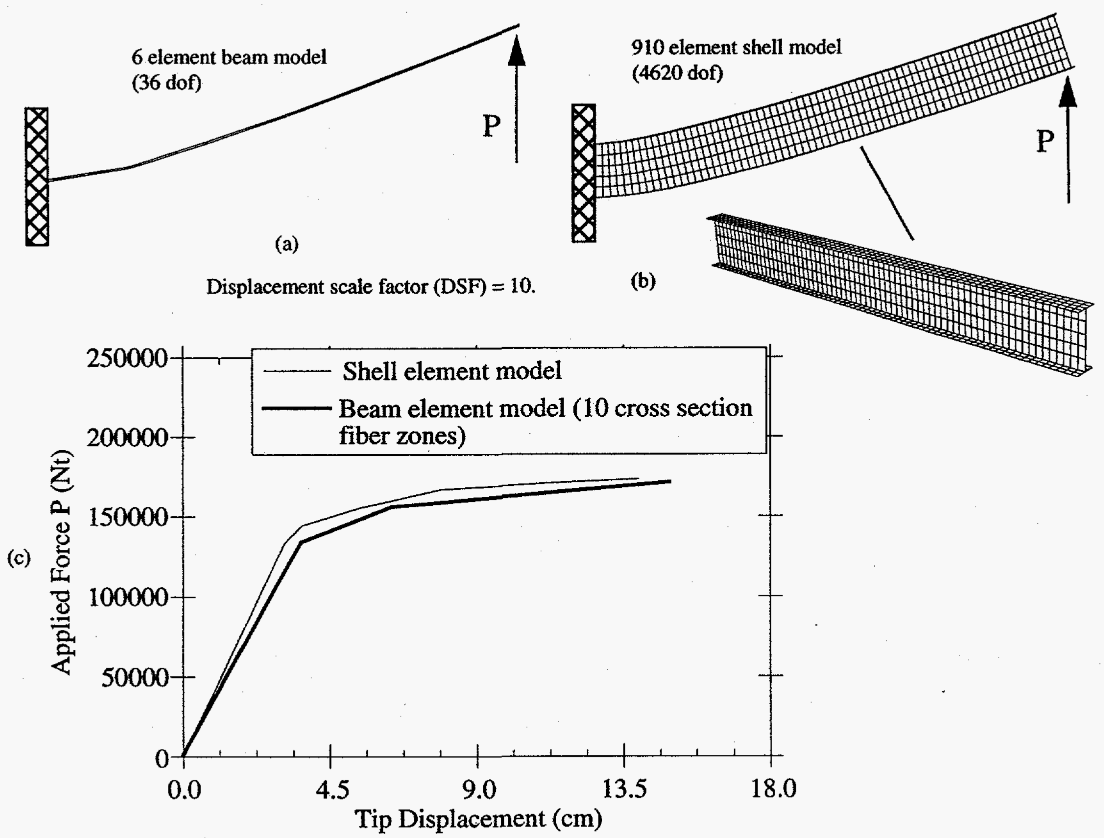

FIGURE 2. Nonlinear, elasto-plastic response of a W21x68 cantilever beam. (a) Fiber beam element computation; (b) Shell element computation; (c) Nonlinear force-deflection relationship.

nonlinear force-deflection behavior predicted by the two models is shown in Fig. 2c.

The NIKE3D program utilizes a quasi-Newton nonlinear solution algorithm based on Broyden-Fletcher-Goldfarb-Shanno (BFGS) stiffness updates. Applications of the NIKE3D program to nonlinear building frame analysis and comparison with other nonlinear frame analysis methods are provided in McCallen and Romstad 1994 and McCallen and Romstad 1990.

Site Specific Ground Motion Estimates and Nonlinear Building Response

As a result of the large number of strong motion instrumentation station locations in the San Francisco Bay area, many strong motion records were obtained in the epicentral area during the 1989 Loma Prieta earthquake (Shakal et. al. 1989). Two sites near the earthquake fault rupture zone which exhibited significantly different ground motion characteristics were a site at Corralitos (7 Km from the epicenter) and a site at the University of California Santa Cruz (16 km from the epicenter). Based on shear wave velocity information provided by Boore et. al. 1993, both these sites were classified as class "B" sites and thus both sites had nominal shear wave velocities between 360 m/s and 750 m/s in the top 30 meters. The site locations are indicated in Fig. 3 and the measured Loma Prieta earthquake ground motions are shown in Fig. 4. The motion at the Santa Cruz site is dominated by high frequency motion compared to the Corralitos site and the ground motions take on a visibly different character. Earthquake aftershock measurements were made by the United States Geological Survey at both of these sites and the aftershock recordings provide site specific empirical Green's functions for the EGF method of ground motion estimation.

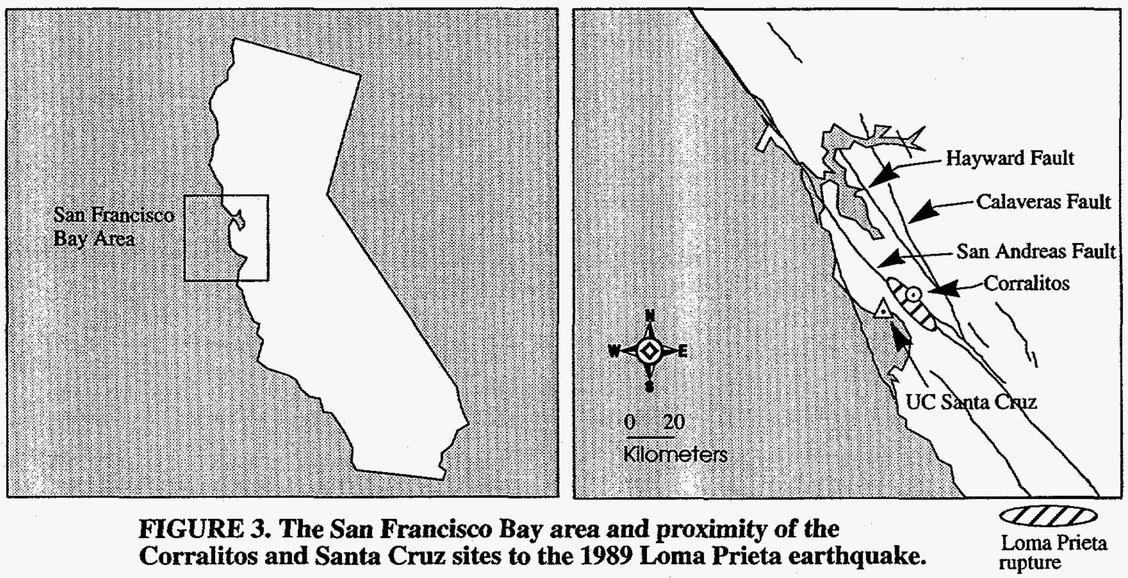

FIGURE 3. The San Francisco Bay area and proximity of the Corralitos and Santa Cruz sites to the 1989 Loma Prieta earthquake.

In light of the availability of Green's functions and the significantly different character of the ground motions at these sites, these two sites were chosen to investigate application of the EGF based method for engineering ground motion estimates. In order to assess the effect of the ground motion estimates on an actual structure, a typical six story steel frame office building was chosen for analysis (Fig. 5). The lateral load system of this building consisted of four moment resisting perimeter frames and the frame design was based on the 1987 lateral force provisions provided by the Structural Engineers Association of California. Details of this frame design are given in Tsai and Popov 1988.

In order to investigate the potential maximum credible earthquakes for these two sites, an earthquake of moment magnitude 7.3 occurring on the San Andreas fault was considered (Fig. 6). This postulated earthquake is approximately 3 times larger than the 1989 Loma Prieta earthquake in terms of energy release. Unlike the Loma Prieta earthquake, the postulated earthquake was assumed to rupture up to the ground surface. The idealized earthquake corresponds to approximately 100 Km of fault rupture

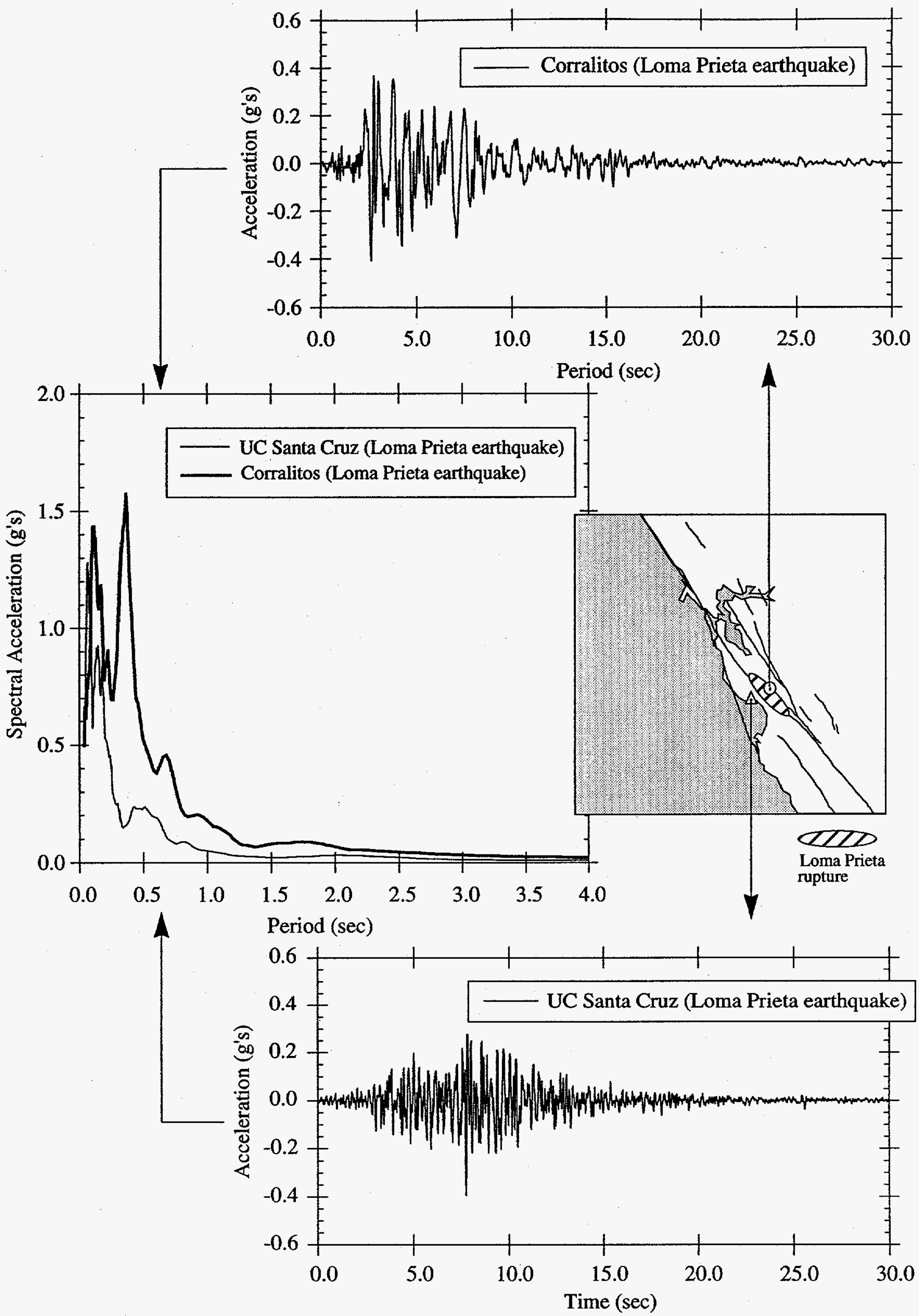

FIGURE 4. Measured ground motions at the Corralitos and Santa Cruz sites from the 1989 Loma Prieta earthquake (Shakal et. al. 1989).

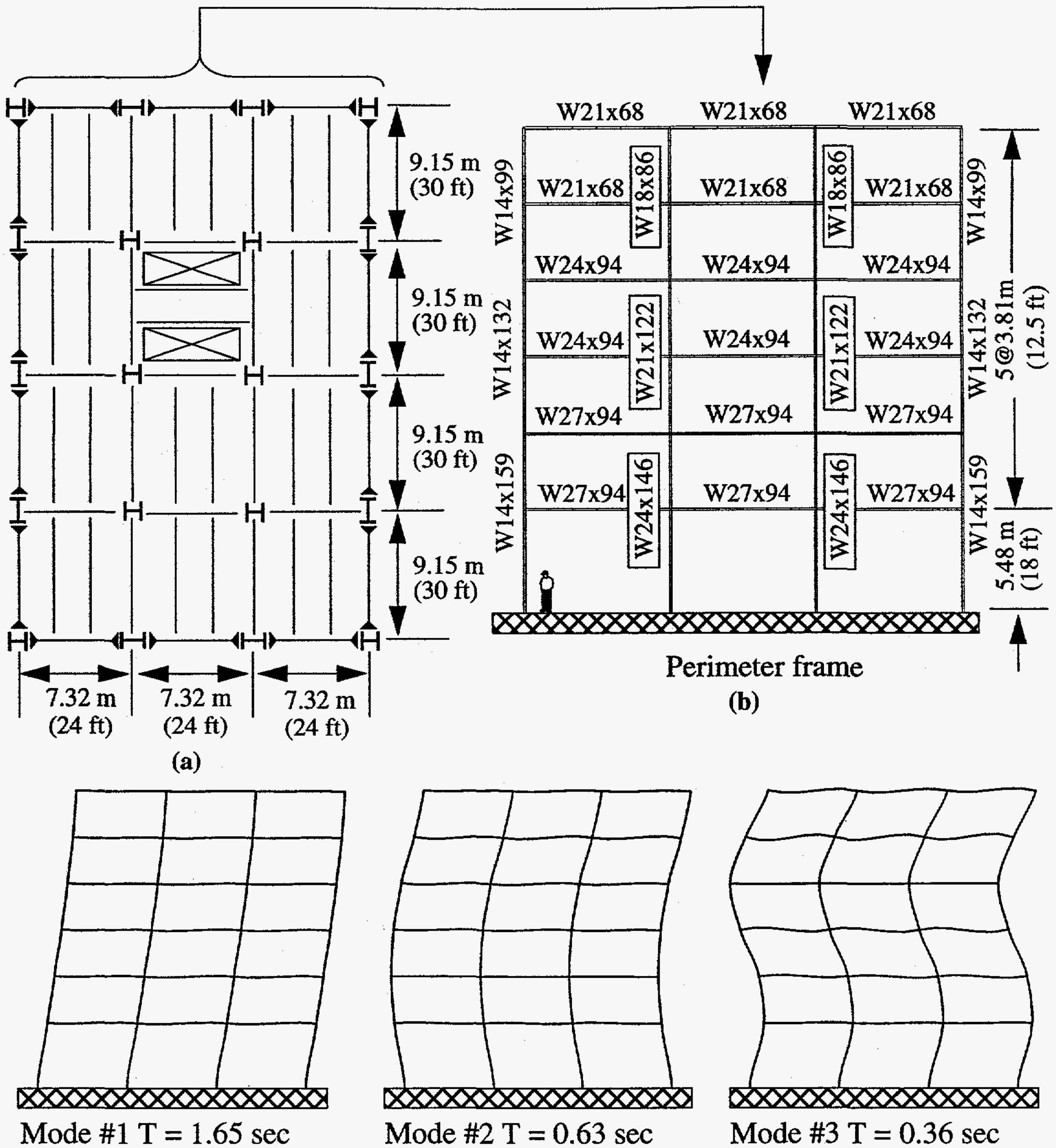

FIGURE 5. Six story steel frame building. (a) plan dimension; (b) end perimeter frame details; (c) natural modeshapes of the building in the short direction.

along the San Andreas fault and completely encompasses the Loma Prieta earthquake fault rupture zone.

The fault rupture parameters were varied in order to obtain extreme ground motions at each of the sites for this earthquake. The resulting synthesized upper bound motions are shown in Fig. 6 for both sites. The motions at the Corralitos site are particularly severe with large response spectra accelerations out to three seconds period. For the postulated earthquake, the Corralitos site is within 1 Km of the surface rupture and the long period pulses appear to be due to constructive interference of body shear waves and surface Rayleigh waves in the fault near field. The worst case rup-

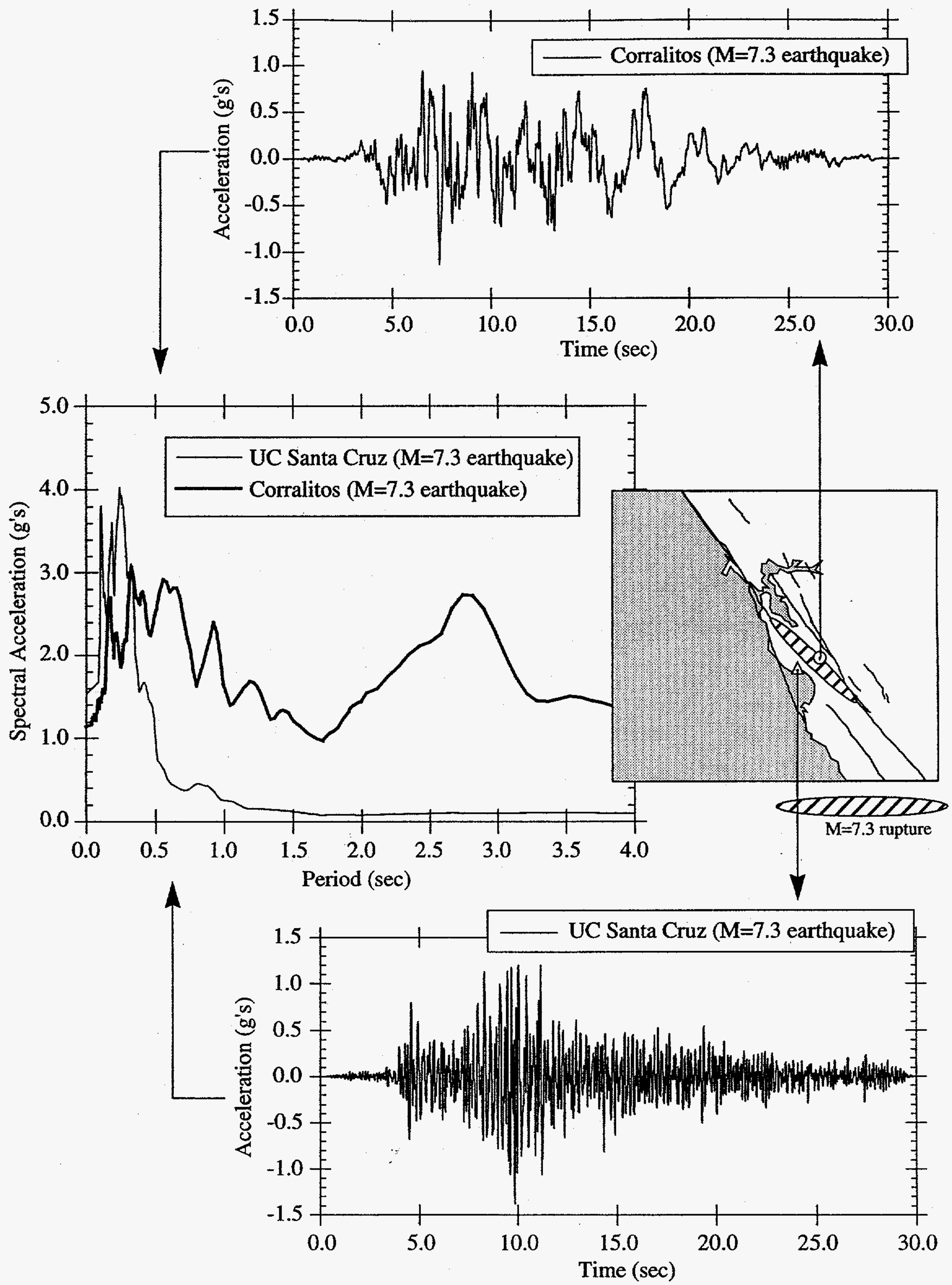

FIGURE 6. Synthesized ground motions at the Corralitos and Santa Cruz sites for M=7.3 earthquake on the San Andreas fault.

ture scenario for this site consisted of the fault rupture propagating towards site. After iterating through a number of rupture scenarios for the Santa Cruz site, it was con-

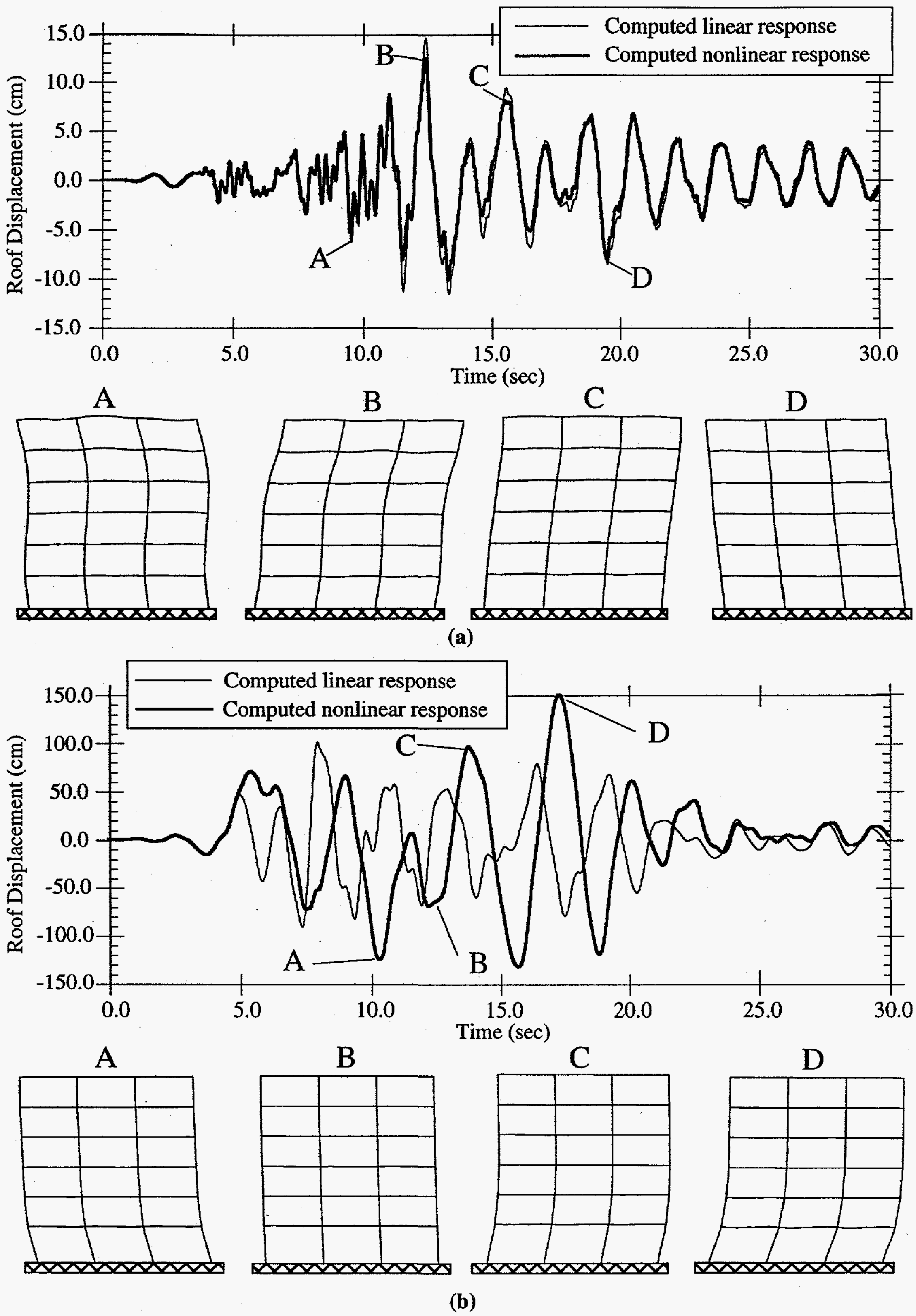

FIGURE 7. Computed linear and nonlinear building response for M=7.3 earthquake. (a) Santa Cruz site (DSF=30); (b) Corralitos site (DSF=2).

cluded that it was not possible to generate similar long period pulses at the Santa Cruz site.

With the exception of the long period pulses at Corralitos, it is noted that the frequency content of the motion at each site is not unlike the ground motions observed from the Loma Prieta earthquake. It appears that the content of the empirical Green's functions have adequately characterized the source-to-site characteristics for both locations.

The response of the six story building to the ground motion at each site is shown in Fig. 7. Figure 7a shows the computed nonlinear and linear (plasticity turned off) responses of the building if it were located at the Santa Cruz site, and Fig. 7b shows the computed nonlinear and linear responses if the building were located in Corralitos. Despite the high acceleration levels at Santa Cruz the building underwent very little inelastic behavior. The frequency content of the Santa Cruz motion was so high that the fundamental mode of the building was not strongly excited by the Santa Cruz record. At Corralitos, on the other hand, the building exhibits extreme nonlinear behavior with very large roof displacements. Despite the fact that the acceleration amplitudes at the Santa Cruz site are actually higher than the Corralitos site, the building nonlinear displacements at the Corralitos site are approximately an order of magnitude greater than at the Santa Cruz site.

Summary and Conclusions

The ground motions computed in the numerical simulation provide some insight into the potential site variability of ground motion for a large earthquake on the San Andreas fault and the potential for extreme motions in the fault near field. While both sites had approximately the same amplitude of ground accelerations, the ground motion at Corralitos had significantly broader frequency content. Based on response analyses with the predicted motions, it is evident that for the postulated earthquake and fault rupture scenarios, the six story office building would have little serious damage at the Santa Cruz site. The building response at Santa Cruz was essentially linear as a result of the lack of frequency content in the ground motion at the natural periods of the structure.

The potential for building damage at the Corralitos site, on the other hand, was extreme and although the nonlinear solution did not explicitly predict collapse of the building, the large interstory drifts indicated that the structure would incur severe damage.

The Lawrence Livermore National Laboratory is currently engaged in placement of sensitive seismic instrument packages near important transportation structures in the San Francisco Bay area in work being performed for the California Department of Transportation. These permanent instruments will allow seismologists to measure small earthquakes over a period of time and establish site specific Green's function signatures for critical transportation structures. This information should provide engineers with a clearer picture of site specific ground motion time histories for nonlinear bridge analysis and shed some light on important issues such as spatial variation of ground motions for long span bridges.

Acknowledgments

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