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DYNAMIC RESPONSE OF THE SUSPENSION SPANS OF THE SAN FRANCISCO-OAKLAND BAY BRIDGE

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ABSTRACT

The dynamic response of the suspension spans of the San Francisco-Oakland Bay Bridge (SFOBB) have been numerically modeled in a case-study to investigate the effects of long-period, near-field ground motions on flexible suspension bridges. The structural simulation model used in the study was developed as a special purpose computer program tailored to efficiently simulate the nonlinear response of cable supported bridges. The simulation model includes a number of special element technologies and solution algorithms that enable efficient nonlinear analysis of suspension bridges. The ground motions used in the study were site specific synthetic records for a *Mw=7.25* earthquake along the Hayward fault at 12-15 km distant, and actual measured near-field records from the Izmit Turkey (1999) and Chi-Chi Taiwan (1999) earthquakes. These records include near- and far-field broad-band motions for three components. The results of the numerical simulations indicate that low frequency waveforms associated with near-field motions can place a significant demand on the structural systems of suspension bridges, and must be accounted for in suspension bridge analysis and design.

Introduction

The dynamic earthquake response of the suspension spans of the San Francisco-Oakland Bay Bridge (SFOBB) have been simulated for a suite of synthetic and measured near-source ground motions. The main objectives of this project are to understand the effect of finite faulting on full-broadband ground motions in the near-source region, and to understand the significance of near-field long period components of motion on the dynamic response of long-period suspension bridges.

The San Francisco-Oakland Bay Bridge is situated across the San Francisco Bay and approximately equidistant between the San Andreas and the Hayward Faults as indicated in Fig. 1. The western crossing of the Bay Bridge, and the subject of this study, consists of twin suspension spans connected at a central caisson as shown in Fig. 1.

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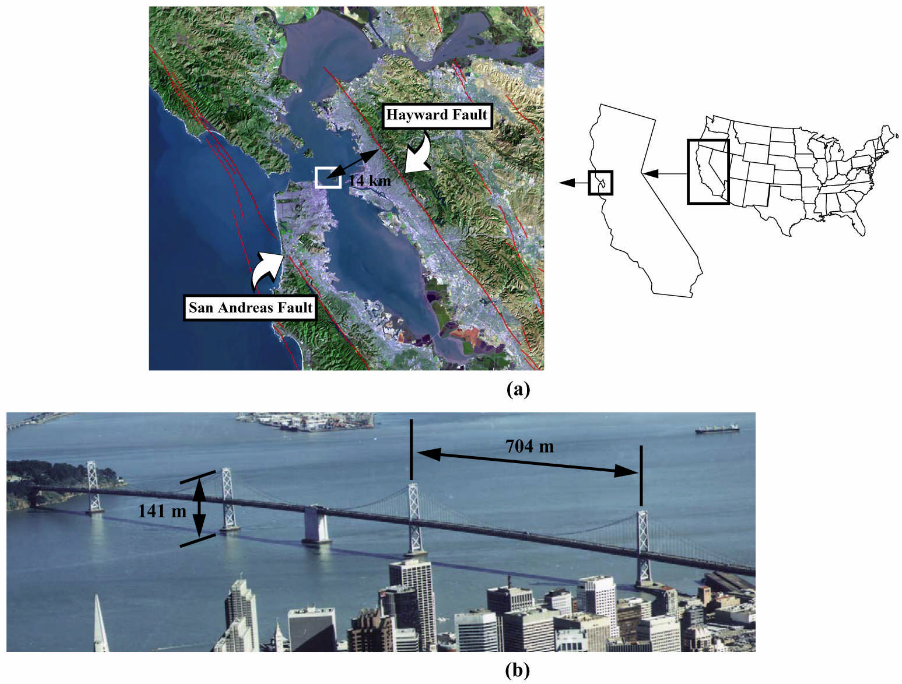

Figure 1. The San Francisco-Oakland Bay Bridge: a) bridge location on the San Francisco Bay; b) twin suspension spans of the western crossing.

Long period ground motions in the near-fault region are generated by the accumulative effect of motions due to tectonic displacements near the fault rupture and the motions due propagating seismic waves. Several long-span suspension bridges in the United States, Europe and Asia are located within a few kilometers of major active earthquake faults – the near-fault region. Seismic design standards and codes for such structures are based substantially on past experience and there is considerable evidence that band limited historical ground motion records are insufficient to predict what may happen in the future, especially in the near-fault region. Until recently, a clear description and understanding of near-field ground motions was elusive because historical strong motion instruments and signal processing methods did not permit accurate measurement of low frequency motions. Limitations of historical instrumentation and processing methodologies resulted in strong motion records that were band-passed filtered between 0.2-25 Hz (period of 0.04-5 seconds). In addition, due to the historical sparsity of strong motion instruments and the infrequency of large earthquakes, there was a lack of many measurements of motions in the near-fault region of large earthquakes. Modern broad-band, digital instruments, and recent near-fault measurements have shed significant light on the character of near-fault motions.

Prior to the 1999 Chi Chi, Taiwan and 1999 Turkey earthquakes only twenty high frequency (band limited) ground motion recordings were available worldwide for earthquakes with magnitude Mw greater than 7.0 and recorded at a distances of less than 20 kilometers from the fault. The recent Turkey earthquake added seven broad-band records and the Taiwan earthquake added sixty-five broad-band records. Still, it should be noted these records have only added two fault rupture scenarios. Much remains to be learned with every new well instrumented earthquake.

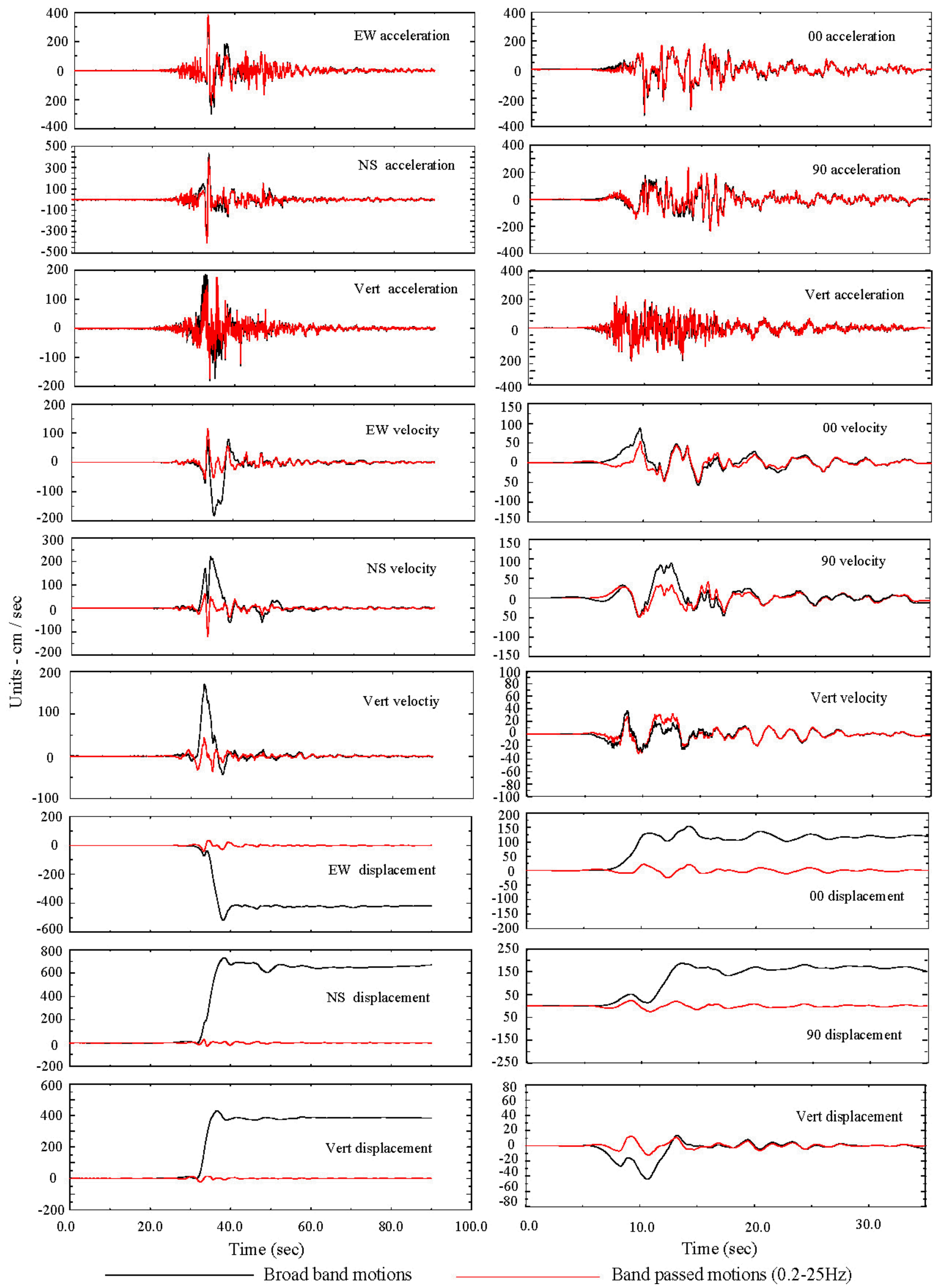

Figure 2. Filtered and unfiltered near-fault strong motion records from the Taiwan and Turkey earthquakes.

The effect of band-pass filtering on near-fault ground motions can be demonstrated by comparing broad-band, near-fault records measured with modern instrumentation with the same records filtered with a 0.2-25 Hz band pass filter. Fig. 2 shows three components for near-source ground motion recorded from the recent Taiwan and Turkey earthquakes. Traces in red are filtered in the conventional manner, and traces in black are low-passed at 25 Hz. Acceleration, velocity, and displacement records are shown, respectively. It is apparent from Fig. 2 that significant long period velocity and displacement energy is not preserved if filtering is done in the historical manner. The historical filtering process has a limited effect on the ground accelerations, which tend to be dominated by higher frequencies (low periods), but can have a pronounced effect on ground velocities and displacements as evidenced by the time histories.

It is essential that the effects of long period motions be clearly understood for all classes of flexible structures, such as long span suspension bridges, that might be at risk. For the majority of structures, including low-rise buildings, the natural frequencies of the structure are significantly higher than 0.2 Hz (lower than period of 5 seconds) and the structure essentially responds as a rigid body to long wavelength seismic waves below 0.2 Hz. However, for flexible structures, such as tall buildings and long-span bridges, the natural frequencies of the structure may be sufficiently low that the structure responds strongly to the low frequency motions.

Until fairly recently, the prevailing engineering wisdom was that the lowest frequency, long wavelength modes of long-span bridges (e.g. the 9 second mode of the Bay Bridge suspension spans) are generally not major contributors to the seismic response of the structure. Arguments suggested in support of this view were based on the notion that the long period earthquake ground motions do not contain much energy in the period range beyond 2 to 3 seconds, and that the time durations of typical earthquakes are too short to allow response buildup of these long period modes. However, the characteristics of the ground motion records collected by a number of actual near-source earthquake seismograms have challenged this line of historical thinking. It is now clear that seismic wave radiation patterns and permanent co-seismic tectonic plate movements can result in large, long period ground displacement pulses which can significantly excite the low frequency modes of flexible bridge structures.

Computational Bridge System Model

A special purpose finite element program for the nonlinear analysis of suspension bridges (named SUSPNDRS) has been developed at the Lawrence Livermore National Laboratory. A complete description, including detailed evaluations of element and software performance, is provided in the referenced papers and reports (McCallen and Astaneh 2000, McCallen and Astaneh 1997). The philosophy in the development of the system model was to maintain simplicity in the element formulations and solution algorithms, and to provide a robust solution algorithm framework that can readily handle a number of strong nonlinearities including both material and geometric nonlinearities.

The developed bridge model consists of five basic elements, as shown in Fig. 3. These include a reduced-order deck model consisting of a composite combination of truss, membrane, and special sway stiffness elements representing the two reinforced concrete upper and lower decks, the two northside and southside steel riveted stiffening trusses and the horizontal bracing system under the lower deck laced members (labeled “a” in Fig. 3). A finite-rotation fiber bending element is used to represent the bridge multi-celled steel braced towers (labeled “b” in Fig. 3). A rocking rectangular block with contact foundation model represents the large reinforced concrete caisson foundations and allows potential rocking and uplift of the caissons (labeled “c” in Fig. 3). A penalty function based node-to-node contact element captures potential contact and impact between the deck system and towers

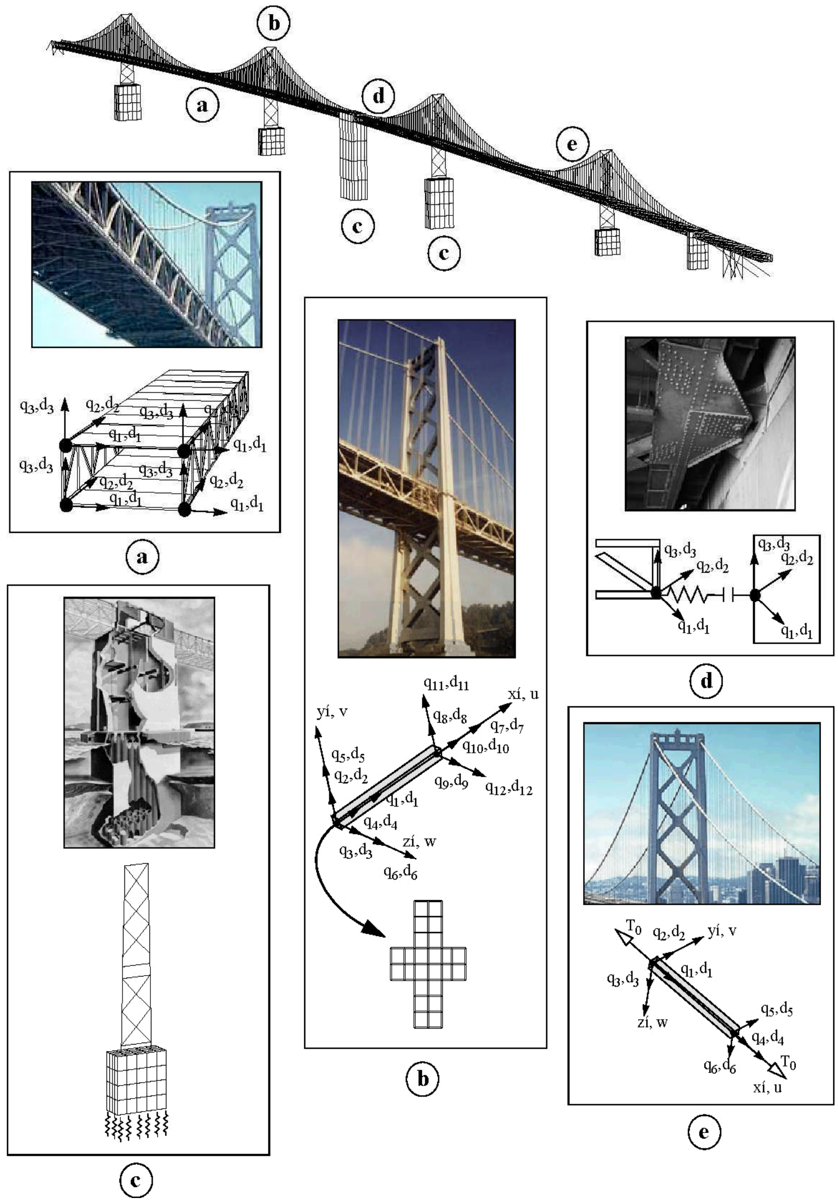

Figure 3. Components of the suspension bridge special purpose finite element model.

(labeled “d” in Fig. 3, and a tension-only cable element with user-defined initial stress represents the bridge cable system (labeled “e” in Fig. 3). Implementation of these elements provides a bridge computational model of significantly reduced degrees of freedom, that can still adequately represent essential aspects of the suspension bridge response (McCallen and Astaneh, 2000).

The model employs a combined implicit/explicit solution algorithm. An iterative, implicit solution algorithm is used to initialize the bridge system model under gravity loading in a way that preserves the appropriate deck force distribution and reaches the appropriate bridge cable/deck geometry under gravity loading. This process is described in detail in McCallen and Astaneh, 2000. Once gravity initialization has been accomplished, the solution switches to an explicit time integration algorithm for the nonlinear time history analysis of the earthquake motions. An explicit integration scheme provides a robust framework for highly nonlinear dynamic problems. Explicit integration schemes are conditionally stable with the time step size governed by the highest frequency of the simulation model. This can be problematic when attempting to use general purpose finite element programs where physical element sizes may be small, thus driving an untractably small time step. However, with the special purpose elements in the SUSPNDRS program, the resulting element sizes are physically large, leading to a relatively large stability time step that permits solution of earthquake duration problems.

Near-Fault Ground Motions

Ground motions in the near-source region are dramatically effected by fault rupture properties such as rupture velocity, slip rate, directivity, and radiation pattern. Near-source ground motion is also significantly effected by superposition of seismic waves, high frequency incoherence, three dimensional geologic focusing and de-focusing, and site geologic response. In addition, the effect of these parameters is significantly different for different rupture scenarios (i.e. the idealization of a specific fault rupture process) along the same fault. Variations in rupture scenario can result in major differences in ground displacements, velocities, and accelerations. In this study, the complexity of the fault rupture mechanics and wave propagation effects were addressed by: 1) providing a massively parallel, finite difference computational simulation of finite rupture along the Hayward fault; 2) using a three-dimensional finite difference calculation for synthesizing wave propagation for frequencies below 0.7 Hz; 3) using empirical Green's functions for synthesizing wave propagation for frequencies from 0.7 to 25.0 Hz; 4) computing the ground motion at seven points along the SFOBB.

It was found that in the near-source region *far-field* arrivals can result in significant fault normal pulses due to directivity effects, usually with periods of 0.2 to 0.5 s, and *near-field* arrivals can result in significant fault parallel pulses resulting from tectonic displacements and have periods of 0.2 to 0.1 sec. In addition, surface waves trap energy in the Bay basins with periods of 0.2 - 0.4 sec. All these long period arrivals could occur in future earthquakes along the Hayward or San Andres faults and have serious consequences to long span bridges in the San Francisco Bay, California, or long period structures in adjacent cities. There are seven bridges within 15 km of either the Hayward or San Andreas faults that have fundamental periods of 0.1 to 0.5 s.

Character of Near-Fault Ground Motions

Ground motions for two rupture models of an Mw = 7.25 (M_o=8.5x10^{20} NM) along the Hayward fault were synthesized at five locations along the suspension spans of the western San Francisco Oakland Bay Bridge (SFOBB). These models were identified as the mean and one standard deviation models, HAY06 and HAY31, respectively (Hutchings et al. 1996). The synthesis of the seismograms captured frequencies from DC to 0.7 Hz (Periods of 1.4 sec. to ∞) using the finite difference wave propagation program E3D (Larsen et al. 1997, Larsen and Schultz 1995). This solution includes full 3-D elastic modeling, extends to zero frequency and the full wavefield of seismic energy. The underlying methodology of the program is based on the elastodynamic formulation of the full wave equation on a staggered grid. We coupled a 3D geologic model for northern California (Stidham et al. 1999) to the finite difference code. The geologic model represents the local near-surface geology averaged over a few kilometers. Deeper and more distant geology is represented in less detail. The model was coupled to the computer code in a volume 175 x 100 x 40 km in size as shown in Fig. 4.

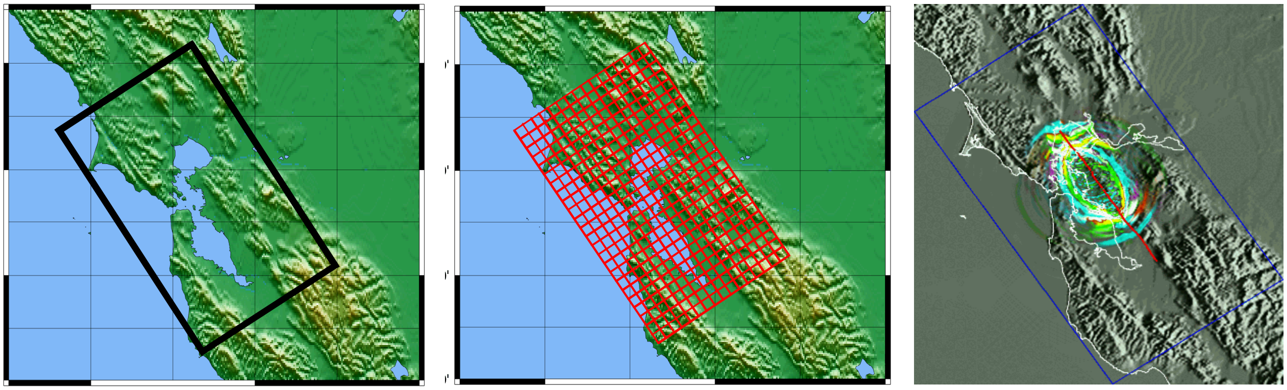

Figure 4. The geophysics simulation model of the San Francisco Bay Area.

The methodology of Hutchings et al. (Hutchings, 1996) was utilized to calculate seismograms for frequencies from 0.7 to 25.0 Hz. (periods of 0.04 to 1.4 s). The approach uses kinematic rupture models along with empirical Green's functions. Empirical Green's functions were obtained at four locations along the bridge from surface and borehole recordings (Hutchings et al., 2005). A four-pole Butterworth filter was used and matched to combine the high and low frequency solutions to obtain a synthetic broad band ground motion time history.

The "mean" fault rupture model (HAY06) generated greater long period ground displacements at the bridge than the "one standard deviation" model (HAY31). However, the "one standard deviation" model created greater accelerations and longer durations. Both models had comparable velocities. The HAY031 rupture model had near unilateral fault rupture away from the bridge and model HAY06 was bi-lateral fault rupture. Analysis with the bridge model indicated that the response to the mean model was actually more stressing to the bridge than the one standard deviation model and thus the focus of discussion below is on the HAY06 model.

As an illustrative example of the effects of near field motions, the response of the Bay Bridge to the eighty seconds of synthetic ground motion from rupture model HAY06 has been computed. The simulated ground motions at the Bay Bridge site for this rupture model are shown in Fig. 5 for selected support locations.

The transient dynamic response of the bridge to this particular fault rupture scenario is shown in Fig. 6. The exaggerated bridge displacements (displacement scale factor = 50) indicate that when the large displacement pulse occurs, the flexible deck cannot react as fast as the stiff towers and lags behind the tower motion. As the towers begin to return with the ground in the opposite direction, the deck begins to respond and flings through the towers in the opposite direction.

The demand-to-capacity ratios computed from the bridge model subjected to the HAY06 motions are summarized in Table 1. A number of components are significantly stressed and retrofit or replacement would be indicated.

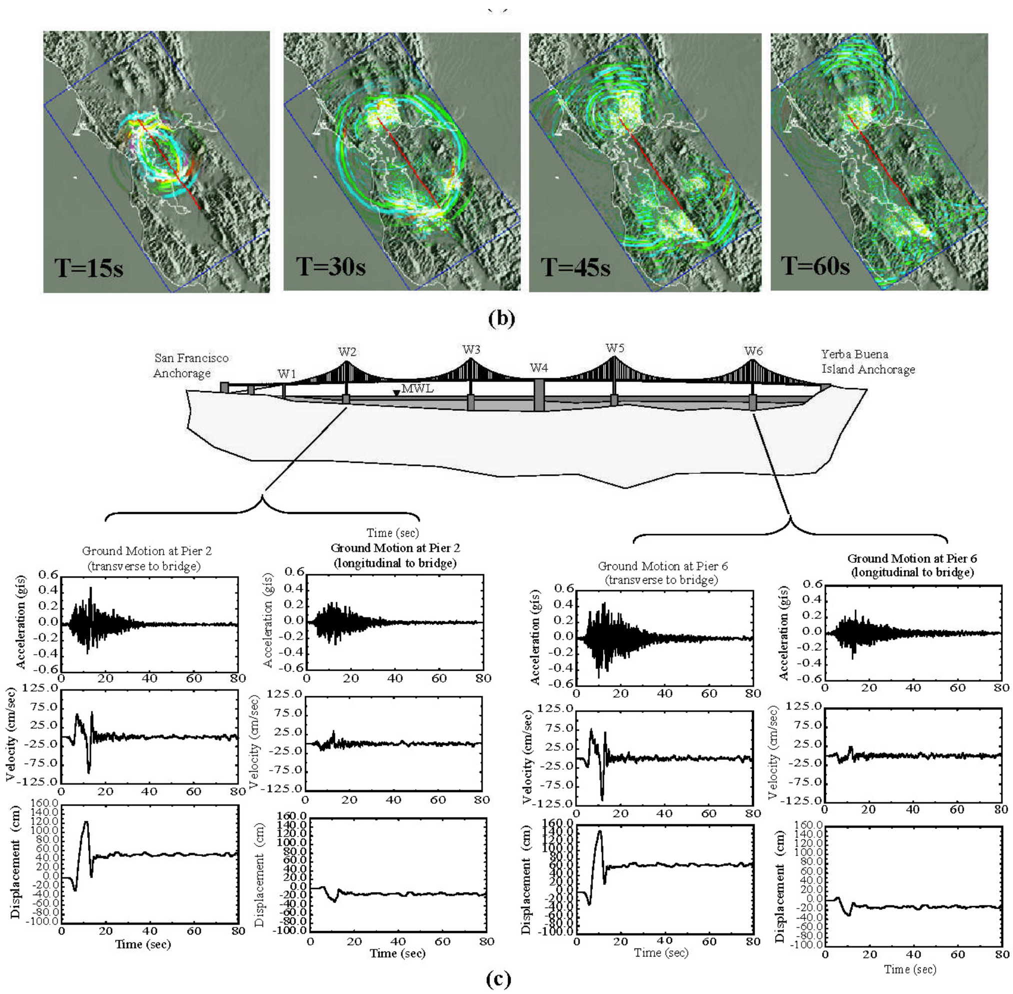

Figure 5. Regional finite difference model and selected ground motions at SFOBB

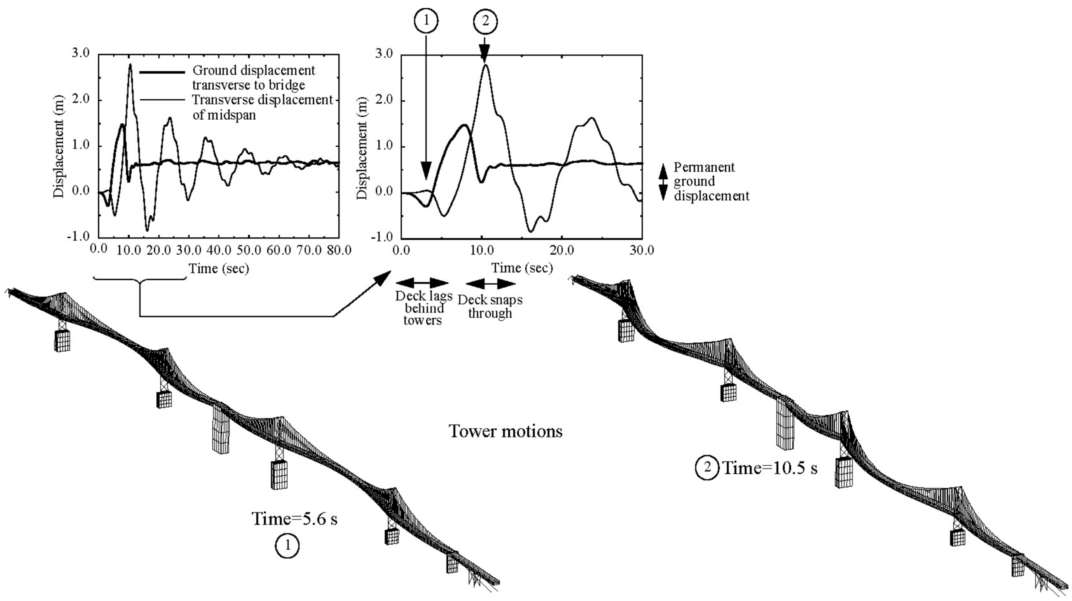

Figure 6. Bridge deformation at selected instants of the earthquake response.

Table 1. Structural component demand-to-capacity ratios.

Structural Component	Demand-to-Capacity Ratio
Deck truss diagonals	1.5 (max)
Deck truss verticals	1.75 (max)
Deck truss chords	1.95 (max)
Main cables	0.79 (max)
Vertical hangers	0.91 (max)
Tower legs	2.15 (max)
Tower braces	2.69 (max)
Tower deck struts	4.97 (max)

Conclusions

We find that:

1. In synthesis of fault rupture scenarios, *far-field* shear-wave generation and *near-field* tectonic ground displacements can result in very large long period ground displacements and velocity pulses.
2. *Far-field* arrivals have the strongest energy at periods of about 0.2 to 0.5 s, and *near-field* arrivals have the strongest energy at periods of about 0.1 to 0.2 s. Similar simultaneously arriving pulses were recorded during the recent Taiwan and Turkey earthquakes.
3. The special purpose computational program SUSPNDRS, which has been developed, provides a powerful research tool for investigating the nonlinear dynamic response characteristics of suspension bridges. The specialized bridge elements allow practical exploitation of an explicit time integration solution of the equations of motion, which is a reliable and robust algorithm for highly nonlinear problems. The program can characterize a full bridge system with a modest number of global degrees of freedom and seismic simulation solution times on a desktop workstation. This makes it economical enough to allow efficient parametric studies.
4. The explicit time integration provides a robust solution framework that will readily accommodate future implementation of complex nonlinear material behavior, such as laced member buckling and connection failures.
5. For some fault rupture scenarios, the large tectonic displacement pulse initially drives the towers with motion parallel to tectonic fault displacement before the bridge deck has "felt" the motion. Just as the deck is beginning to respond to the tectonic displacement, the far-field S-wave energy arrives and drives the towers in the opposite direction. Thus, the two main members of the super-structure can be driven in opposing directions. This motion can result in considerable stressing of the stiffening truss

supporting the roadway as well as the towers.

6. The type of long-period modal response observed in the Bay Bridge can occur in other long period structures such as base-isolated systems and tall buildings.

Acknowledgments

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