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GOLDEN GATE BRIDGE RESPONSE – A PRELIMINARY STUDY WITH LOW AMPLITUDE EARTHQUAKE DATA

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ABSTRACT

Sitting at the entrance to San Francisco Bay from the Pacific Ocean, the Golden Gate Bridge (GGB) is an important lifeline connecting the City of San Francisco and the Peninsula to the south with Marin County to the north. It serves more than 40 million vehicles per year. Built in late 1930's, GGB has a suspension span of 1280 m (4200 ft) and total length of 2737 m (8981 ft), and was the longest suspension span bridge in the world until 1964. The dynamic response characteristics of the bridge have been identified and studied by others using both ambient vibration data and finite-element models. However, to the best knowledge of the authors, this is the first study of the response of the bridge to excitation from an earthquake.

Under an agreement with GGB Authority, the GGB has a strong-motion structural response array installed by the California Geological Survey (CGS) that has recorded small earthquakes since 1993. Because it was not instrumented at the time of the 1989 Loma Prieta earthquake, strong shaking of the bridge was not recorded. As a result, all of the responses due to earthquakes recorded to date are from small events originating at distances of 30 km or more; hence, the amplitudes of the shaking data from sensors on the bridge are small. The best earthquake response data that provide an opportunity for understanding the dynamic characteristics of the bridge are from the M_L=5.2 September 3, 2000 Yountville (CA) earthquake at an epicentral distance of 62 km from the bridge. The largest peak accelerations recorded on the bridge at ground level and on the structure are approximately 1% g and 4% g respectively. Data from the October 30, 2007 Alum Rock earthquake (M_w=5.4) at epicentral distance of 75 km from the bridge are also analyzed. In this study, the raw earthquake response bridge array data recorded from the two earthquakes are carefully processed for use in identifying dynamic characteristics to facilitate comparison with those from previous studies.

Fundamental periods (and therefore the frequencies) for several important modes are identified by spectral analyses. The results are quite variable and not

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consistent. This may be due to the source of excitation. Compared with previous studies, the earthquake response data used in this study indicate a shorter fundamental period for transverse modal response of the bridge deck center span as compared to that from previous modal analyses (8.33s versus 9.1-10.9s). It is noted that interactions between the tower, cable, suspenders, and bridge deck are significant during even the low-amplitude shaking of the two earthquakes. A much larger difference for the transverse deck fundamental period is identified from the records when compared with previous studies (13.9s versus ~18.2s). This paper provides detailed comparisons of dynamic characteristics obtained from all studies, and discusses their differences and implications.

Introduction

The Bridge

The Golden Gate Bridge (GGB) is an important lifeline connecting the City of San Francisco and the Peninsula in the south to Marin County in the north – serving more than 40 million vehicles per year. Completed in 1937, GGB with a suspension span of 1280 m (4200 ft) and total length of 2737 m (8981 ft), was the longest suspension span bridge in the world until 1964. The two towers of the bridge are 214.1 m (702 ft) tall with respect to the top of the piers and are built of several cells composed of plates and angles that are braced by horizontal cross-beams. After 1951, some of the trusses that support the 6-lane roadway were stiffened by adding wind braces. It should be pointed out that the bridge and its important approaches are currently undergoing an extensive retrofit program that started in 2002. At the time of writing this paper, retrofitting of the approaches to the bridge were completed but retrofit of the suspension bridge has not yet started; hence, none of the data from the suspension bridge used in this paper are related to possible changes in response characteristics due to future completion of its retrofit. Hence, data recorded from either future earthquakes or tests to be conducted on the suspension bridge may reveal important differences in the dynamic characteristics as compared to those presented herein.

Past Instruments, Tests and Analyses

The dynamic response characteristics of the bridge have been identified and studied by others using both ambient vibration data and finite-element models. However, to the best knowledge of the authors, and although preliminary, this is the first study of the responses of the bridge to actual earthquake excitation input.

During and following construction, instruments have been deployed on the bridge, and various analyses have been performed on these non-earthquake data. Mathematical models of the bridge have also been developed to assess its various dynamic modal characteristics. Summarizing from Abdel-Ghaffar and Scanlan (1985a and b), instruments were deployed by the U.S. Geodetic Survey [Vincent 1958, 1962a and b] during and after construction of the bridge and later by California Bureau of Public Roads until about 1954. Vincent (1958, 1962a and b) analyzed the instrumental data and compared them with mathematical models he developed. Later Baron, Arikan and Hamati (1976) made 3-D finite element analyses of the bridge. By far the most exhaustive ambient tests and analyses of data from such tests, as well as two (2-D) and three dimensional (3-D) mathematical modeling, have been done by Abdel-Ghaffer and Scanlan (1985a and b). Furthermore, Ghaffar and Scanlan (1985a and b) summarized and compared in great detail their results with other prior studies. Within the last two decades, limited studies on the bridge have been performed by Kim and others (2007) using a temporary deployment of sensors.

Objectives and Scope

The purpose of this paper is to study the dynamic characteristics of the GGB using earthquake data, albeit small amplitude motions, and compare them to those from past ambient tests and theoretical analyses performed by others. Only selected results from other studies deemed pertinent are referred to later in the paper when comparing them with earthquake data analyses performed in this paper. Furthermore, no mathematical models are developed in this preliminary study. Only spectral analyses are performed to identify relevant frequencies. Only dominant frequencies in the response are identified. System identification analyses are not performed in this study. Determination of critical damping percentages are left to future work.

Recent Modern Permanent Instrumentation and Data

In this paper, dynamic response characteristics of the GGB are identified using some of the limited number of earthquake response data since the bridge was instrumented after the 1989 Loma Prieta (M_w=6.9) though an agreement between Golden Gate Bridge Authority and California Strong Motion Instrumentation Program (CSMIP) of California Geological Survey (CGS). A general schematic of the Golden Gate suspension bridge and associated instrumentation is shown in Figure 1.

The recently developed Center for Engineering Strong-Motion Data (CESMD) currently offers GGB response data from four different earthquakes (Figure 2). Because the processed data provided at CESMD exhibits considerable variation in processing parameters, in this paper, two of the earthquakes listed in Figure 2 for which raw data were available (Yountville 2000 [M_L=5.2] and Alum Rock 2007 [M_w= 5.4] are re-processed using a much wider filtering bandwidth [0.05-50Hz] in order not to exclude longer periods of the modes of the bridge suggested by previous studies.

Analyses of Earthquake Data

Figure 3 shows plots of time-histories of accelerations from the Yountville earthquake recorded at different locations on the bridge, and classified according to the orientations of accelerometers deployed on the bridge as indicated in Figure 1. Figure 4 shows selected time-histories of accelerations in the lateral direction of the bridge during the Alum Rock (2007) earthquake. These accelerations are used to compute Fourier amplitude spectra from which the dominant frequencies are identified.

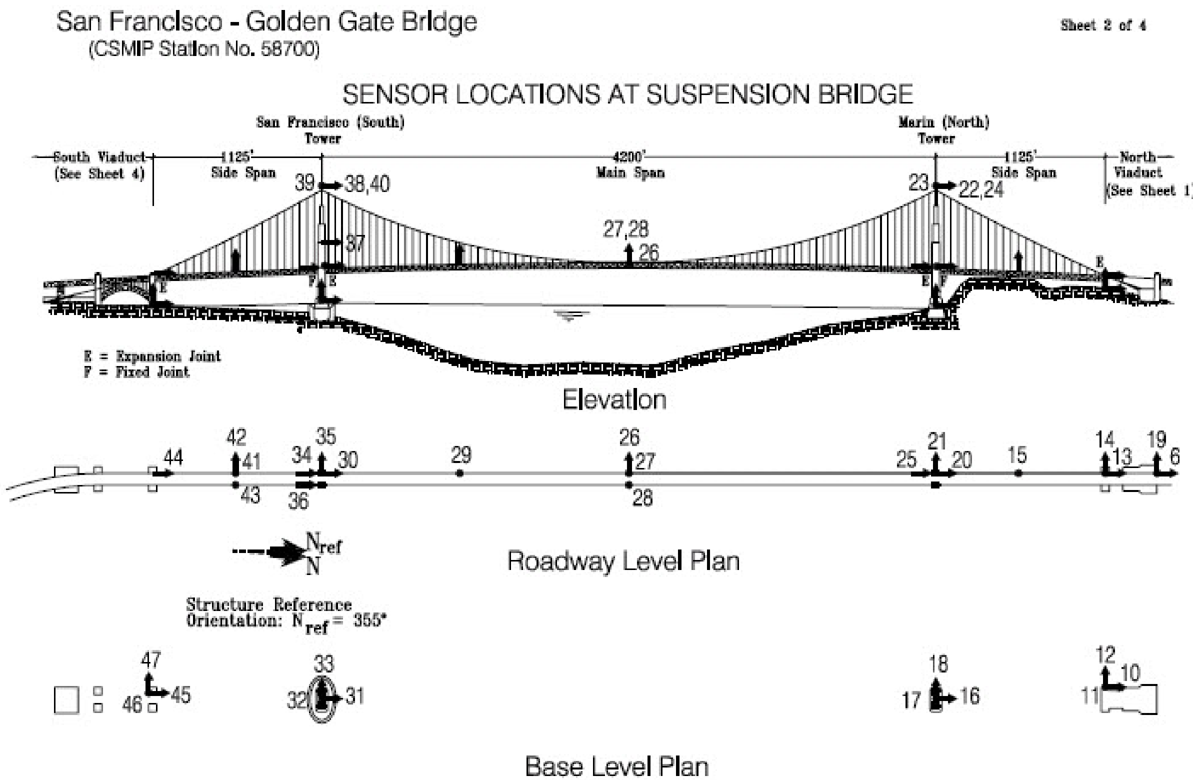
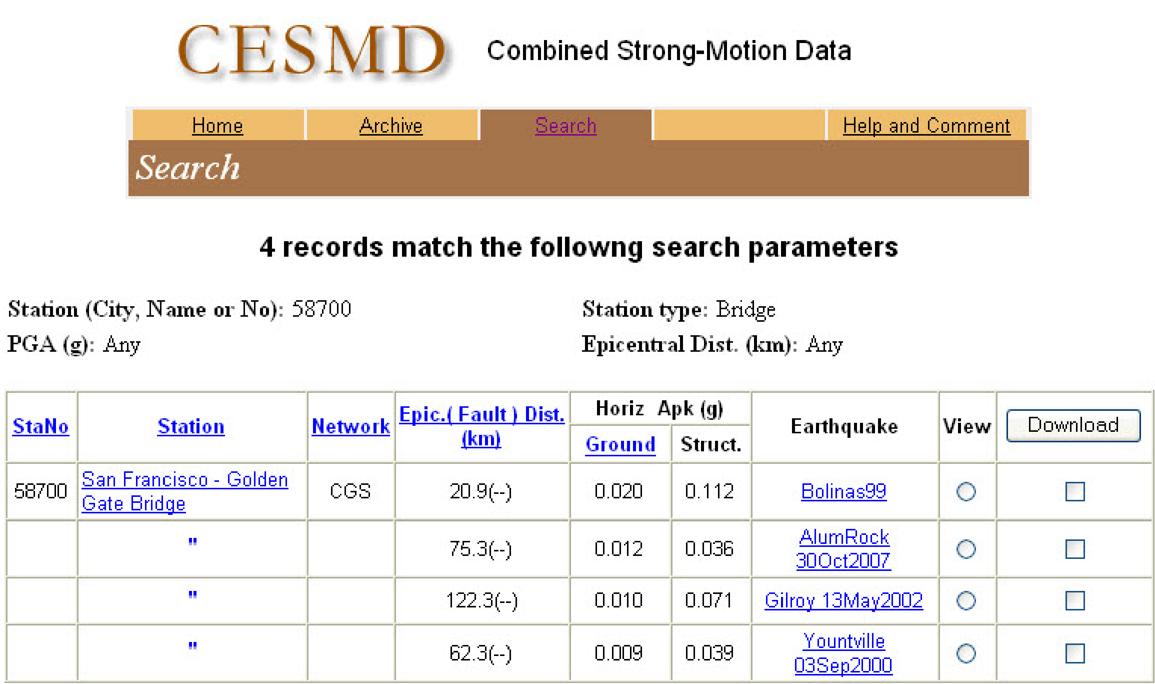


Figure 1. General schematic of the Golden Gate Bridge and associated instrumentation depicting sensor locations and orientations (http://www.strongmotioncenter.org).



CESMD Combined Strong-Motion Data

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Search

4 records match the followng search parameters

Station (City, Name or No): 58700 **Station type:** Bridge

PGA (g): Any **Epicentral Dist. (km):** Any

StaNo	Station	Network	Epic.(Fault) Dist. (km)	Horiz Apk (g) Ground	Horiz Apk (g) Struct.	Earthquake	View	Download
58700	San Francisco - Golden Gate Bridge	CGS	20.9(--)	0.020	0.112	Bolinas99		
	"		75.3(--)	0.012	0.036	AlumRock 30Oct2007		
	"		122.3(--)	0.010	0.071	Gilroy 13May2002		
	"		62.3(--)	0.009	0.039	Yountville 03Sep2000		

Figure 2. List of available GGB earthquake response data from CESMD. (http://www.strongmotioncenter.org)

As shown in Figure 5, even though some peaks in the vicinity of 1 Hz are visible, it is difficult to reliably identify lower frequency (longer period) modes of the bridge from the amplitude spectra of accelerations of either earthquake. Hence, Fourier amplitude spectra were computed using both accelerations and displacements obtained though double integration of the accelerations. Whichever spectrum provided the best result is shown. Figure 6 show two such spectra computed from displacements for the Yountville (2000) earthquake which clearly illustrate fundamental frequencies, lowest at 0.08 – 0.12 Hz (period 8.33-12.33 s) for the towers in the longitudinal direction and for the deck center in the vertical direction. Higher frequency vertical modes at 0.29 and 0.44 Hz (periods 3.45 s and 2.27 s) are also clearly identifiable from the spectrum in Figure 6a. In the transverse direction, as seen in Figure 6b, the deck center and towers again exhibit frequencies at 0.08 – 0.12 Hz (period 8.33 - 12.33 s) possibly indicating complex modes *(e.g.* coupling interaction of modes generated via cable and vertical suspenders). This possibility is also discussed by Abdel-Ghaffar and Scanlan (1985a and b). A second dominant frequency at 0.22 Hz (period 4.55 s) is also common to both towers and deck center.

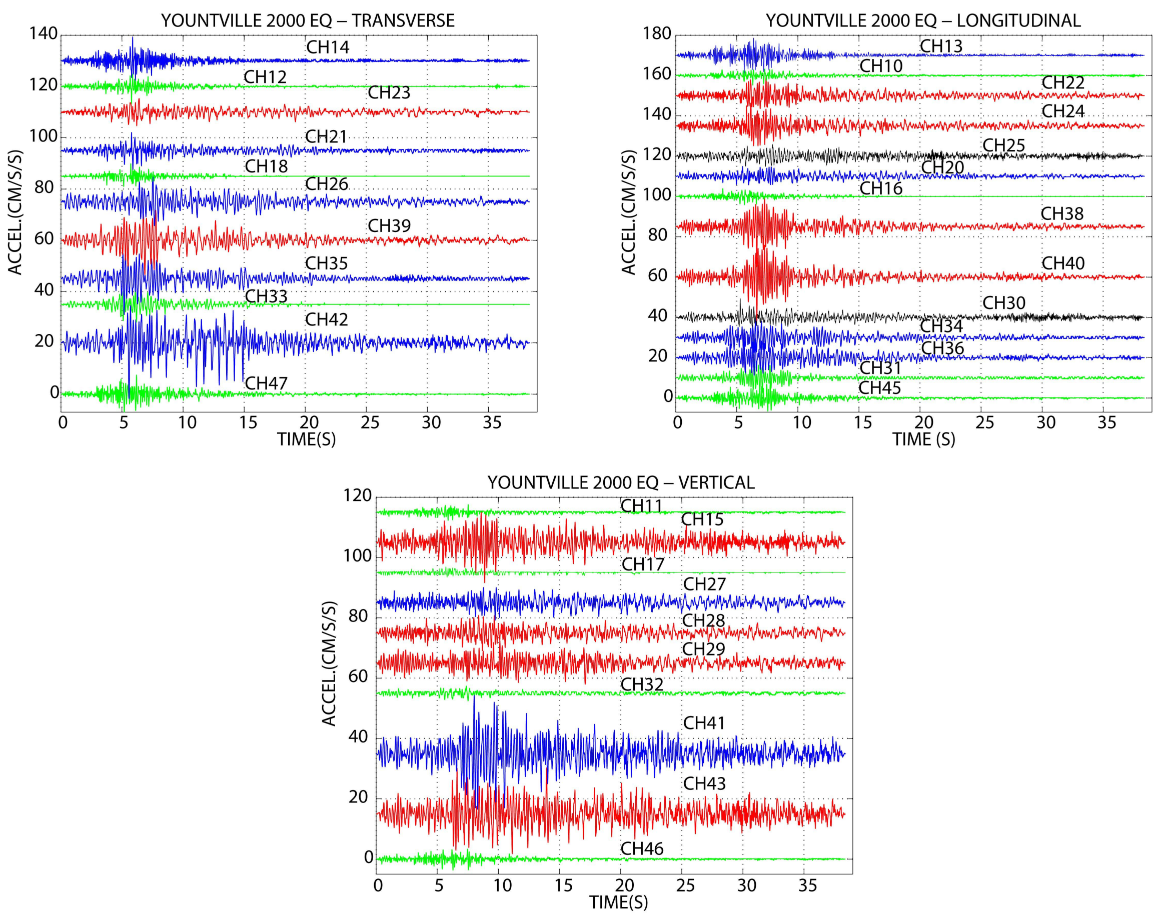

Figure 3. Time-histories of bandpass-filtered accelerations recorded at Golden Gate Bridge from the Yountville (2000) earthquake in the (a) top left: transverse, (b) top right: longitudinal, and (c) bottom: vertical direction of the bridge, respectively.

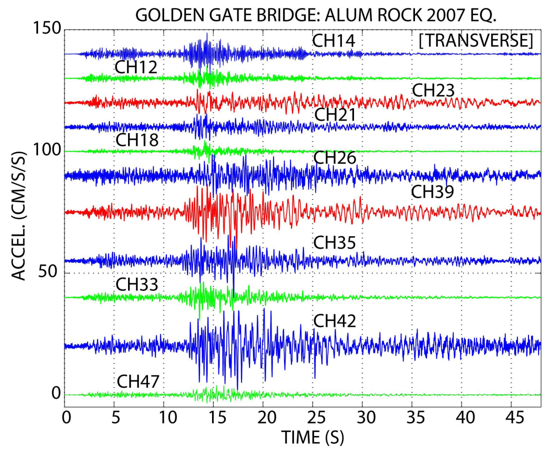

Figure 4. Time-histories of bandpass-filtered accelerations in the lateral direction of the bridge during the Alum Rock (2007) earthquake.

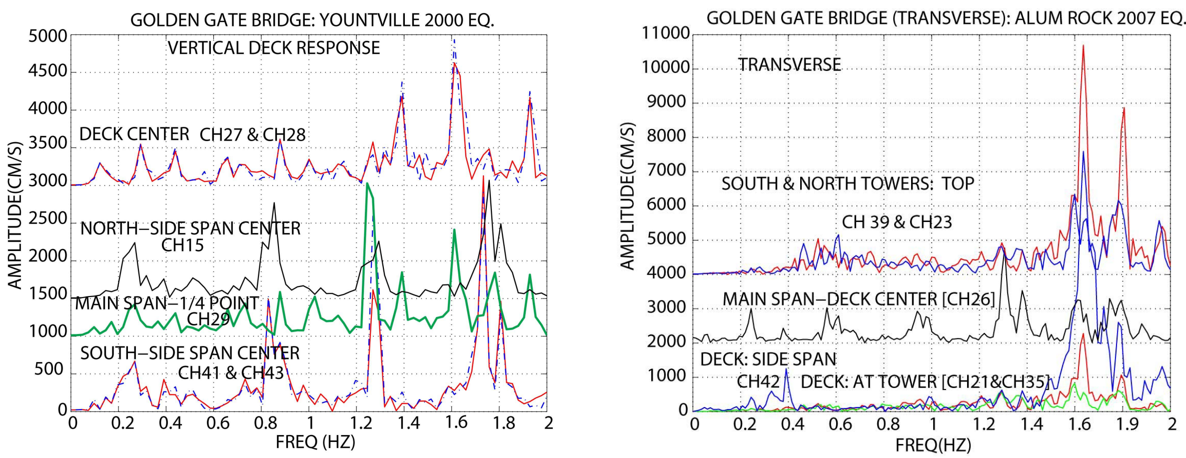

Figure 5. Sample amplitude spectra using bandpass-filtered accelerations from Yountville (2000) and Alum Rock (2007) earthquakes do not reliably identify modes <0.2 Hz.

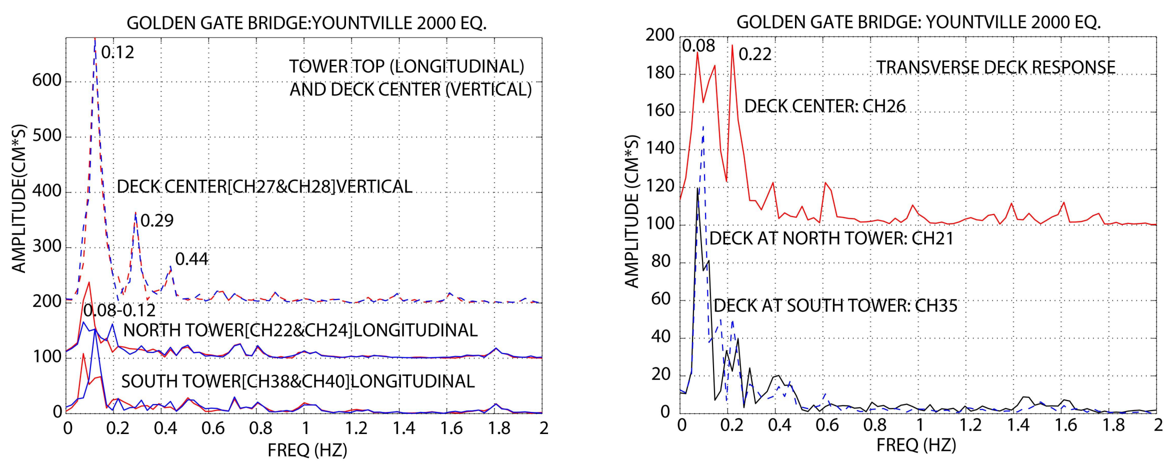

Figure 6. Amplitude spectra computed using displacements from Yountville (2000) earthquake reveal the low frequency peaks representative of fundamental modes.

In the case of the Alum Rock (2007) earthquake (Figure 7a), the frequencies determined for the tower top longitudinal direction and the deck center vertical direction are similar to those determined from Yountville data (0.08-0.12 Hz [period 8.33-12.33 s]). However, in the transverse direction, a lower frequency (0.058-0.08 Hz [period 12.33-17.2 s]) is obtained. For the deck center, the peak at frequency of 0.22 Hz is consistent with that for this mode for the Yountville earthquake.

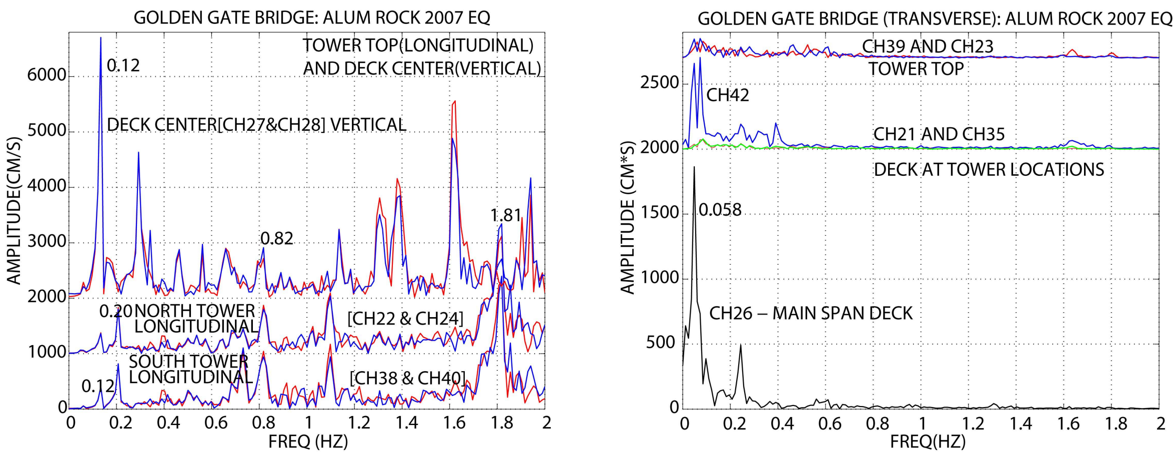

Figure 7. Alum Rock (2007) earthquake amplitude spectra computed using (left) vertical accelerations at deck center and longitudinal accelerations at top of towers, and (b) transverse displacements at deck center, deck at tower locations, and top of tower indicating the low frequency peaks representative of important modes.

Comparison of Dynamic Characteristics

Table 1 summarizes some of the modal fundamental frequencies (periods) identified in this preliminary study using low-amplitude earthquake data, along with selected results from two other prior studies performed using mathematical models and ambient data. There is no consistency in the frequencies of some of the important modes of the GGB obtained from any one source of excitation. Such inconsistencies were observed and documented for buildings using strong shaking and low-amplitude vibration data (Çelebi, Phan and Marshall 1993; Çelebi 2007). Furthermore, as Abdel-Ghaffar and Scanlan (1985a and b) have indicated, the fundamental frequencies are repeated in several key locations due to interaction of tower, cable, suspenders, and deck. Not surprisingly, this interaction was also observed in another long-span bridge (Bill Emerson Memorial Bridge at Cape Girardeau, MO) data and analyses (Çelebi 2006).

Conclusions

Some of the principal modal frequencies (periods) have been identified along key directions of the bridge using low amplitude response data from two earthquakes obtained from the GGB seismic array. These results are compared to other studies which used data obtained from ambient tests and also from mathematical models. Although the results are not consistent, they may shed light on what variability of expected lower frequencies (longer periods) is to be expected from much stronger shaking that may be generated from a larger earthquake at closer distances. Large motions from future earthquakes should no doubt excite some of the modes better than the low amplitude motions. Interaction of the tower top, cable and deck during earthquake are inferred from similarity in frequencies along different directions of the bridge. This interaction has also been noted in past studies with ambient data.

Table 1. Summary of Fundamental Frequencies in Hz (Periods, in seconds)] from Past and Current Study

Location/ Direction	Abdel-Ghaffar et al (1985) (*)		Kim et al (2007)		This Study (2009): Earthquake Data	
	Ambient	**Finite Element (**)**	**Ambient**	**Finite Element**	**Yountville 2000**	**Alum Rock 2007**
Transverse (Deck)	0.055 (18.2)	.049-.064 (15.6-20.4)			0.08-0.12 (8.33-12.33)	0.06-0.08 (12.33-16.33)
Transverse (Tower)	0.46 (2.18)	0.43 2.30			0.08-0.12 (8.33-12.33)	0.06-0.08 (12.33-16.33)
Vertical Center Span (sym. mode)	0.122 (8.2)	.124-.127 (7.9-8.1)	0.095 (10.55)	0.106 (9.41)	0.08-0.12 (8.33-12.33)	0.12 (8.33)
Longitudinal (Towers)	0.75 (1.33)	.66-.69 (1.44-1.52)			0.08-0.12 (8.33-12.33)	0.12 (***) (8.33)
Longitudinal (Suspension Structure)	0.262 (3.81)				Evaluation not yet completed	
Torsional (Tower)	0.82 (1.21)	0.91 (1.10)				
Torsional (Deck)	0.24 (4.10)	0.21-0.22 4.53-4.72				
* limited modes of the study by Abdel-Ghaffar et al is also summarized in Chopra, 1996, **variation due to 2 or 3 dimensional modeling), *** Tower interaction with deck						

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