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AMBIENT VIBRATION STUDIES OF THREE SHORT-SPAN REINFORCED CONCRETE BRIDGES

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ABSTRACT

This paper describes the results from ambient vibration studies conducted in 1993 on three short-span bridges located in the Cape Mendocino area, in Northern California. One of the bridges is the Painter Street Overpass in Rio Dell, which has permanent instrumentation that has recorded the motions from significant earthquakes in the area since 1980. Each overpass is a two-span reinforced concrete bridge with either two or three piers near the middle and monolithic abutments, typical of highway overpasses in California. The three bridges have decks that are skewed at about 39°, 19° and 6°, respectively. The ambient vibration studies were conducted to determine the dynamic characteristics of these bridges during low amplitude vibrations produced by wind, traffic and micro-tremors. The results show that the fundamental natural frequencies of these bridges are all similar. Because of the significant amount of strong motion data from Painter Street, it was of interest to determine its dynamic characteristics at low levels of vibration and to compare these with those determined using the recorded strong motion events. The results for Painter Street are also compared with those obtained from a series of ambient vibration tests conducted more than thirteen years ago.

KEYWORDS

Ambient vibrations; natural frequencies; mode shapes; bridges; earthquakes; structural dynamics.

INTRODUCTION

The damage to bridges caused by recent earthquakes such as the 1989 Loma Prieta and 1994 Northridge earthquakes in California, and the 1995 Kobe earthquake in Japan, has demonstrated the need to assess the seismic resistance of existing bridges built before the advent of modern seismic design codes. A great deal of effort is being placed today on developing economical and effective seismic retrofit methods for bridges in order to minimize the potential damaging effects of earthquakes. An effective seismic retrofit study requires good information about the bridge dynamic characteristics, which may be used to calibrate computer models of the structure needed for the seismic assessment study.

The bridges selected for the studies described in this paper offer a good opportunity to assess existing methods to determine the seismic behaviour of short-span reinforced concrete bridges. The three bridges studied are located in the Cape Mendocino area in California, one of the most seismically active areas in the Pacific Coast on North America. Two of the bridges are located in the city of Arcata and the other one about 45 km to the south, in Rio Dell. Of significant interest in these studies was the Painter Street Overpass in Rio Dell which is instrumented with 20 accelerometers. The motions of several earthquakes have been recorded by the instruments installed on the bridge and its vicinity. An ambient vibration study of this bridge was also performed by CALTRANS (Gates and Smith, 1982) as part of a comprehensive series of vibration tests on 57 bridges in California. Because of the importance of the seismic data from the Rio Dell bridge and the interest on learning about the dynamic behaviour of short-span bridges, the Department of Civil Engineering at the University of British Columbia (UBC) conducted a series of ambient vibration tests on these three bridges during the first week of November of 1993. The bridges were tested as part of a research project on seismic retrofit of bridges being carried out jointly by three Canadian universities, McGill, Ottawa and UBC, and supported by a Strategic Grant from the Natural Science and Engineering Research Council (NSERC) of Canada. This paper presents the results of these tests.

DESCRIPTION OF THE BRIDGES TESTED

The Painter Street Overpass (PSO) is a two-span, prestressed concrete box-girder bridge that was constructed in 1973 to cross over the four-lane US Highway 101 in Rio Dell (see Fig. 1a). Its construction is typical of the type of California bridges used to span multilane highways. The bridge is 15.85 m wide and 80.79 m long. The deck is a multi-cell box girder, 1.73 m thick and is supported on monolithic abutments at each end and two piers that divide the bridge into two spans of unequal length; one of the spans is 44.51 m long and the other is 36.28 m long. The abutments and piers are supported by concrete friction piles and are skewed at an angle of 38.9°. Longitudinal movement of the west abutment is allowed by means of a thermal expansion joint at the foundation level. The piers are about 7.32 m high and each is supported by 20 concrete friction piles. The east and west abutments are supported by 14 and 16 piles, respectively. The bridge was instrumented in 1977 as part of a collaborative effort between the California Strong Motion Instrumentation Program (CSMIP) and CALTRANS to record and study strong motion records from bridges in California. Twenty strong motion accelerometers were installed at the site (see Fig. 2a.).

Since 1980, ten significant earthquakes have been recorded at PSO. Most of the earthquakes occurred southwest of the bridge, in the vicinity of the San Andreas fault. The magnitude of these events ranges from M_L= 4.4 to M_L=6.9, with epicentral distances of 15 km to 86 km. Recorded peak ground horizontal accelerations from these events range from .08g to 0.54g, while horizontal structural accelerations range from 0.10g to 1.09g. Although large structural accelerations have been recorded, no significant structural damage has been observed at the bridge. The extent of damage has been limited to settlement of the backfill and some cracking of the concrete.

The strong motion records from PSO have been studied in detail by several investigators. See, for example: Maroney, Romstad and Chajes (1990); Goel and Chopra (1994); Makris, et al (1994); and McCallen and Romstad (1994). Detailed studies of the ground motions recorded near the bridge, the influence of the foundations for different levels of shaking on the response of the bridge, and the correlation between the recorded motions on the ground and the superstructure are being conducted at UBC (Ventura et al., 1995; Finn et al., 1995).

The 7th Street Overpass (7SO) was constructed in 1966 and is a two-span, seven-cell prestressed concrete box-girder bridge that crosses over the six-lane US Highway 101 through the City of Arcata (see Fig. 1b). Its construction is similar to that of the Painter Street. The bridge is 16.46 m wide and 73.17 m long. The deck is 2.13 m thick and is supported on monolithic abutments at each end and a three-pier bent that divides the bridge into two spans of unequal length; one of the spans is 39.63 m long and the other is 33.54 m long. The abutments and piers are supported by concrete friction piles and are skewed at an angle of 19.2°. The piers are about 5.03 m high and each is supported by concrete friction piles.

The 11th Street Overpass (11SO) is located about 350 m to the North of 7SO, and also crosses over Highway 101. It was constructed in 1976 and is a two-span, five-cell prestressed concrete box-girder bridge (see Fig. 1c). Its construction is similar to that of PSO as well, except that the deck has a slope of about 6.5%. The bridge is 15.85 m wide and 82.32 m long. The deck is supported on sliding abutments at each end two piers that divide the bridge into spans of 33.54m and 48.78 m long. The abutments and piers are supported by concrete friction piles and are skewed 6°. The piers are about 5.12 m high and are supported by concrete friction piles.

a) Painter Street Overpass

b) 7th Street Overpass

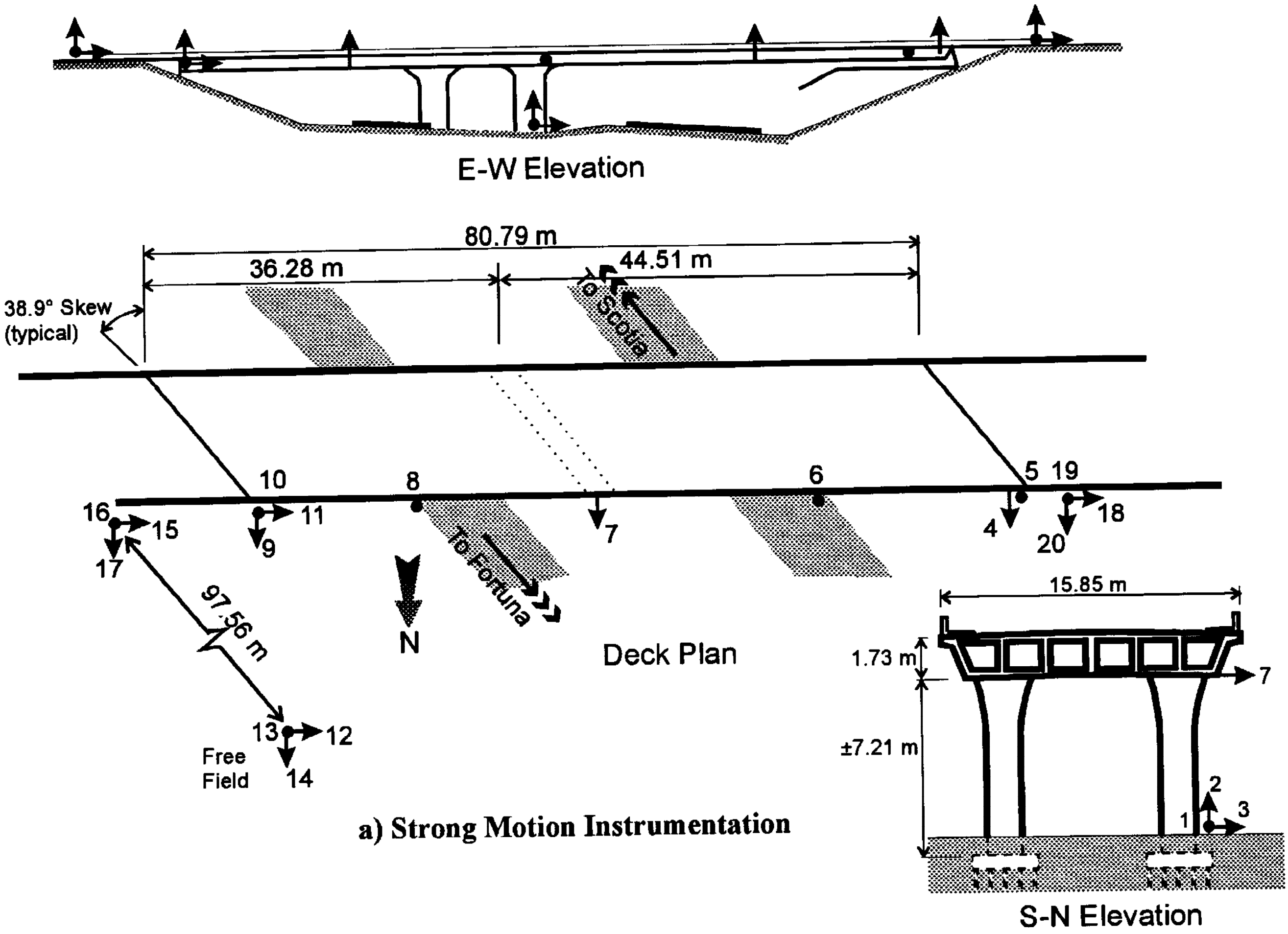
c) View of deck of 11th Street Overpass

Fig. 1. General views of the short-span bridges tested in these studies.

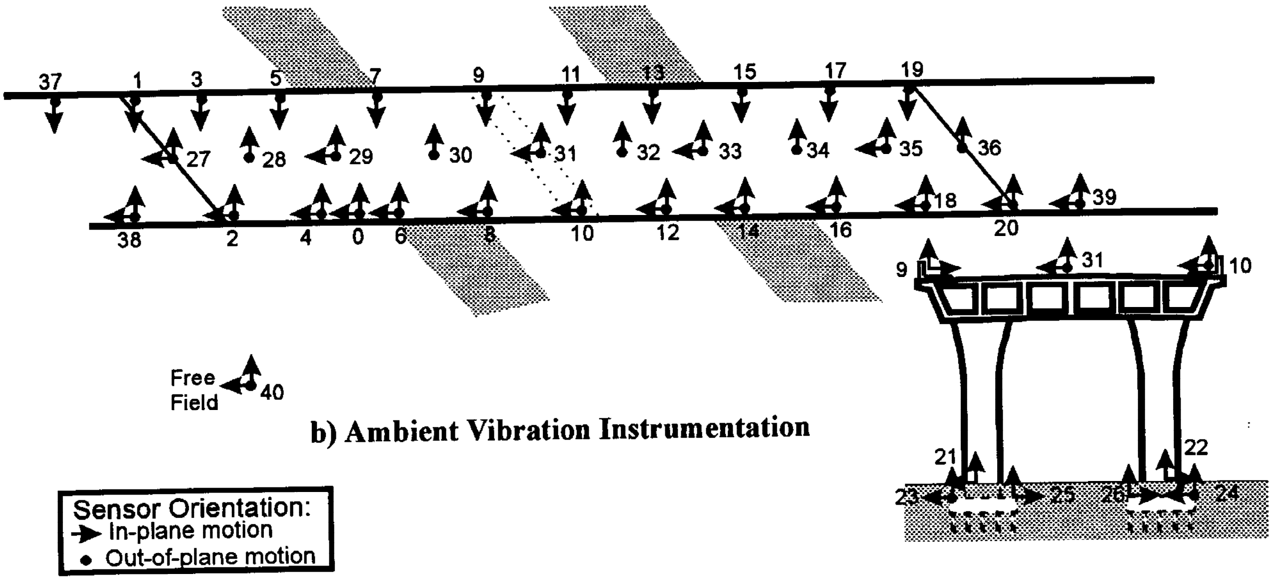
AMBIENT VIBRATION STUDIES

The purpose of this study was to determine key dynamic characteristics of the three bridges during low amplitude vibrations produced by wind, traffic and micro-tremors. The series of tests at PSO included vibration measurements of the superstructure, abutments, backfill, pile caps and the free field. The measurements at 7SO and 11SO were limited to deck, pier base and free field motions.

An accelerometer-based, data acquisition system was used to collect the data from a number of setups at each of the three bridges. Vibration data was obtained using 8 force balanced accelerometers (Kinemetrics FBA-11: 50 Hz natural frequency, 70% damping, 5 volts/g sensitivity, 130 dB dynamic range). Two PC computers were included in the setup. The data acquisition computer, a portable PC with an Intel 80286 processor, was dedicated to acquiring the ambient vibration records. In between measurements, the data files from the previous setup were transferred to the data analysis computer. This second computer was a PC with an Intel 80486DX processor. This arrangement allowed data to be collected on one computer while the second, and faster, computer could be used to process the data in-situ. This approach maintained a good quality control that allowed in-situ preliminary analyses of the collected data. Typical test parameters were as follows: a) Sampling rate = 40 sps (20 Hz Nyquist); b) Signal conditioner gain = 250 to 2000; c) Signal conditioner filters = 0.1 Hz high-pass, 12.5 Hz low-pass; d) Number of independent data segments per channel = 8, with 4096 data-points each; and e) Duration of data acquisition = ±15 minutes per set up (average). Details of the components of the test equipment are described by Felber (1993).



a) Strong Motion Instrumentation



b) Ambient Vibration Instrumentation

Fig. 2. General dimensions and instrumentation of Painter Street Overpass

Recorded data was analysed using computer programs U2, P2 and V2 (EDI 1994). Program P2 was used to generate and combine power spectral densities (PSD). Program U2 was used to compute the relative transfer functions between the signals from a reference location and other locations. This program computed the amplitude, phase and coherence between pairs of signals. V2 was subsequently used to assemble, visualize and animate the deflected shapes corresponding to the computed transfer functions. The identification of the significant frequencies of each bridge from the ambient vibration data was accomplished by analysing the PSDs of the recorded accelerations. To optimize the frequency identification procedure, the average of the normalized PSDs, called ANPSD (see Felber, 1993), of all the recorded motions for each of the principal directions of motion were computed and analysed. The data analysis was limited to the evaluation of modes of vibration in the frequency range 0 to 20 Hz.

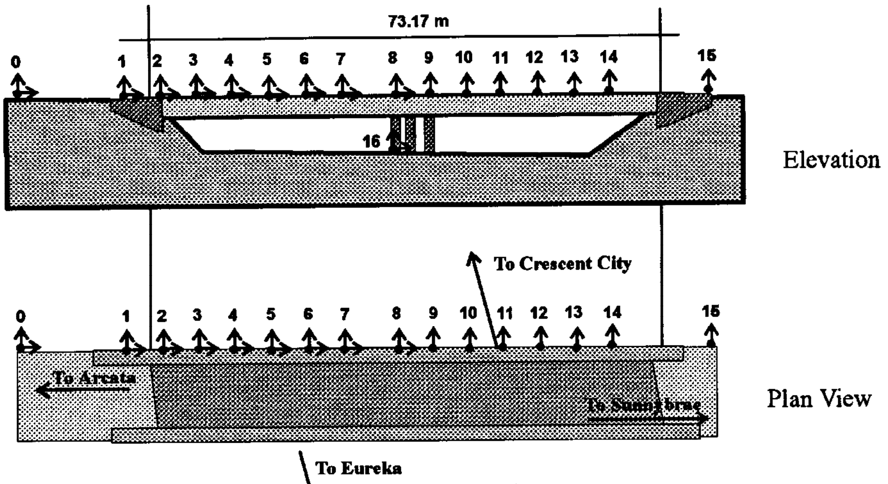
The selected locations and orientations of the accelerometers installed at PSO are shown in Fig. 2b. Three reference accelerometers were installed permanently at location 0 in Fig. 2b, while the other five were moved from location to location. The measurement locations for 7SO and 11SO are shown in Fig. 3. A total of 17 sites were measured at 7SO, with a reference location at 3 (Fig. 3a). Due to access problems, only one side of the deck could be measured, and therefore torsional motions of the bridge could not be separated from bending motions. At 11SO, 19 locations were measured, with reference sensors installed at location 12 (Fig. 3b).

The vertical modes of vibration of all the bridges were excited by the highway traffic underneath them and could be identified quite readily from the records. This was a particular advantage since secondary effects associated with vertical modes contributed significantly to the observed lateral motions. ANPSDs were computed for all the vertical, transverse and longitudinal signals recorded on the deck. The results for the transverse and vertical directions are shown in Fig. 4. For the frequency range shown, seven significant peaks clearly identify the first seven vertical modes of vibration of PSO. In contrast, only five significant frequencies can be identified for 11SO, and eight are identified for 7SO. Corresponding mode shapes were also identified, but the results are not shown here because space limitations. The fundamental vertical frequency for the three bridges are 3.4 Hz for PSO, 3.05 Hz for 11SO and 3.59 Hz for 7SO. Fundamental torsional frequency for PSO and 11SO was identified at 4.92 Hz and 5.78 Hz, respectively. The higher order frequencies exhibited significant coupling between vertical and torsional modes of vibration of the deck.

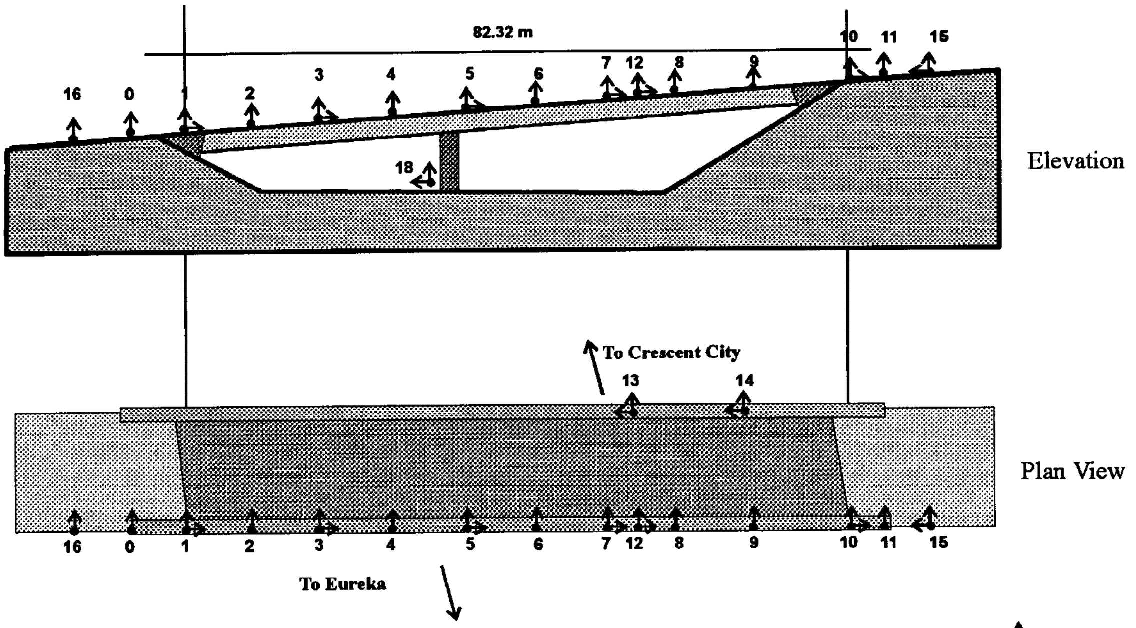
For the transverse direction, six significant frequencies were identified for PSO and 11SO, but only five for 7SO. In all the results it was found that the frequency of the fundamental mode was well defined in the ANPSD plot (4.14 Hz for PSO, 4.06 Hz for 11SO and 4.61 Hz for 7SO) while the frequency for the second transverse mode of each bridge was difficult to detect due to the coupling with transverse components of torsional modes.

The elevation and plan views of the first six mode shapes of PSO below 10 Hz are shown in Fig. 5. The vertical mode at 3.52 Hz is very well defined and has very small transverse components. The modes at 4.92, 6.02 and 7.10 Hz show significant torsional and translational components. This is also apparent in Fig. 4 where the peaks for the transverse direction are significant at these frequencies. The transverse modes do not exhibit significant vertical or torsional components. Similar behaviour was observed in the mode shapes of 7SO and 11SO.

The ambient vibration study of PSO by Gates and Smith in 1982 reported four frequencies within the same range: a) 3.61 Hz and 7.28 Hz for the first and second vertical modes, respectively, and b) 4.49 Hz and 7.42 Hz for the first and second transverse modes, respectively. Considering that testing equipment and data analysis methodologies were different for each study and that the large number of measurement points in the UBC test permitted a better definition of the mode shapes, the difference between identified values for the fundamental frequencies is less than 10%. The largest difference occurs for the second transverse mode, the difference is in this case about 16%. Gates and Smith, however, did not identify two vertical modes between 3.6 and 7.4 Hz, and therefore their second vertical mode shape matches well with UBC's fourth mode shape. It is interesting to note that the frequencies of the fundamental modes determined by UBC are lower than those determined by Gates and Smith (3.40 Hz vs 3.61 Hz, and 4.10 Hz vs 4.49 Hz) indicating, perhaps, some softening of the structural system through the years as a consequence of the severe ground shaking.



a) 7th Street Overpass



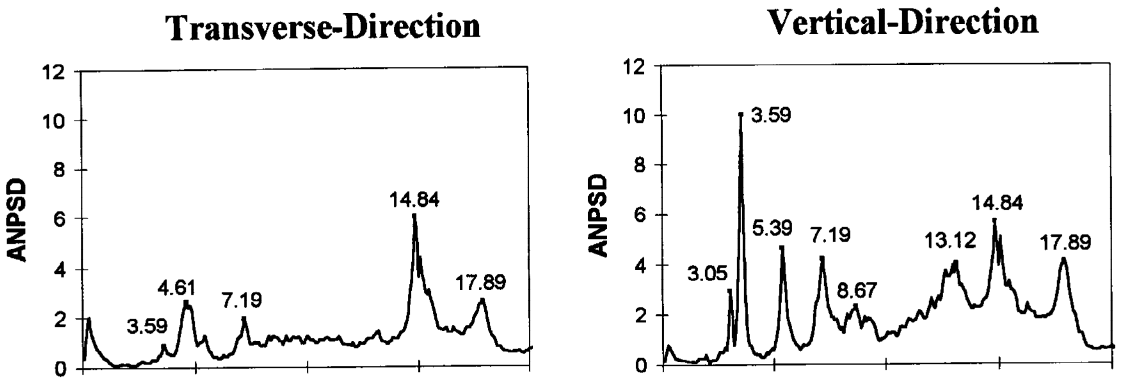
b) 11th Street Overpass

Fig. 3. Ambient vibration instrumentation of bridges in Arcata, California.

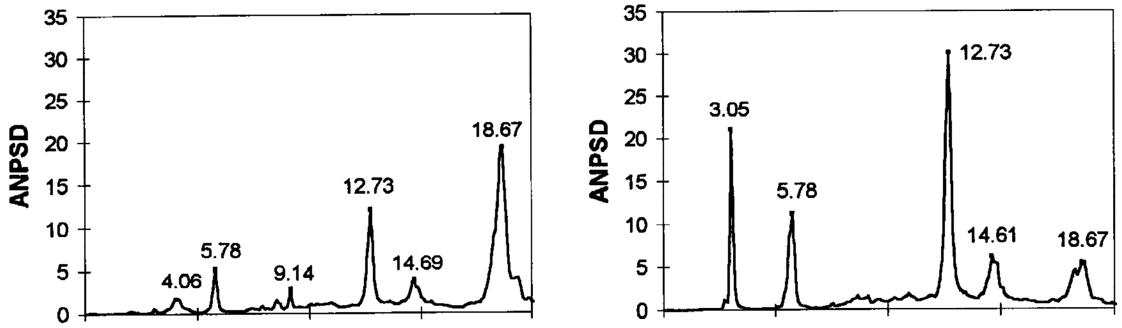
CONCLUSIONS

Extensive ambient vibration studies of three highway overpasses have been conducted, and some of the most significant findings from this study have been presented here. The frequencies of the fundamental modes of vibration in the vertical and transverse directions of the bridges have been identified in the ranges of at 3.4 to 3.6 Hz and of 4.10 to 4.6Hz, respectively. The main source of dynamic excitation for these structures during this investigation was vehicle traffic. Since the vertical modes of vibration are well excited by traffic, these modes had to be clearly identified with proper measurements. A significant number of locations on and off the bridges deck were measured in order to evaluate the potential coupling between vertical and lateral modes, and the relative amplitude of the excitations in the vertical and lateral direction had to be accounted for during the data interpretation process.

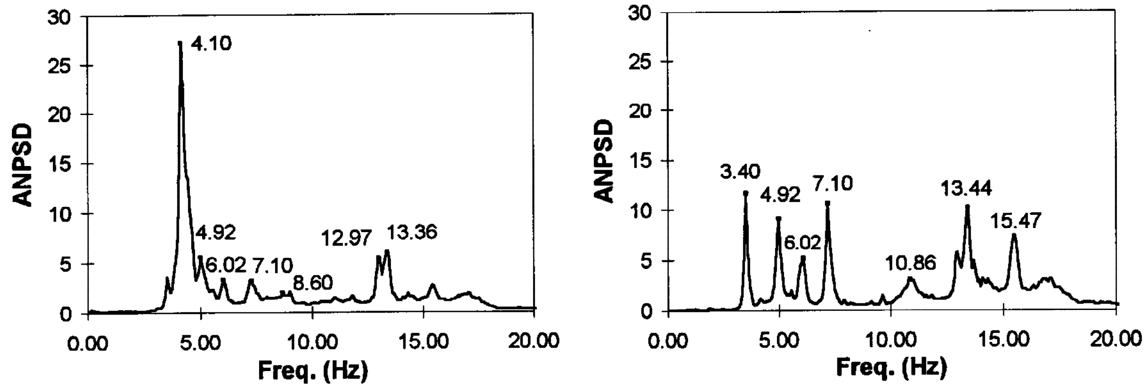
The ambient vibration results from Painter Street Overpass were compared with those obtained from a series of ambient vibration tests conducted more than thirteen years ago. The analysis showed that the fundamental frequencies determined from the latter tests are lower than those determined from the earlier test, indicating perhaps some degree of structural degradation through the years due to the significant seismic activity in the region.



a) 7th Street Overpass



b) 11th Street Overpass



c) Painter Street Overpass

Fig. 4. Averaged normalized PSDs of ambient vibration accelerations at three short-span bridges.

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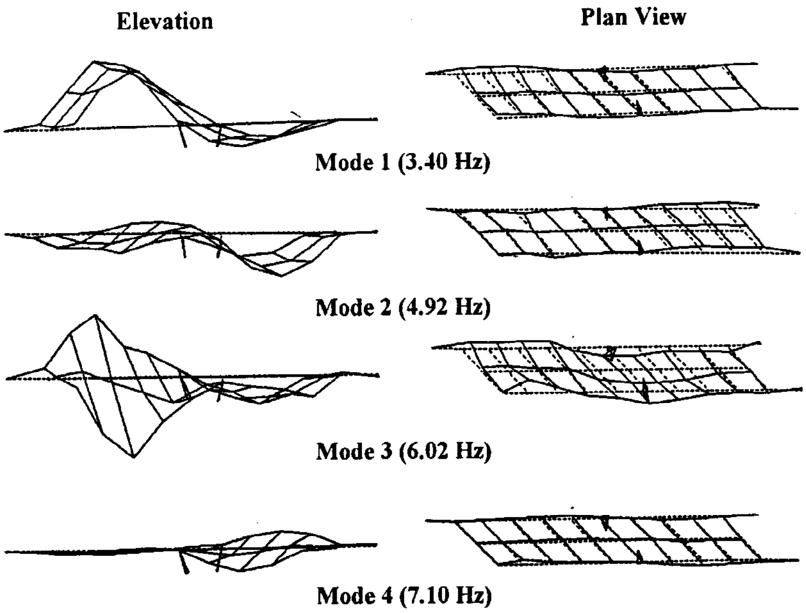
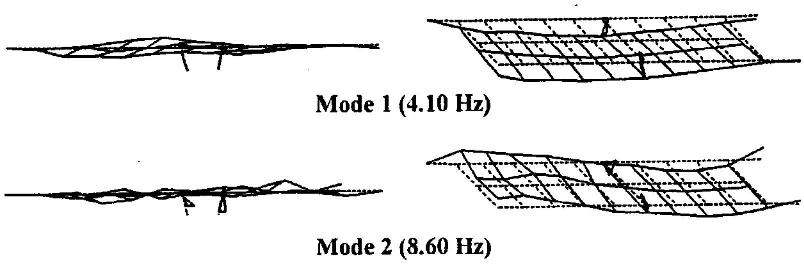


a) Vertical Mode Shapes



b) Transverse Mode Shapes

Fig. 5. Vertical and transverse mode shapes of Painter Street Overpass under 10 Hz.

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