7th Canadian Conference on Earthquake Engineering / Montreal / 1995
7ième Conférence canadienne sur le génie paraséismique / Montréal / 1995

Ambient Vibration Study of the Painter Street Overpass

C.E. Ventura[1], W.D.L. Finn[2] and A.J. Felber[3]

ABSTRACT

This paper describes the results from a series of ambient vibration studies conducted on the Painter Street Overpass in Rio Dell, California, in November of 1993. Painter Street is a two-span, skewed reinforced concrete bridge with two single piers near the middle and monolithic abutments, typical of bridge overpasses in California. The instrumentation installed on the bridge in 1977 has recorded the motions from more than ten earthquakes to date. The aim of the ambient vibration tests was to determine the dynamic characteristics of the bridge at low levels of vibration and to compare these with those determined using the recorded strong motion events. In this paper, a brief description of the recorded strong motion events is presented first, then the vibration tests and data analyses are described and the results are compared with those obtained from analyses of seven selected strong motion records. The magnitude of the events investigated ranges from M_L=4.4 to M_L=6.9, which produced accelerations of up to 0.54g at the free field site, 1.3g at the abutments, and 0.86g on the deck. The deck motions are compared for each event with the ambient vibration data. This study shows that the superstructure exhibited a nearly elastic response for all the events. The results are also compared with those obtained from a series of ambient vibration tests conducted more than twelve years ago.

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 on developing economical and effective seismic retrofit methods for bridges in order to minimize the potential damaging effects of earthquakes. Effective seismic retrofit studies require a great deal of information regarding the type of bridge being studied. In addition to that, information about the actual dynamic characteristics of the bridge may be used to calibrate computer models of the structure used as part of the seismic assessment study. The Painter Street Overpass in Rio Dell, in northern California offers a great opportunity to assess existing methods of analyses to determine the seismic behaviour of bridges. This bridge was instrumented with 20 accelerometers by the California Strong Motion Instrumentation Program (CSMIP) in collaboration with the California Department of Transportation (CALTRANS) in 1977. Because of the high level of seismic activity in the region, the motions of more than ten earthquakes have been well recorded by the instruments. An ambient vibration study of the bridge was also performed by CALTRANS (Gates and Smith, 1982) as part of a comprehensive series of vibration tests on 57 seven bridges in California. Because of the importance of the seismic data from this bridge, UBC conducted a series of ambient vibration tests on this bridge, and on another two bridges in the area, during the first week of November of 1993. The bridge was 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

[I]Asst. Professor, Dept. of Civil Engineering, University of British Columbia, Vancouver, B.C., V6T 1Z4
[II]Professor, Dept. of Civil Engineering, University of British Columbia.
[III]Former Post-Doctoral Researcher, Dept. of Civil Engineering, University of British Columbia and now President, EDI Experimental Dynamic Investigations Ltd., Vancouver, B.C.

by a NSERC Strategic Grant. This paper presents the results of these tests.

BRIDGE DESCRIPTION AND STRONG MOTION INSTRUMENTATION

The Painter Street Overpass is a two-span, prestressed concrete box-girder bridge that was constructed in 1973 to cross over the four-lane US Highway 101 (see Fig. 1). Its construction is typical of the type of California bridges used to span two or four lane highways. The bridge is 15.85 m wide and 80.79 m long (Fig. 2a). The deck is a multi-cell box girder, 1.73 m thick and is supported on monolithic abutments at each end and a two-pier bent that divides 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 as part of a collaborative effort between 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. 2.) The free-field site was originally located on the median of the highway, but in the mid 1980s was relocated to the current position along the highway embankment.

Figure 1. Painter Street Overpass

STRONG MOTION DATA

The 10 most significant earthquakes recorded to date are summarized in Table 1 and the relative epicentral location and magnitude for each earthquake with respect to the bridge is shown in Fig. 3. The size of the circles in the figure is proportional to the magnitude of the event being represented. Most of the earthquakes occurred southwest of the bridge, in the vicinity of the San Andreas fault. Table 1 also includes the peak horizontal accelerations recorded at the free-field and on the structure during each event. Recorded peak ground horizontal accelerations from these events range from .08g to 0.54g, while horizontal structural accelerations range from .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. All the records, except those from Petrolia event of 1991 (91ML6.0), have been digitized and processed by CSMIP. The strong motion records from the Painter Street Overpass have been studied in detail by several

Table 1. Significant Earthquakes Recorded at Painter Street

Event Code	Earthquake (Date)	Mag. (M_L)	Dist. (km)	Accel. (g) FF	Accel. (g) Struct.
80ML6.9	Trinidad Offshore (8 Nov 1980)	6.9	88	0.15	.17
82ML4.4	Rio Dell (16 Dec 1982)	4.4	15	--	.42
83ML5.5	Eureka (24 Aug 1983)	5.5	61	--	.22
86_1ML5.1	Cape Mendocino-1 (21 Nov 1986)	5.1	32	.43	.40
86_2ML5.1	Cape Mendocino-2 (21 Nov 1986)	5.1	26	.14	.35
87ML5.5	Cape Mendocino (31 Jul 1987)	5.5	28	.14	.34
91ML6.0	Petrolia (17 Sep 1991)	6.0	37	.08	.10
92ML6.9	Cape Mendocino - Petrolia (25 Apr 1992)	6.9	24	.54	1.09
92ML6.2	Cape Mendocino - Petrolia (AS1) (26 Apr 1992)	6.2	42	.52	.76
92ML6.5	Cape Mendocino - Petrolia (AS2) (26 Apr 1992)	6.5	41	.26	.31

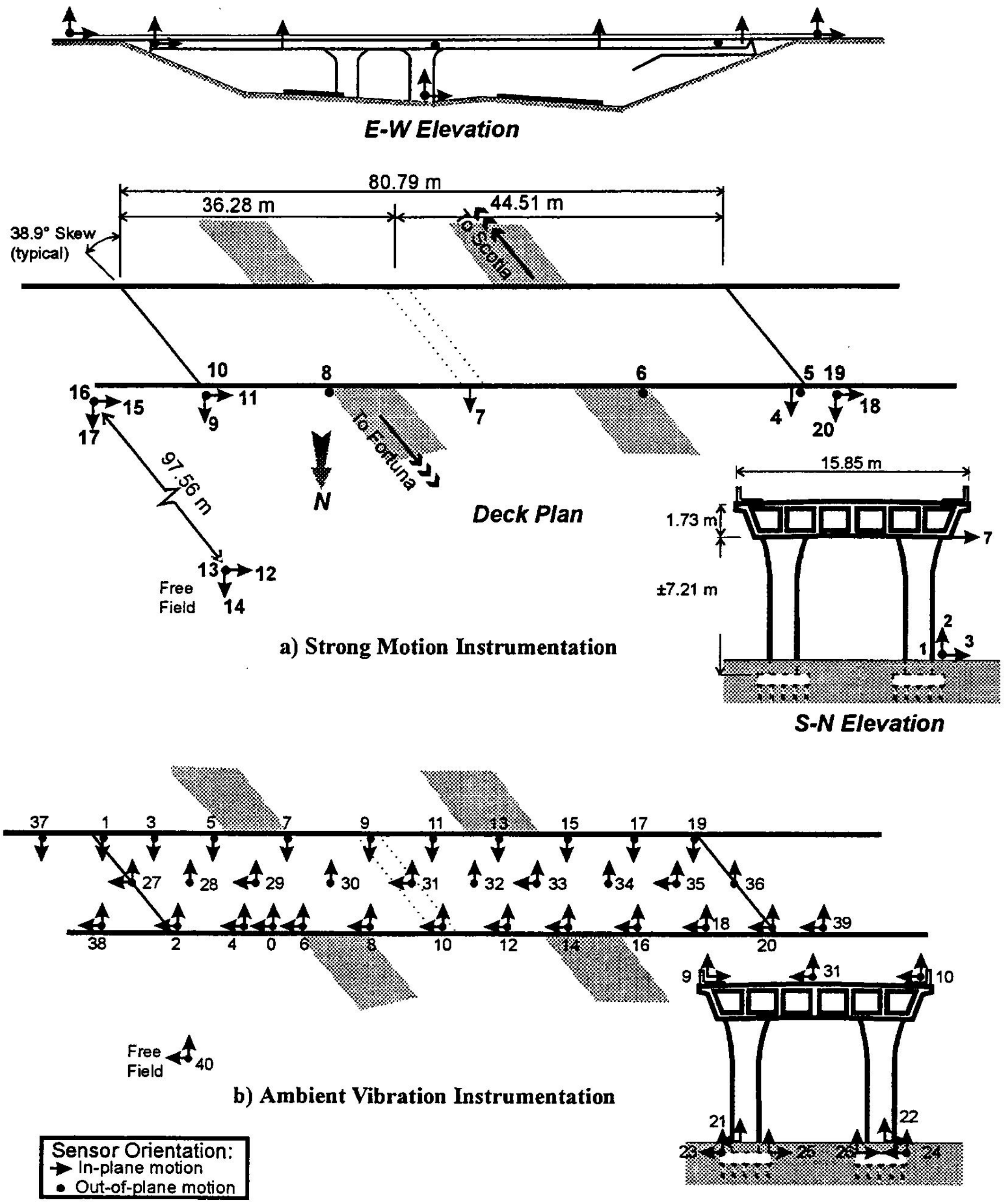

Figure 2. General Dimensions and Instrumentation of Painter Street Overpass

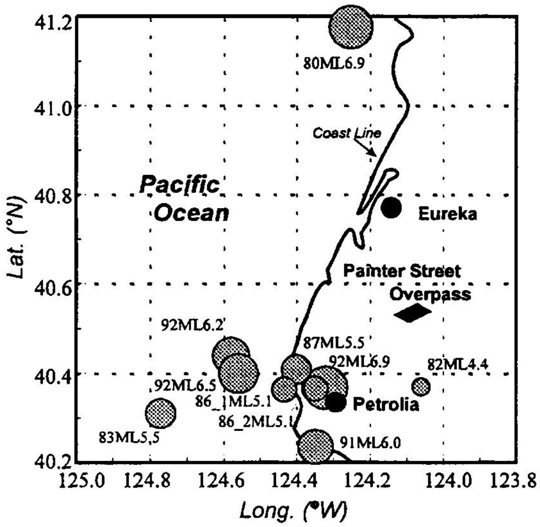

Figure 3. Location of Significant Earthquakes Recorded at Painter Street Overpass

investigators. Maroney, Romstad and Chajes (1990) studied the response of the bridge to six of the events listed in Table 1. This study attempted to correlate the inferred natural periods from the recorded motions with those obtained by a finite element model of the bridge. The results were found to be very sensitive to the choice of the equivalent spring stiffness of the abutments. Goel and Chopra (1994) investigated the variation of abutment stiffness during strong shaking and the effect of torsional motions of the deck. This study was based on the records from the Cape Mendocino events of 1986 and 1992 (86_2ML5.1 and 92ML6.9). Makris, et al (1994) used the 1992 Cape Mendocino earthquake records (92ML6.9) to calibrate a simple procedure to evaluate soil-foundation-superstructure interaction of pile-supported bridges. This study concluded that the predicted superstructure response by computer analysis is greatly affected by the foundation modelling. McCallen and Romstad (1994) used the same set of records to investigate two different approaches to modelling the response of simple bridge structures, a stick model and a detailed, large scale three-dimensional finite element model, including soil nonlinearities. 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. Part of this effort includes the understanding of the bridge behaviour at very low levels of excitation and comparing this behaviour with that for strong motion.

AMBIENT VIBRATION STUDIES

The purpose of this study was to determine key dynamic characteristics of bridge during low amplitude vibrations produced by wind, traffic and micro-tremors. It was aimed at providing an improved insight into how the different components of bridges interact dynamically to aid in the selection of seismic retrofit alternatives. The series of tests at the bridge included vibration measurements of the superstructure, abutments, backfill, pile caps and the free field.

UBC's testing methodology and equipment were specifically developed to conduct on site data analysis in order to ensure good data quality and to obtain preliminary estimates of the experimental mode shapes and frequencies of bridges (Felber, 1993). The software part of the system was also used for more refined detailed analyses back at the office. This approach has been successfully used to test two important bridges in Vancouver that are being seismically evaluated by consulting engineers. Details of these tests are given in Ventura, et al (1994) and Felber and Ventura (1995).

A total of 41 measurement locations on the structure were selected considering the test objectives and bridge accessibility. The selected measurement locations and orientations of the accelerometers are shown in Fig. 2b. An eight-channel, accelerometer-based, data acquisition system was used to collect the data from a number of setups. Three of the accelerometers were installed permanently at location 0 in Fig. 2b, while the other five were continuously moved from location to location until all the desired sites were measured. Each setup included installing the sensors, recording their signals for about 15 minutes and relocating them to the next locations. The analog signals were amplified and filtered before being converted to binary information, which was then stored on a Data Acquisition computer. After a setup was completed, the data was transferred to a Data Analysis computer and analyzed for quality control and for a preliminary determination of the natural frequencies and mode shapes of the bridge. This approach permitted a fast and reliable on site data analysis. Details of the components of the test equipment are described by Felber (1993).

The recorded accelerations were analyzed using computer programs U2, P2 and V2 (EDI 1994). Program P2 was used to generate power spectral density functions (PSD), which were normalized and averaged to aid in the identification of natural frequencies. Program U2 was used to compute the relative transfer functions between the signals from the reference location (location 0 in Fig. 2b) and locations 1 through 40. 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. These programs were used for preliminary data analysis on site and for further detailed data analysis at the office.

The data analysis was limited to the evaluation of vertical and transverse modes of vibration in the frequency range 0 to 10 Hz. The average of the normalized PSDs, called ANPSD, was computed for all the vertical signals recorded on the deck, and the result is shown in Fig. 4. The ANPSD for all the transverse signals is also shown in the figure. For the frequency range shown, four significant peaks clearly identify the first four vertical modes of vibration of the bridge. For the transverse direction, the frequency of the fundamental mode is very distinct while the frequency for the second transverse mode is more difficult to detect. The elevation and plan views of each of the mode shapes corresponding to these frequencies are shown in Fig. 5. The mode at 3.40 Hz is a very well defined vertical mode with 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. In summary, the fundamental vertical and transverse modes are well defined and have unique directions, the higher modes are have significant components in three directions and it is more difficult to identify which one is dominant direction in each case.

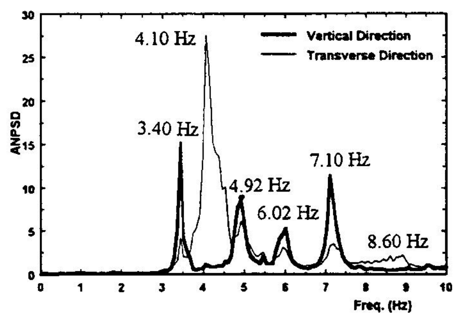

Figure 4. Averaged Normalized PSDs of Recorded Ambient Vibration Accelerations

The ambient vibration study 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 twol modes between 3.6 and 7.28 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.

COMPARATIVE ANALYSES

A frequency domain analysis of strong motion records and ambient vibration signals from selected locations of the bridge was conducted and the results are reported here. The discussion is limited to characteristics of the PSDs for the ambient vibration data and strong motion records from some of the earthquakes listed in Table 1. The events considered here are 80ML6.9, 82ML4.4, 83ML5.5, 86_1ML5.1, 86_2ML5.1, 87ML5.5, and 92ML6.9, in addition to the ambient vibration records. In order to identify and compare the frequency ranges in which the response of the bridge was prominent, the PSD of each record considered was normalized with respect to its peak value. The normalized PSDs for the vertical component of accelerations recorded near the centre of the east-side span of the bridge (channel 6 for strong motion

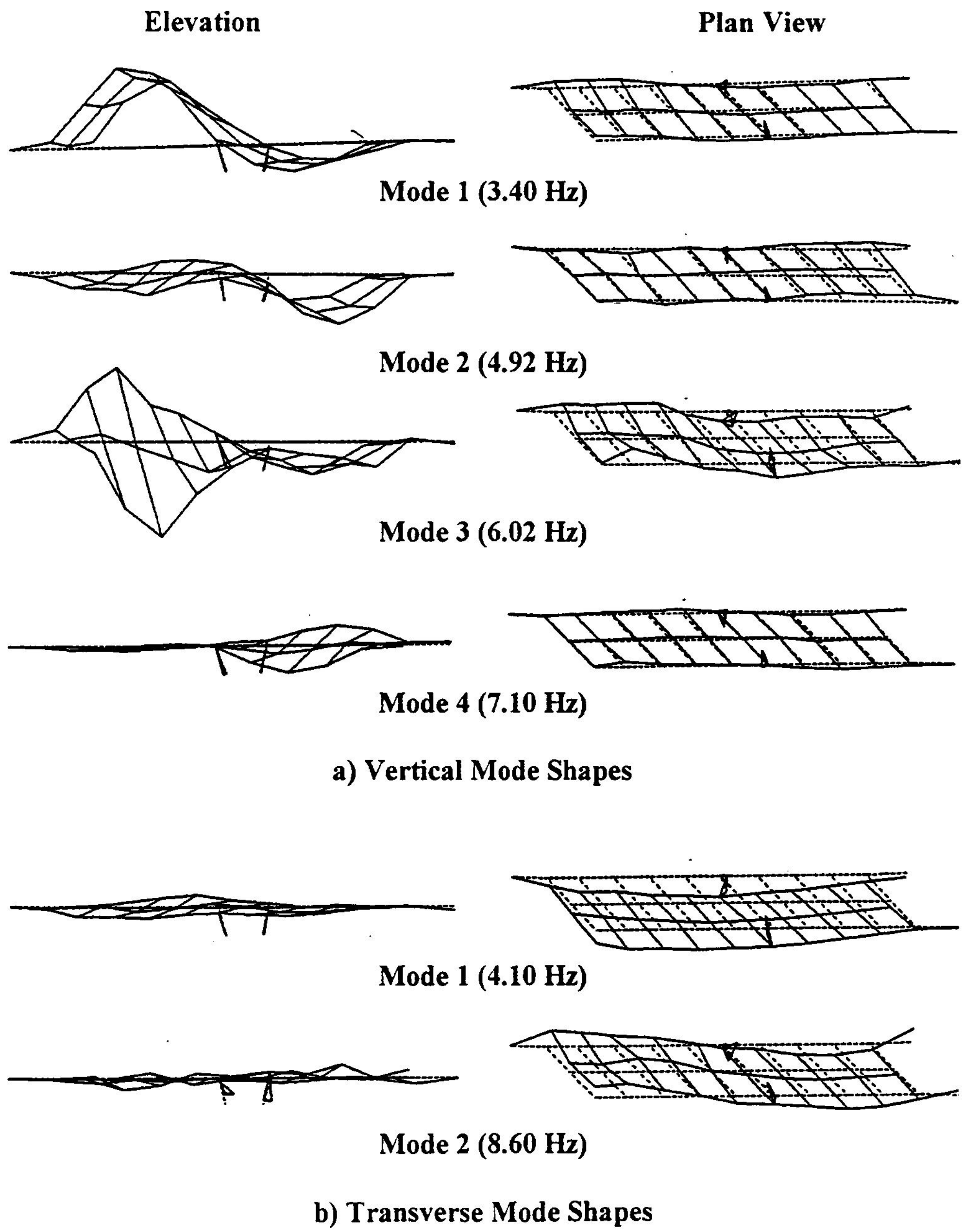

Figure 5. Vertical and Transverse Mode Shapes of Painter Street Overpass Under 10 Hz Determined from Ambient Vibration Measurements

instrumentation and vertical component of location 16 for the ambient vibration instrumentation shown in Fig. 2) are plotted in Fig. 6. Peaks in the vicinity of the first three vertical modes identified in the ambient vibration study (3.40, 4.92 and 6.02 Hz) are also apparent in most of the strong motion records. As expected, the shift of the fundamental frequency toward lower values during strong shaking is noticeable, especially for the larger events in which the shift is largest (up to 10% of variation). A shift of the peaks toward lower frequency values for the higher modes can also be noticed. The first mode controls the response in most of the events, except for the largest event (92ML6.9) in which the second and third modes appear to have a significant contribution to the response.

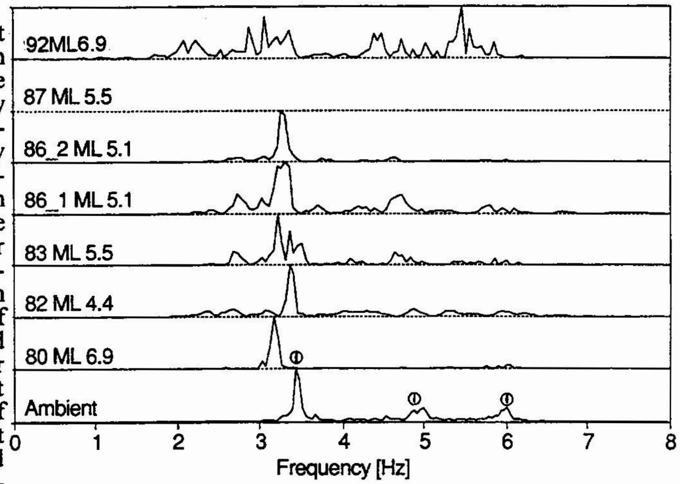

Figure 6. Normalized PSDs of Vertical Accelerations Recorded Near the Centre of the East Span

The normalized PSDs for the horizontal component of accelerations recorded on the deck, just above the top of the north-side pier (channel 7 for strong motion instrumentation and transverse component of location 10 for the ambient vibration instrumentation shown in Fig. 2) are plotted in Fig. 7. Peaks in the vicinity of the first transverse mode identified in the ambient vibration study (4.10 Hz) are also apparent in all, but the largest of the strong motion records. Again, the shift of the fundamental frequency toward lower values during strong shaking is noticeable. The most significant peak for event 92ML6.9 occurs at about 2.2 Hz, which is almost 50% of the frequency of the fundamental mode. The significant peaks below 4.10 Hz in all of the PSDs for strong motion records indicate that the bridge motion is mostly likely a rigid body response to the ground motion, rather than structural deterioration. The significant energy of most the ground motions was concentrated in a frequency region below 4 Hz, which did not excite the bridge significantly.

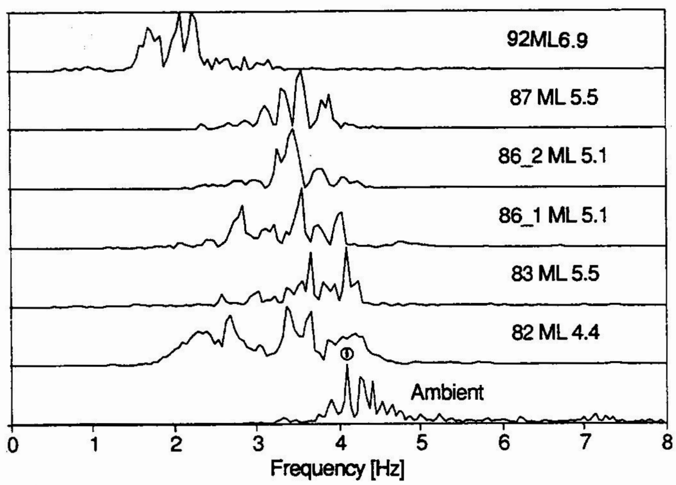

Figure 7. Normalized PSDs of Transverse Accelerations Recorded Near the Centre of the Bridge

CONCLUSIONS

An extensive ambient vibration study of the Painter Street Overpass has 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 bridge have been identified at 3.40 Hz and 4.10 Hz, respectively. The main source of dynamic excitation for the structure 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 bridge 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 salient features of recorded strong motions at the Painter Street Overpass bridge have been presented and compared with the recorded ambient vibration motions. The comparative analyses showed that the events investigated excited the vertical modes of vibration of the bridge more than its transverse modes of vibration. The results of indicate that the superstructure exhibited a nearly elastic response for all the events and that the fundamental frequencies tended to lower values as the level of shaking increased.

The ambient vibration results ware also compared with those obtained from a series of ambient vibration tests conducted more than twelve 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.

ACKNOWLEDGEMENTS

This study was funded by the second author under a tri-university NSERC Strategic Grant. The authors greatly appreciate the support of CALTRANS for providing access to the bridges tested in the Cape Mendocino area. The authors are also grateful to Mr. Jim Gates and Mr. Pat Hipley, Office of Structures, CALTRANS, for their help in obtaining the necessary permits to conduct the tests. Their interest and enthusiasm in facilitating this work is also acknowledged. Special thanks are also extended to UBC graduate students Vincent Latendresse and Norman Schuster who collaborated during the preparation and performance of the field tests

REFERENCES

EDI Ltd. 1994. *U2, V2 & P2 Manual.* Experimental Dynamics Investigations, EDI. Ltd., Vancouver, B.C., Canada.

Felber, A. J. 1993. *Development of a Hybrid Bridge Evaluation System.* Ph.D. Dissertation, Department of Civil Eng., University of British Columbia, Vancouver, B.C., Canada.

Felber, A.J. and Ventura, C. E. 1995. *Port Mann - Modal Testing and Model Correlation; Part I: Experimental Testing and Modal Analysis.* Procs. 13th International Modal Analysis Conference, Nashville, Tennessee, February.

Gates, J.H. and Smith, M.J. 1982. *Verification of Dynamic Modeling Methods by Prototype Excitation.* FHWA/CA/SD-82/07, Calif. Dept. of Transportation, Office of Structures Design, Sacramento, CA, November, pp. 17-27.

Goel, R. and Chopra, A.K. 1994. *Seismic Response Study of the US 101/Painter Street Overpass Using Strong Motion Records.* Procs. of SMIP94 Seminar on Seismological and Engineering Implications of Recent Strong-Motion Data, M. Huang, editor, May, pp. 75-88.

McCallen, D.B. and Romstad, K.M. 1994. *Dynamic Analyses of a Skewed Short-Span, Box-Girder Overpass.* Earthquake Spectra, Vol. 10, No. 4, pp. 729-755.

Makris, N., Badoni, D., Delis, E., and Gazetas, G. 1994. *Prediction of observed Bridge Response with Soil-Pile-Structure Interaction.* ASCE J. of Structural Engineering, Vol. 120, No. 10, October, pp. 2992-3011.

Maroney, B., Romstad, K.M., and Chajes, M.J. 1990. *Interpretation of Rio Dell Freeway Response During Six Recorded Earthquake Events.* Procs. of the 4th U.S. Natl. Conf. on Earthquake Engineering, Palm Springs, CA., Vol. 1, pp. 1007-1016.

Ventura, C. E., Felber, A. J., Prion, H. G. L. 1994. *Seismic Evaluation of A Medium Span Bridge by Modal Testing.* Procs. 4th. Intl. Conf. on Short and Medium Span Bridges, Halifax, N.S., Canada, August 8-11, pp. 545-556.