# FIELD TESTING AND ANALYSIS OF TWO VIADUCTS IN WALNUT CREEK, CALIFORNIA

by

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## ABSTRACT

Field testing of two bridges has recently been completed in Walnut Creek, California. The opportunity for the field testing program arose out of demolition and reconstruction activities of the I-680/24 interchange reconstruction project. The two structures tested were a new seismically-isolated bridge, part of the recently-opened southbound I-680 temporary viaduct, and an existing single-column viaduct, also on southbound I-680, that will be replaced with a new, larger connector. The primary objectives of the investigation were to collect field data for assessing the typical design assumptions and analytical methods employed for seismically-isolated bridges and the reliability of analytical models and techniques for large, curved single-column viaduct structures.

This paper provides a summary of the testing programs that were conducted on the two bridges and the subsequent data interpretation and numerical analyses that have been and will be performed.

## INTRODUCTION

The analysis and design of bridge structures requires the adoption of numerous assumptions. In many cases, these have been validated on the basis of satisfactory performance of structures under service conditions, laboratory testing of components and assemblages, refined analytical models, and observed behavior during earthquakes. In the case of new types of structures, only limited laboratory testing can generally be done prior to field application. Similarly, component and assemblage tests and analyses may not provide sufficient information to predict with certainty the overall response of a structure. Thus, field testing of full-scale structures has been used successfully by Caltrans and others to assess complications arising from the interaction of components, foundation and abutment conditions, and uncertainties in mechanical and dynamic characteristics. Reconciliation of measured response values with analytical predictions obtained using standard techniques provides verification of current design methods. Where correlation of predicted and measured responses is inadequate, the measured data provides the motivation and basis for developing improved methods.

An example of successful prior Caltrans-sponsored field investigations includes testing of a segment of the I-880 Cypress Viaduct in Oakland, California, following the Loma Prieta earthquake in 1989 [Bollo et al., 1990]. These tests included ambient and forced vibration tests of the as-built structure and destructive lateral load tests of the as-built and retrofitted structure. The tests indicated that simple elastic models were able to predict the mode of failure observed, and provided important quantitative information on the efficacy of various retrofits. They also indicated the importance of foundation modeling in computing the periods, mode shapes, and damping of the structure.

Many new concepts, such as seismic isolation, are being suggested for the design of bridges in California, and numerous modeling uncertainties remain in the analysis of bridges in general. Uncertainties in analysis and performance may result in hesitation on the part of designers to utilize these new concepts. Real world field tests and related analyses can be effectively utilized to reduce these uncertainties, address issues related to the integrity of new types of structures, and improve design and analysis methods.

## OBJECTIVES

A number of field tests and related analyses currently underway with Caltrans sponsorship take advantage of some unique opportunities made possible by the construction, retrofit, and demolition activities at the I-680/24 interchange in Walnut Creek, California. The overall goal of this work is to evaluate and, where necessary, suggest improvements to design methods and analysis assumptions. In addition to field testing and analyses of the new temporary seismically-isolated viaduct, tests were performed and analyses are currently underway of an elevated, curved single-column viaduct at the interchange, which was constructed in 1960 and has recently been demolished as part of the reconstruction program.

## 1. NEW SEISMICALLY-ISOLATED FOUR-SPAN BRIDGE

### Description

The new temporary viaduct in Walnut Creek, California, carries southbound I-680 traffic through the I-680/24 interchange. It is a temporary diversion for I-680 traffic while larger, permanent interchange connectors are constructed under the temporary viaduct. (The connector that the temporary viaduct replaces is the subject of Task 2 of the research project, described later in this paper.) The southern end of the temporary viaduct consists of a seismically-isolated, four-span, 700-ft. long, composite steel girder concrete deck structure. This is the first new bridge in California to be seismically isolated. The bridge is straight over most of its length, with an up-grade to the north of about eight percent and an 11.6 degree curve to the east at the north end.

Assumptions and criteria used in the design of the viaduct, methods employed to specify required isolation bearing characteristics for the contract bidding process, and the typical details utilized in construction have been presented by Thorkildsen (1992). Of significance is the fact that the viaduct was designed as if it were a permanent structure and it complies with all Caltrans design requirements in effect at the time of the design.

A peak ground acceleration of 0.60 g was assumed in the design. The design spectrum is based on 10 to 80 ft. of soil underlying the viaduct. The periods of the un-isolated portions of the viaduct range from 0.5 to 0.8 second. The effective period considered in the design of the isolation system was 1.8 seconds. The isolation system consists of 15 lead-rubber bearings, ranging in size from 23 to 27 inches square and 10 inches high. The design displacement for the isolation system was 9.0 inches. Prototype bearings were tested to a displacement of 1.5 times the design displacement (13.5 inches).

The temporary viaduct will be demolished in about 1998. The steel deck girders used in the seismically-isolated portion of the viaduct will be moved a short distance and used as part of a new off-ramp connector. In its new location, the connector will again be seismically isolated.

Non-isolated portions of the viaduct consist of post-tensioned concrete box girder frames supported monolithically on reinforced-concrete columns. Drop-in, simply-supported steel girders were utilized between the reinforced-concrete frames in order to facilitate demolition of the sections of the viaduct that pass over lower- and surface-level roadways in the interchange.

## RESEARCH PROGRAM

The availability of the isolated bridge represented a unique opportunity to obtain field test data on the mechanical and dynamic properties of the bridge and to assess the reliability of modeling and analysis assumptions used in its design. The dynamic properties were experimentally measured at different stages of construction, and the data is being used, along with information on the mechanical properties of the individual isolators and of the soil at the site, in dynamic response analyses to validate modeling and analysis assumptions. Three different phases of vibration testing were undertaken. These tests have, for the first time, permitted careful determination of a number of dynamic properties that have not previously been investigated.

### Phase 1 - Column Tests

Pull over and quick-release tests were performed on all four of the individual bents supporting the seismically-isolated portion of the viaduct prior to placement of the deck structure. The results of these tests were used to determine the stiffness and damping characteristics of the CIDH column/pile assemblages. This information is now being used to develop a reliable analytical dynamic model of the entire structure, and in assessing the contribution of various structural components to the overall system damping.

The tests consisted of lateral loading of each bent. A hydraulic jack was used to load 1 1/8”-dia. wire cables connecting two adjacent bents (Fig.1). Several levels of loading, up to 50 kips - approximately 20% of the design load - were applied in this manner. Quick release was achieved by detonation of an explosive bolt installed between segments of the cabling. The ensuing free vibration response was measured and used to determine frequencies and damping for each bent. Instrumentation consisted of two accelerometers located at the top of each bent cap and one at ground level. Seismometers were used for ambient vibration and ground-level measurements. A portable data acquisition system with a spectrum analyzer were used to capture the response data.

Results obtained were clean, with very little transient interference. Typical results are shown in Fig. 2. Peak accelerations up to about 0.25g were induced at the tops of the column bents, while accelerations at ground level were about 25 to 40 percent of the column-top accelerations, typically about 0.04g. In Fig. 2, both the measured acceleration and the response of an analytical viscously-damped SDOF oscillator (determined by a nonlinear curve fit) are shown. For the three taller (about 7 m) bents, measured periods ranged between approximately 0.15 and 0.2 second, and the damping ratios ranged from 5 to 6 percent of critical. For the shortest bent (only about 2 m tall), the period was about 0.11 second, and the damping was about 15 percent of critical.

### Phase 2 - Forced-Vibration Tests of the Entire Four-Span Bridge

The second phase of testing involved the forced vibration of the completed bridge using two rotating mass vibration machines. Two steel platforms were fabricated and attached to the bridge deck, providing level surfaces for the installation of the shakers. The shakers were located about 20 ft. from bent caps 2 and 4 - about 340 ft. apart - at approximately the quarter points along the length of the deck. By altering the rotational speed and the weights of the machine, the vibration can be precisely controlled over a broad range of frequencies. The two machines were synchronized to apply loading in the transverse, longitudinal, and torsional (in plan) directions during different tests.

Instrumentation consisted of 44 accelerometers and 10 wire pot displacement transducers. A set of two accelerometers, one transverse and one longitudinal, were placed on four different levels at each of the five bents of the bridge. These levels were the deck level, just above the isolators, the top of the bent caps (just below the isolators), and ground level. In addition, an array of six accelerometers was placed on the deck half-way between bents 3 and 4. These accelerometers were oriented in the longitudinal, transverse, and vertical directions. A set of two wire pots at each bent cap measured the relative displacement across the isolator in the longitudinal and transverse directions.

The testing program consisted of locking the shakers at the desired frequency and obtaining steady-state response data at that frequency. This was repeated over a wide range of frequencies. Closer to resonance, finer frequency intervals were used.

Fig. 3 shows typical results from a longitudinal accelerometer for a 2.60 Hz test. As a consequence of the stiffness characteristics of the isolation system, it was anticipated that several modes would be coupled, and some frequencies closely spaced. Observed “beating” response (a typical example is shown in Fig. 4) confirmed this coupling. The analysis of the measured data is being performed using a sine-pair, least-squares error method to identify frequencies and amplitudes. This analysis is in progress.

**Phase 3 - Snap-Back Free-Vibration Tests of the Entire Four-Span Bridge**

The third phase of testing involved loading the completed bridge deck in the longitudinal direction using hydraulic jacks, and rapidly releasing the imposed displacement using explosive bolts and specially-designed collapsible quick-release devices. This permitted free vibrations of the bridge to be measured.

It was believed to be important to obtain good free vibration response measurements from the bridge deck during the crucial first large-amplitude cycle of nonlinear response. Careful consideration was given to the method that was finally adopted. Initially, specially-modified hydraulic jacks capable of retracting quickly (as were used in the testing of the Yamaage Bridge [Kakinuma et al., 1994] in Karasuyama, Japan) were considered. The success of the explosive bolts in the phase 1 tests and concerns regarding the ability of the hydraulic jacks to retract faster than the initial response of the bridge deck led to the selection of a special collapsible quick-release device as the load-release method.

The device used was of a type first developed by ISMES in Italy for the quick-release testing of a full-scale seismically-isolated building [Bettinali et al., 1991]. Four devices were borrowed from ISMES for the bridge tests. The device is shown schematically in Fig. 5. The device carries load in compression, and equilibrium is maintained by the tension bolt orthogonal to the load-carrying axis. An explosive charge is loaded into each bolt in each of the four devices, and these are detonated simultaneously from a single firing unit. Specially designed bolts were manufactured and tested prior to their use in the bridge test. A licenced blaster oversaw site safety and carried out the actual firing of the quick-release bolts. The firing system is configured in such a way that if one bolt should be faulty and fail to detonate, none of the bolts fire.

The capacity of the abutment at the south end of the isolated bridge was inadequate to carry the loads from the hydraulic jacks. Instead, the bridge was loaded by pushing off the adjacent three-span reinforced-concrete frame at its north end. Loading was accomplished with four 400-kip capacity hydraulic jacks located in the seismic gap joint between the isolated deck and the concrete frame. To prevent twisting of the bridge on the isolation bearings, the resultant of the applied loads coincided with the center of rigidity of all of the bearings. This corresponded to a loading with an 8 degree offset from the tangent to the deck axis at bent 5. Once the desired offset displacement was reached, the collapsible devices were installed to hold the bridge in position and the hydraulic jacks were retracted and removed (Fig. 6). The test was initiated by setting off the detonators from the firing unit.

Free vibration decay was measured by a total of 57 channels of instrumentation. In addition to the instrumentation described for the phase 2 tests, displacement transducers were placed at a number of locations. These measured absolute and relative displacement of both viaduct sections in several directions. An electronic pressure gauge was used to measure the total magnitude of the jacking force applied to the isolated bridge deck.

Three quick-release tests were conducted. In the first test, the total applied load was about 400 kips, resulting in a bridge displacement of about 0.3 inch. This test corresponded approximately to the “yield” displacement of the lead-rubber isolation bearings. The release displacement for the second and third tests was approximately 5.5 inches, which was approximately two-thirds of the bearing design displacement. A force of almost 1200 kips was initially required to achieve this displacement. The force later reduced as the bearings relaxed somewhat prior to the quick release. (This relaxation occurred slowly. In the second test, when, due to technical difficulties, the release was delayed several hours after the load had been applied, the load holding the bridge deck in the displaced position reduced to about 800 kips). The force-displacement plot for the loading phase of the second quick-release test is shown in Fig. 7, and Fig. 8 shows a typical displacement time-history of the bridge deck before and after load release. From the quick-release data, the damping of the entire isolated bridge was calculated to be about 13 percent, and the frequency of the free-vibration response was approximately 1.9 Hz.

Further analysis and interpretation of the collected data is continuing. Dynamic modeling and analyses of the isolated deck using the finite element program, SADSAP, is also in progress. The analytical model is aimed at accurately representing the complete structural system, accounting for foundation, bent, isolation bearing, and superstructure dynamic properties. Experimental and analytical results will be compared. Improvements in modeling and analysis assumptions will be recommended, if necessary, to obtain better agreement between predicted and measured responses.

Closure strips and expansion joints were not in place during the quick-release tests, allowing unrestricted free vibration of the bridge deck. After placement of the closure strips at the ends of the bridge deck (at the completion of construction), ambient tests were conducted to obtain the dynamic properties of the completed bridge. Instrumentation for the ambient tests consisted of four seismometers, two each placed at bents 2 and 4 in the principal directions of the deck. Typical results obtained from the spectrum analyzer are shown in Fig. 9.

## 2. ELEVATED SINGLE-COLUMN VIADUCT SCHEDULED FOR DEMOLITION

### Description

A 1190-ft. long reinforced concrete structure (called the Mt. Diablo Separation) with in-plan curvature, is being replaced as part of the I-680/24 interchange reconstruction. Although constructed in 1960, the Separation is typical of pre-1971 bridge construction. The viaduct has a box-girder superstructure and is supported by ten single-column bents in four frames (Fig. 10). The tallest column is 51 ft. and the foundations typically consist of 20 piles per column. The abutments are of a seat-type with nominally six-inch wide seats. The abutment bearings were replaced in 1984 and two seven-cable restrainer units were installed at each expansion joint at that time. The deck centerline has a radius of curvature of 1200 ft. and an included angle from abutment 1 to abutment 12 of 57 degrees. (At the time of writing, testing had recently been completed, and demolition was almost finished).

## RESEARCH PROGRAM

Since the seismic evaluation and retrofit design of bridges depend on analysis of seismic demand, there is a need to calibrate the structural models used for earthquake analysis. The objective of the tests is to conduct forced and ambient vibration tests on the bridge, determine vibration properties, and evaluate the effectiveness of typical modeling assumptions used in bridge design. Although the deformations in the tests were much less than those expected during an earthquake, the data will help determine whether the overall modeling of mass, stiffness, damping, articulations, and soil-structure interaction are adequate. If current modeling techniques are found not to correlate well with the field data, then suggestions for improvement will be made.

The availability of the Mt. Diablo Separation presented an opportunity to obtain field test data on the dynamic properties of a large, curved, single-column box-girder viaduct. The dynamic properties were measured by forced-vibration testing of the entire viaduct, and ambient vibration measurements were taken of parts of the structure prior to, and at various stages during the demolition.

### Preliminary Modeling and Dynamic Analysis

A preliminary numerical model was developed and dynamic analyses performed using the finite element program, SADSAP. The purpose of these preliminary analyses was to estimate the vibration periods and mode-shapes prior to forced-vibration testing. The results were also used to help in determining the optimal location of the two rotating-mass vibration machines for the tests.

### Field Testing - Viaduct in Original Condition

Forced-vibration testing of the structure took place immediately prior to demolition, after traffic was redirected onto the new temporary viaduct. Ambient vibration measurements taken before the forced-vibration tests were performed were used to establish approximately the frequencies of interest. Two rotating mass vibration machines (the same as those used for the isolated bridge forced-vibration tests) were used to excite the structure with in-phase and out-of-phase transverse (radial) and longitudinal harmonic loading over a range of frequencies. The shakers were installed on concrete leveling pads at bent 5 and bent 8, about 340 ft. apart. A total of 56 channels of data were recorded. Instrumentation consisted of accelerometers placed longitudinally and radially on the deck at each bent, longitudinal and radial pairs of accelerometers located at the ground level of bents 5, 6, and 8, pairs of vertical accelerometers on each side of the deck along its length, and 10 DCDT displacement transducers to measure the east- and west-side longitudinal displacements at the abutment joints and the frame hinges, and a number of seismometers to record low-level vibrations.

### Field Testing - Partial Structure During Demolition

Ambient vibration tests were conducted on parts of the bridge during the demolition sequence. As the demolition progressed over a period of two weeks, individual frames, individual spans, and a single column were tested. Seismometers and a spectrum analyzer were used for these tests. This data will provide additional information on the smaller portions of the structure tested, and will help in identifying effects such as stiffness and effective mass.

### Data Interpretation and Analysis

The field data will be processed to identify vibration periods, mode-shapes, and damping for the entire viaduct. Additional information will be obtained from the ambient vibration data for the portions of the structure tested. The dynamic characteristics identified from the measured data will be compared with the preliminary analysis model, and the model will be refined as necessary.

## ON-GOING ACTIVITIES

Analysis of the forced vibration and quick-release test data obtained from the isolated bridge tests is in progress. Numerical analyses that incorporate the observed mechanical and dynamic properties of the bridge are also being conducted.

At the time of writing, testing of the Mt. Diablo Separation has only just been completed, and data analysis and interpretation is in progress.

## SUMMARY

The field testing program has provided data on the dynamic characteristics of the first new seismically-isolated bridge in California. Explosive release techniques were used in two phases of the isolated bridge tests, providing good results. The dynamic characteristics of an existing single-column curved viaduct have also been investigated by testing. This data will be used to evaluate in detail the dynamic characteristics of this type of structure.

## ACKNOWLEDGMENTS

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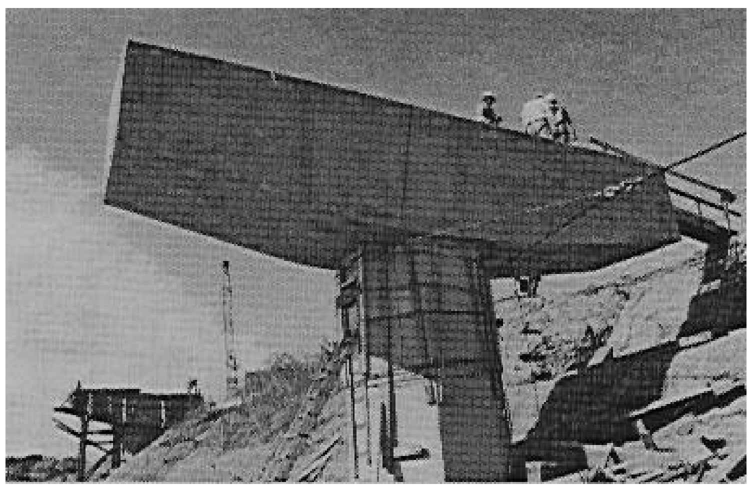

Fig. 1: View of bent 3 with loading cabling at right

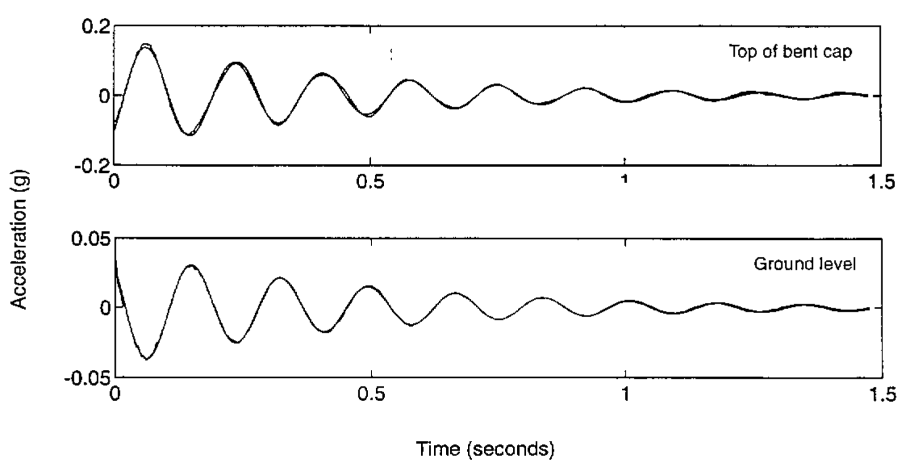


Fig. 2: Bent 4 free vibrations (exptal and analytical responses shown)

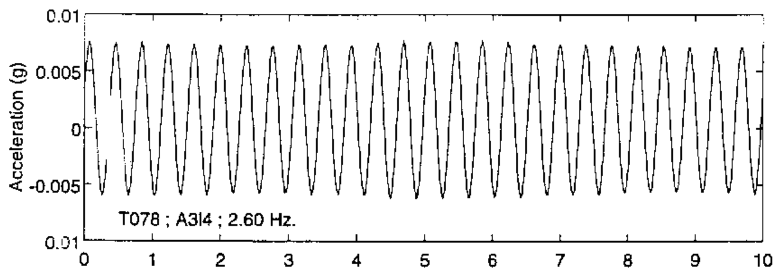

Fig. 3: Typical longitudinal forced-vibration response of isolated bridge

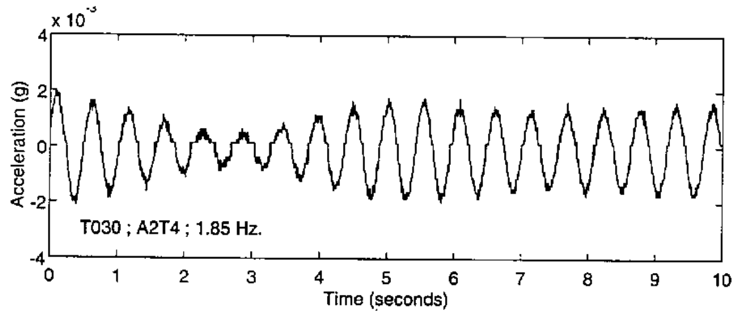

Fig. 4: Typical transverse forced-vibration response of isolated bridge, showing beating

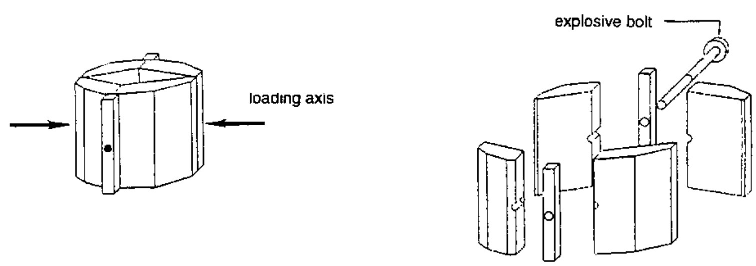

Fig. 5: Schematic of ISMES collapsible device


Fig. 6: Collapsible device and hydraulic jack prior to load release

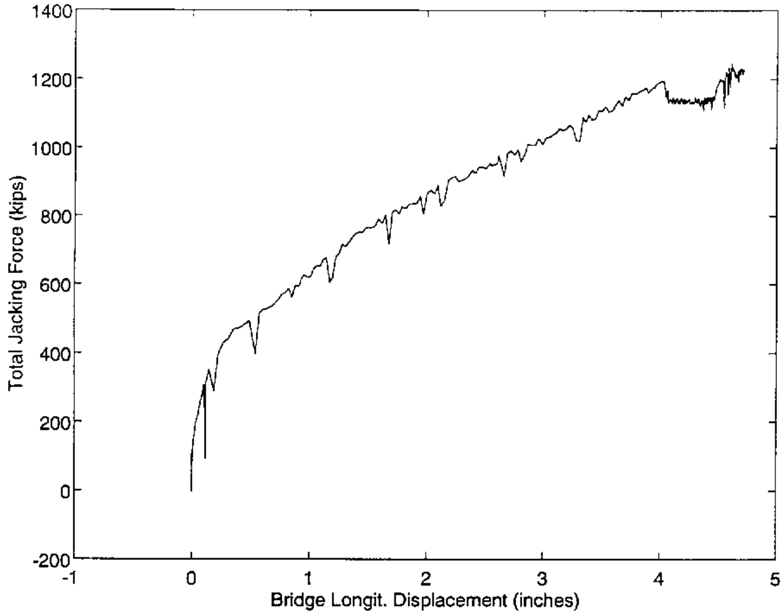


Fig. 7: Force-displacement plot for loading stage of quick-release test no. 2

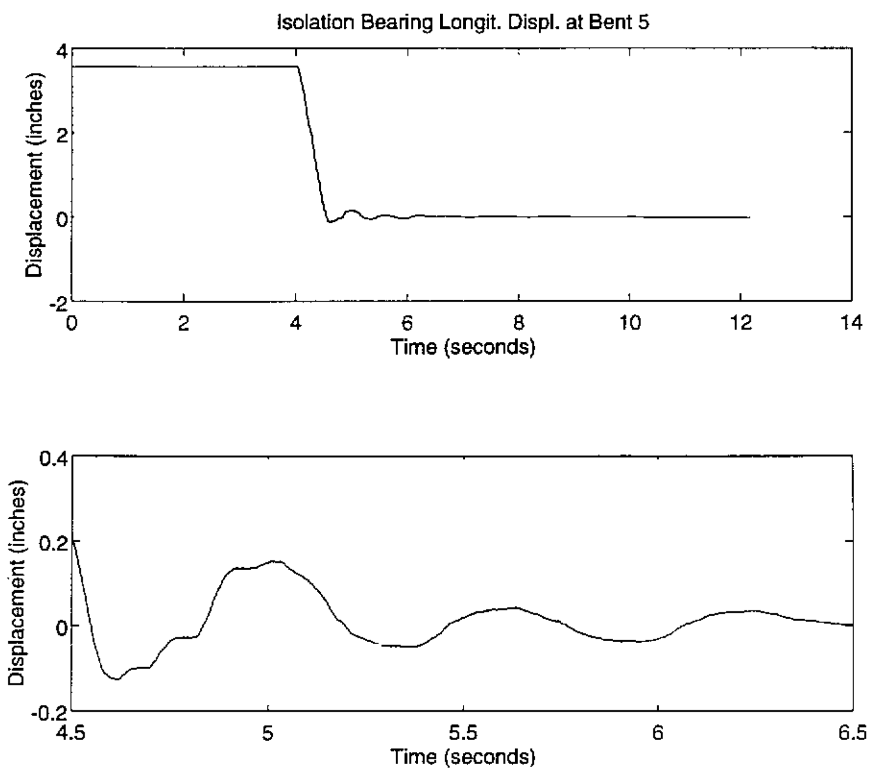


Fig. 8: Displacement time history for quick-release test no.3

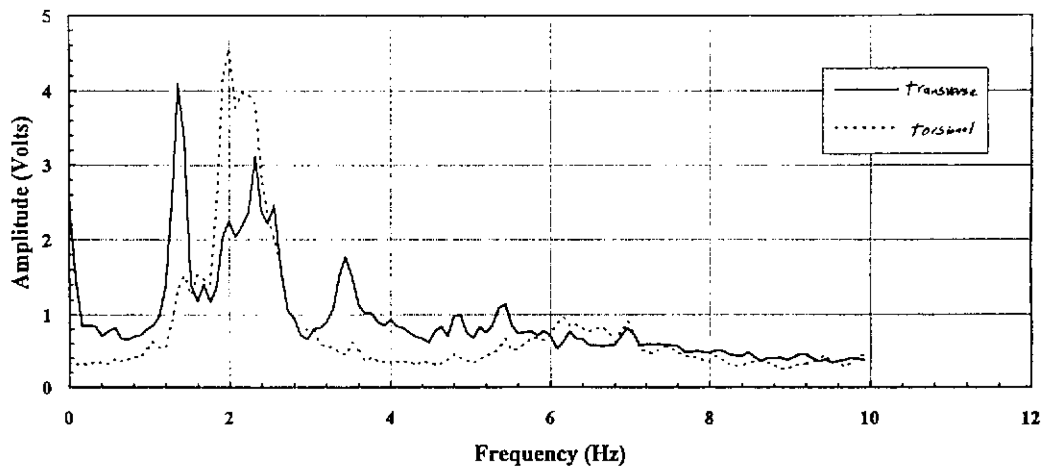


Fig. 9: Ambient Vibration response of completed isolated bridge - frequecy domain

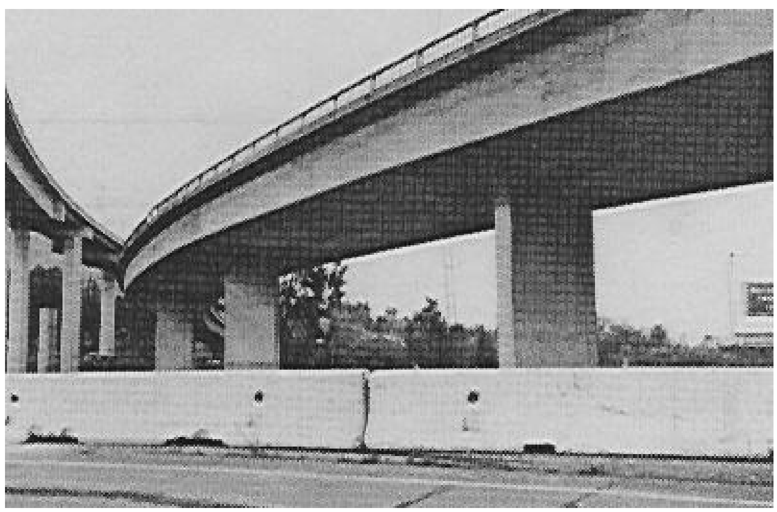

Fig. 10: View of Mt. Diablo Separation, looking north
(new temporary viaduct can be seen at left)