DYNAMIC TESTING,FINITE ELEMENT MODELING, AND LONG-TERM INSTRUMENTATION OF A BOX GIRDER POST-TENSIONED BRIDGE FOR THE LONG-TERM BRIDGE PERFORMANCE PROGRAM

by

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ABSTRACT

Dynamic Testing, Finite Element Modeling, and Long-Term Instrumentation of a Box Girder Post-Tensioned Bridge for the Long-Term Bridge Performance Program

by

Timothy Paul Thurgood, Master of Science
Utah State University, 2010

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As part of the Long-Term Bridge Performance (LTBP) program, a flagship research program funded by the Federal Highway Administration in response to the aging bridge network, the Lambert Road Bridge near Elk Grove California was selected as the California Pilot bridge set to undergo non-destructive testing and monitoring. The purpose of the program is to obtain a database of scientific quality data concerning the health and maintenance procedures currently in use across the nation. FHWA program managers along with members of the Utah State University LTBP research team selected the bridge with the assistance of the National Bridge index and site visits.

Dynamic modal analysis and long-term health monitoring are two of the test procedures that the test bridge will undergo. Dynamic modal analysis is performed by introducing a known vibration into the system and recording the response. The dynamic properties are extracted in this manner, which allows any changes in the structure to be tracked over time as the dynamic properties change. The long-term health monitoring of
the bridge will include an array of sensors designed to capture the real-time structural response of the bridge under normal operating conditions at key locations.

An array of 1-Hz Velocity Transducers was used to record the bridge response to the introduced vibrations. The data collected over 4 days of testing was analyzed using the “peak picking method” to locate the resonant frequencies, mode shapes, and damping ratios of the structure. In this thesis the dynamic testing results and the finite element model were compared and correlated both visually and with a modal assurance criterion.

The long-term health monitoring is also discussed in this thesis. The types and reason for each sensor are presented and the installation procedure is explained and documented.

(138 pages)
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I would first like to thank my major professor, Dr. Marvin Halling, for his guidance, encouragement, and friendship throughout years and on this project. I will never forget the long cold nights of testing, the great food and even better 100% juice provided by the “juice snob.” I would also like to express my appreciation to Dr. Paul Barr and Dr. Joseph Caliendo for the guidance and support during this project. The three of you have been great teachers and role models. I thank you for providing me with the precious gift of knowledge throughout my academic career here at Utah State University.

I give special thanks to my wife, Renata, for her love and support. I could not have finished without her. I also give special thanks to my children, Renan, Lucas, Isabela, and Cecilia, for their patience during this long journey.

Timothy P. Thurgood
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INTRODUCTION

The highway transportation system in the United States is used daily by millions in both commerce and leisure. The transportation system is essential to the nation’s current and future economic growth, as well as for the enjoyment and leisure of its citizens. Bridges are an integral part of that highway traffic network. Due to the age, tough climatic conditions faced daily by many of the bridges across the nation, heavy traffic loads, and many other factors, deterioration of key structural components must be monitored and evaluated on a regular basis. With over 590,000 bridges and related structures on record in the National Bridge Inventory, the maintenance and evaluation of the bridges is a daunting task faced by federal and local traffic agencies (FHWA, 2010).

In response to this task, the Federal Highway Administration’s (FHWA) Office of Research and Development recently launched a new flagship research program to establish a data base of scientific quality data from a representative sample-set of bridges across the nation. The Long-Term Bridge Performance program (LTBP) is projected to be twenty years in duration, which will allow researchers to document the effects of aging and degradation of the subject bridges over a relatively long period of time. The goal of the LTBP program is to provide improved methods of evaluating bridge health, increased knowledge of bridge performance, and to ensure the safety, and reliability of the nation’s bridge network. These goals will be met by Non-Destructive Evaluation (NDE) methods on structures currently in use in the traffic network and also by destructive testing of obsolete bridge components at the end of their service life. As part of the NDE process, dynamic modal analysis and long-term bridge monitoring techniques will be implemented. LTBP researchers perform a series of tests designed to establish
the current or “insitu” condition of the subject bridge, while simultaneously providing a
standard by which to compare and/or rank similar structures. The tests will be repeated at
specified intervals ranging from continuous monitoring to intervals of 2-5 years. The
results will be compared to the initial conditions as well as that of previous tests of the
structure.

Dynamic modal analysis has been utilized in practice for many years, but only, in
the last 30 years with the advent of computers, has it become both feasible and accurate
sufficiently to be used on a large scale. Experimental modal analysis as defined by the
Encyclopedia of Vibrations is a testing method where experimental vibration
(acceleration or velocity) data is recorded and analyzed to extract the modal properties of
an object. Furthermore, this data can be used to construct a mathematical model which
describes the behavior of the test subject (Braun, Ewins, and Rao, 2002). In the context
of Structural Engineering, dynamic testing is frequently used to obtain the dynamic
properties of large structures such as buildings and bridges. The dynamic properties of a
structure can be tracked and observed as a structure ages. The change in the dynamic
properties can be correlated to a change in the stiffness of the structure, or in other words
they can be used to detect damage and deterioration of the structural components and
evaluate the health and safety of the structure (Ren, Zhao, and Harik, 2004).

Long-term instrumentation is becoming a more common approach used by many
in the field of Structural Health Monitoring. Long-Term bridge monitoring is the process
of real-time tracking of the response of a structure under ordinary operating conditions, or
in other words ambient conditions (Omenzetter and Brownjohn, 2006). Tracking bridge
health involves the use of many data measuring devices, such as strain gages,
accelerometers, tilt-meters, and weather station equipment all linked to a central data acquisition system where data is collected, stored, and in most cases, analyzed to provide a real-time quantitative estimation of the condition of the structure. Long-term monitoring of the bridge is also used to observe the deterioration process of the structures as it occurs. The data can be used in better understanding the deterioration process, in improving future designs and in making important management decisions regarding the maintenance and repair of the structure.

As both dynamic modal analysis and long-term monitoring are a part of the LTBP projects NDE, their effectiveness and feasibility in meeting the objective of the program must be evaluated. Installation protocols must be established in order to judiciously compare results obtained from the wide variety of structure types anticipated over the life of the LTBP project. The first objective of this study was to assess the feasibility of forced excitation modal analysis under live traffic conditions. As many bridge structures are crucial to the traffic network, a complete bridge closure is neither permissible nor practical. The Lambert Road Bridge Undercrossing (LRB) is the candidate bridge chosen as the Pilot Bridge in the state of California. As the bridge is located 30 miles south of Sacramento on the main I-5 corridor connecting Sacramento to Stockton and Los Angeles, and with an Annual Daily Traffic count (ADT) 25,000 vehicles; it is extremely vital to the traffic network in the area and as such a complete closure is not possible. It will be an excellent candidate bridge to evaluate the logistics of forced vibration testing under operating conditions. The Second objective is to verify and refine a Finite Element Model (FEM) using the results from the dynamic modal analysis. The FEM was constructed of solid elements using SAP 2000. The third and final objective was to establish
quantitative based protocol for the long-term instrumentation and monitoring aspects of the LTBP project.
BRIDGE SELECTION AND DESCRIPTION

The criteria used in selecting a suitable pilot bridge in California will be discussed in this section. The National Bridge index was consulted and site visits were made. The selected bridge will be presented and description and structural evaluation provided.

California was selected as one the preliminary (pilot) states in which bridge monitoring would be conducted. The LTBP research team determined that a cast-in-place (CIP) box girder beam bridge was an appropriate representative structure for the region. The National Bridge Inventory (NBI) is a database compiled by the FHWA with data concerning the 590,000 bridges, tunnels, and culverts with roads passing over or under throughout the United States (FHWA, 2010). The Utah State University (USU) LTBP research team used the NBI to assist in the bridge selection process in the state of California. A copy of the NBI for California was provided to USU researchers. A selection criteria table was created in corroboration between researchers from USU and the Virginia Polytechnic Institute and State University. This table outlined the key characteristics that the selected bridge in California should posses. Selection of the California Bridge utilized approximately 14 of 116 items contained in the NBI. The 14 items considered in the selection process are presented in Table 1. The fourteen categories were evaluated in level of importance. A hierarchy was established among them for the purpose of conducting an efficient search of the California NBI. An iterative search approach was taken. Categories lower in the importance hierarchy were allowed to change in magnitude until a reasonable number of structures were selected. Google Maps was then used to obtain areal and street views of the bridges and surrounding location.
Table 1. NBI Search Criterion California Bridge Selection

<table>
<thead>
<tr>
<th>NBI #</th>
<th>Description</th>
<th>Range</th>
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<tbody>
<tr>
<td>1</td>
<td>State Code</td>
<td>CA-069</td>
</tr>
<tr>
<td>2</td>
<td>Highway District</td>
<td>03-10</td>
</tr>
<tr>
<td>21</td>
<td>Maintenance Responsibility</td>
<td>01-State Highway</td>
</tr>
<tr>
<td>27</td>
<td>Year Built</td>
<td>1960&lt;Present</td>
</tr>
<tr>
<td>28A</td>
<td>Lanes On</td>
<td>2</td>
</tr>
<tr>
<td>28B</td>
<td>Lanes Under</td>
<td>&lt;2</td>
</tr>
<tr>
<td>29</td>
<td>ADT</td>
<td>&gt;6,000</td>
</tr>
<tr>
<td>34</td>
<td>Degrees Skew</td>
<td>&lt;25</td>
</tr>
<tr>
<td>42A</td>
<td>Service On</td>
<td>1-Highway : 6-Highway-waterway</td>
</tr>
<tr>
<td>42B</td>
<td>Service Under</td>
<td>1-Highway</td>
</tr>
<tr>
<td>43A</td>
<td>Structure Kind</td>
<td>5-pre-stressed concrete</td>
</tr>
<tr>
<td>43B</td>
<td>Structure Type</td>
<td>06-box beam or girders</td>
</tr>
<tr>
<td>45</td>
<td>Main Units Span</td>
<td>&gt;2</td>
</tr>
<tr>
<td>109</td>
<td>Percent ADT Truck</td>
<td>&lt;5</td>
</tr>
</tbody>
</table>

Bridges and locations were evaluated in terms of the accessibility under and around the structure. Consideration was also given to driving distance from major metropolitan airports. A list of five bridges was obtained through this iterative procedure. This list was sent to the California Transportation department (Caltrans) Division of Maintenance with a request for more information concerning the bridges on the list. Pete Whitfield, P.E., Office of Chief Investigation North, coordinated the site visits by Caltrans and a detailed list was sent to USU researchers. The detailed list contained information regarding bridge attributes, utility access, bridge underside access, and interior access.

The short list was reviewed by the USU researcher team, which met to discuss the advantages and disadvantages of each structure. Among the topics discussed were the type of structure, when construction was completed, Average Daily Traffic Count (ADT), and local amenities available at the site, power, phone, etc. Location of the bridge with
respect to major cities and airports was also a factor in the selection process. From this meeting three bridges were selected.

Pete Whitfield was again contacted and a request for site access by the USU research team was submitted. October 6th 2009 was chosen to visit the three selected bridges. Visits to each of the three bridges were conducted by a small number of researchers from the FHWA, USU, and Caltrans, to document the bridge with pictures and a personal assessment of the bridge conditions.

Site visits were made to each location. Researchers discussed advantages of each location in respect to the others. From the site visits the Lambert Road Bridge undercrossing (LRB), was selected as the California pilot Bridge. Lambert Road Bridge (CalTrans structure # 24-287L), was selected. LRB is on the I-5 corridor in California. This section of I-5 is 30 minutes south of the capital Sacramento making access to the bridge very convenient for out-of-state researchers and visitors. The main disadvantage was the extremely heavy traffic load experienced on a daily basis. With an ADT of \(\approx 25,000\) vehicles per day access to the deck and lanes would be difficult. However, this was also one of the primary reasons that the Lambert Bridge was chosen. Due to the young nature of the LTBP program much was still being learned in relation to bridge access and traffic disruption. Access to the bridge would be a very delicate process and would require a great deal of planning and coordination between LTBP researchers and Caltrans officials. The Lambert Road Bridge provided researchers the opportunity to better understand how to obtain data with minimal impact to the public in a highly traveled area.
The two-span, southbound Lambert Road Bridge (LRB) is the focus of this study. It is located 30 miles south of Sacramento, California near Elk Grove, California. More detailed location is given by latitude and longitude: 38° 19’ 14” and -121° 27’ 55”, respectively. Figure 1 illustrates the geographic location of the pilot bridge in relation to California.

Construction for the LRB was completed in 1975. It has two lanes of traffic on the deck surface and two large shoulders. It is part of Interstate-5 (I-5) corridor.

![Figure 1. Location of California pilot bridge.](image)

It carries southbound I-5 traffic over Lambert Road and a small earth canal towards Stockton and Los Angeles. Lambert Road is a very lightly traveled country road.
A side view and aerial view of the bridge are given in Figure 2; the arrow indicates the subject bridge. Figure 3 shows a schematic drawing in plan view of the bridge and also a schematic plan view drawing of the interior cell layout.

The superstructure is comprised of continuous pre-stressed concrete box girder spans with Reinforced Concrete (RC) piers and RC open ended hinged diaphragm abutments all founded on Cast-In-Drill-Hole (CIDH) concrete piles as indicated in Figures 4 and 5 (Caltrans Bridge Inspection Report 2008). The structure has two continuous spans at 129 feet for an overall structure length of 258 feet, from abutment to abutment. The bridge is skewed at 8°.

It was also noted in the last inspection that the pourable joint seals between approach pavement and approach slabs have failed at both ends of the bridge. The approaches in both north-bound and south-bound directions show considerable cracking and wear of the asphalt as shown in Figure 6.
Figure 3. A) plan view of deck; B) interior cell layout.

Figure 4. A) RC pier; B) under-side box girder.
The deck is 42 ft (12.8 meters) in total width with an actual road width of 40 ft (12.2 meters). There are type 9 concrete and steel barriers along each side the entire length of the structure. The deck is 8-inch thick concrete with a clear polymer overlay as seen in Figure 7. The June 2008 inspection reports indicate that several “moderate” sized deck cracks were forming near the abutments. There were also several “fine to
moderate” size “moderate to severe” density and pattern cracks near bent 2 (pier). There were also “superficial to fine size severe density” longitudinal cracks throughout out the deck. Figure 8 and Figure 9 show schematic drawings of the bridge elevation and cross-section.

Figure 7. Concrete deck with clear polymer overlay.
Figure 8. Schematic elevation drawing of California pilot bridge.

Figure 9. Cross-section of deck and box.
DYNAMIC TESTING

Field Testing Layout and Process

Dynamic testing accomplishes the objectives of the LTBP program in that it allows researchers to quantitatively track the degradation processes in the bridge.

Dynamic testing of a bridge structure serves to:

1. Increase the knowledge available for structures with similar structural characteristics, which can be used to predict the responses of future structures
2. Determine the integrity of a structure after a structure has been overloaded or has been loaded beyond prior known or prescribed limits
3. Validate theoretical and/or mathematical models of the bridge structure
4. Assess the capacity of the structure when a load increase of the surrounding network is desired
5. Monitor the overall condition of the structure by regular measurement of the structure’s modal properties
6. Verify that a particular system behaves in a manner which conform with the expected outcome.

The LTBP program will primarily focus on the overall health monitoring of the bridge and validating the mathematical model (Finite Element Model, FEM) for the purposes of the dynamic testing; corresponding to points 3 and 5 above. In their 1995 review of full scale dynamic bridge testing, Salawu and Williams (2005) noted that the observed changes in modal parameters corresponds to the magnitude of the damage or
deterioration which occurred in the structure. Therefore the effects of aging and degradation of structure can be evaluated based on the observed changes in the modal parameters.

The equipment for the dynamic testing was provided by the Utah State University Structural Engineering Department. The sensors used in the modal analysis were Mark Products L-4 seismometers. This type of sensor does not require external excitation and was therefore the preferred sensor. The sensor specifications are: Frequency-1.0 Hz, Coil Resistance- 5500 ohms; Mass: ~970 grams. The sensor measures the change in voltage as the magnetic core passes through the exterior coils. The change in the resulting voltage can be converted to in/s by means of a calibrated electro dynamic constant. The exact electro dynamic constant is sensor dependant; however the average is approximately 7 volts/in/sec. The cables used were of a typical shielded 14 gage wire, with BNC and military type connectors. All cables and sensors were appropriately grounded using a 4 ft copper Rod driven approximately 3 feet into the soil at the bridge site. Table 2 contains serial # and corresponding Electro Dynamic Constants for all sensor used in testing.

Two data acquisition units were utilized during testing. The first was a Data Physics ACE Quattro 4 channel dynamic signal analyzer with signal calc 240 software, and the second was a Data Physics Mobilyzer 8 channel ABAQUS based Dynamic Signal Analyzer with Signal Calc 730 software. The input excitation was provided by an APS Dynamics 400 Series Linear bearing Long-Stroke vertical shaker with added reaction mass assembly. This unit is capable of producing 100 lb of force per stroke. An APS 145 dynamic amplifier was
Table 2. Sensor and Corresponding Calibration Factor Used in Dynamic Testing

<table>
<thead>
<tr>
<th>USU#</th>
<th>Serial #</th>
<th>Direction</th>
<th>Electro Dynamic Constant (Volts/In/Sec)</th>
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<tbody>
<tr>
<td>NA</td>
<td>2292</td>
<td>Vertical</td>
<td>6.87</td>
</tr>
<tr>
<td>NA</td>
<td>2293</td>
<td>Vertical</td>
<td>6.84</td>
</tr>
<tr>
<td>NA</td>
<td>2294</td>
<td>Vertical</td>
<td>7.03</td>
</tr>
<tr>
<td>NA</td>
<td>2295</td>
<td>Vertical</td>
<td>6.89</td>
</tr>
<tr>
<td>NA</td>
<td>2296</td>
<td>Vertical</td>
<td>6.87</td>
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<td>Vertical</td>
<td>6.81</td>
</tr>
<tr>
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<td>Horizontal</td>
<td>6.92</td>
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<tr>
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<td>2301</td>
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</tr>
<tr>
<td>6</td>
<td>2303</td>
<td>Horizontal</td>
<td>6.9</td>
</tr>
</tbody>
</table>

used to amplify the input signal. A conventional PC laptop was used to operate the signal calc software.

The author and other researchers from Utah State University (USU) designed and implemented the dynamic testing of the LRB. Testing of the LRB was conducted in November 2009. All testing was scheduled for between the hours of 9:00 P.M. - 6:00 A.M. The testing time was established by the California Transportation Department to minimize the negative effects of testing on traffic flow. The effects of temperature variation were noted by the researchers and included in the data sets. For this study fluctuations in temperature were not used in calculations.

The original test plan is found in Appendix A; please note that modifications were made to the original plan based on in-field conditions and preliminary results. Researchers determined that a forced vibration stepped-sine test (SSN) should be implemented due to the poor input signal to noise ratio from ambient vibrations caused by traffic and environmental factors.
Forced vibration testing, as implied by the name, is the process of introducing a controlled vibration into a structure and measuring the response of the structure due to the excitation. Due to the significance of the LRB to the overall traffic network of the region, a complete closure of the bridge was not permitted. As such, the tests noise to signal ratios were very high. A Stepped Sine Analysis test (SSN) was implemented to counteract the high noise content in the signal. An SSN is a systematic process in which the signal analyzer directs an internal signal generator to create a sine wave at a single user-defined frequency. The system is allowed to respond, the response is measured at that frequency, the data point is recorded, and the signal generator then increments the sine wave to a new frequency. The system is once again allowed to reach “steady state” response, another measurement is recorded, the system increments again, and the iterative process continues in the same manner until the end of the test is reached. SSN testing is very useful in noisy environments and/or when testing is conducted under normal operating conditions (Data Physics Corporation, 2010). Averaging and filtering can also be completed during the SSN to increase the quality of the data.

The vertical velocity transducers were secured to the structure by placing a small amount of plumbers putty on the base of the transducer, the transducer was then placed on the deck base down and the putty was compressed. The horizontal transducers were placed in adjustable leveling cradles and adjusted accordingly. Figure 12 illustrates the instrumentation placement of a vertical and horizontal transducer in the second interior cell of the southern span.
Data acquisition set-up was similar for all four days of testing. A typical data acquisition setup may be seen in Figure 10 and a flow chart diagram of a typical test instrumentation set-up configuration is shown in Figure 11.

Velocity transducers were placed on the deck on the interior side of the concrete barrier, and in the interior girder cells at the base of the web. The sensor placement on the deck was selected for two reasons: first, this sensor configuration maximized the measurement of the torsional response of the system, and second it allowed safe testing under live traffic conditions both for the USU researchers in placing the sensors and for motorist using the interstate.

Figure 13 illustrates the typical deck sensor placement while the previous Figure 12 illustrated placement in the cells. The shaker was positioned on the deck in two different locations for testing during the first day of testing. For convenience of the researchers and safety of the motorist the shaker was moved to the second interior cell of span 2 (south span) 50 feet from the centerline of the bridge for all other test days (position 3). The shaker in position 3 allowed researchers to test without the need of traffic control and testing was not limited to night time lane closures. Figure 14 displays the placement of the shaker in the cell and on the deck.
Figure 10. A) Data acquisition layout diagram; B) actual in-field setup.

Figure 11. Flow chart of test instrumentation setup.
Figure 12. Vertical and horizontal velocity transducer placement in cell.

Figure 13. Aerial view: deck placement of vertical sensor.
The sensor positions were labeled by USU researchers from A-G corresponding to the channel label on the Signal Analyzer. Note that in set up #1 and #2 only three sensors were used (A-C). The first day of testing was done using a Data Physics 4 channel Quattro signal analyzer. All other days, a Data Physics 8 channel Mobilyzer system was used. Note that with both systems, channel 1 was used as the “Input” or reference channel. The signal generated by the analyzer was connected to the amplifier using a “T” connector, and it also was connected to channel 1 of the analyzer to be used as the reference channel.

Instrumentation was installed each test day prior to testing. Test Day 1 was used to perform a broad frequency sweep from 2.6 Hz-18 Hz at a frequency step of .088 Hz. Test Days 2 and 3 were used to perform several narrow ranged tests focusing primarily on the suspected resonant locations. The frequency range of days 2 and 3 was from 2.9 Hz-13.2 Hz with an average incremented frequency step of .04 Hz. Day 4 testing was scheduled to verify previously located resonant frequencies. Several ambient vibration tests were conducted. The ambient testing used the traffic stimulation to introduce vibration into the structure. The vibrations were compared to white noise, 16-90
averages of the data were taken depending on the test. The Day 4 testing was also conducted in conjunction with the Live-Load testing. Live-Load Testing used a “rolling-stop” traffic lane closure procedure. This procedure involved California Highway Patrol slowing traffic approximately five miles north of the bridge. This allowed the bridge to be free of traffic, and likewise noise induced by vehicles, for 10-15 minutes periods during each live load run. A series of swept sine tests were performed during these traffic breaks. A swept sine tests begins at a predefined frequency and sweeps quickly through a predefined range of frequencies. The frequency range used during these tests was on the range of 2.5Hz-25Hz.

The shaker was also positioned to shake horizontally at the end of the Day 4 testing. However, due to time constraints only one SSN test was completed using the horizontal shaker. Due to insufficient filtering of the input signal the data collected was of very poor quality.

A complete set of sensor/shaker instrumentation plans are provided in Figures 15-23. These figures document the sensor positions and shaker locations used in the forced vibration analysis. The sensor locations are also the nodal coordinates used in the comparison of the analytical and experimental models.
Figure 15. Left: plan view (north span) of 1st test setup; right: cross-section.
Figure 16. Plan view of 2nd setup.
Figure 17. Setup 2 cross-sectional view.
Figure 18. Plan view of 3rd setup.
Figure 19. Setup 3 cross-sectional view (arrow indicates sensor facing east).
Figure 20. Plan view of 4th setup.
Figure 21. Setup 4 cross-sectional view (horizontal sensor facing west).
Figure 22. Plan view of 5th setup.
Figure 23. Setup 5 cross-sectional view (all horizontal sensors facing east).
Dynamic Testing Analysis, Results, and Evaluation

A dynamic signal analyzer, which allows for real time conversion of data from the time domain to the frequency domain, and a Transfer Function Layout were used for all tests. A transfer function layout consists of three graphs a coherence function, TRF magnitude and TRF unwrapped phase. In all graphs the “x”, or Horizontal, axis is in units of Hertz (Hz). The top graph is the Transfer Function with y axis in magnitude and the middle graph, also a Transfer function, with the y axis being in terms of the unwrapped phase. A brief explanation of the three graphs and how they are created will be the next topic of discussion.

The term Transfer Function (TRF) is a mathematical model defining the input-output relationship of a physical model (Agilent Technologies, 2000). The system response (output) is caused by the excitation (input); this relationship is shown in the block diagram of Figure 24. The term transfer function is often used synonymously with the term Frequency Response Function (FRF), although they are not the same they are related mathematically. This relationship will not be discussed herein. However, the basic definition of the FRF will be presented as it pertains to the current subject. The FRF is the Fast Fourier Transform (FFT) of the output divided by the FFT input. The (FRF) is used to derive the TRF. The TRF values calculated by the analyzer are complex functions, meaning they have real and imaginary components. The TRF describes the structural response of a system, to an applied force, in terms of the frequency (Irvine, 2000). Peter Avitabile, University of Massachusetts Lowell, described the TRF as the ratio of the output response of a structure to an applied force (Avitabile, 2001).
Isolating the transfer function on the left side of Equation 1 produces the TRF ratio of output response divided by the input response as seen in Equation 2.

\[ X(\omega) = H(\omega) * Y(\omega) \]  

(1)

\[ H(\omega) = \frac{X(\omega)}{Y(\omega)} = \frac{OUTPUT}{INPUT} = \frac{G_{yx}}{G_{xx}} \]  

(2)

where,

\( G_{xx} \equiv \text{Power Spectrum of the input } x(t) = S_x * S^*_x \)

\( S_x \equiv \text{Linear Fourier Spectrum of } x(t) \)

\( S^*_x \equiv \text{Complex Conjugate of } S_x \)

\( G_{yy} \equiv \text{Power Spectrum of the input } y(t) = S_y * S^*_y \)

\( S_y \equiv \text{Linear Fourier Spectrum of } y(t) \)

\( S^*_y \equiv \text{Complex Conjugate of } S_y \)

\( G_{yx} \equiv \text{Cross Power Spectrum between input and output} \)

\( G_{yx} = S_y * S^*_x \)

(Ramsey, 1975)
The TRF can also be obtained by taking the Fast Fourier Transform (FFT) of the input time signal divided by the FFT of the output time signal as shown in Equation 3.

\[ FRF = H(\omega) = \frac{fft(OUTPUT)}{fft(INPUT)} \]  

(3)

The data collected in the time domain is passed through an (FFT), as mentioned previously, this results in complex numbered values of the form shown in Equation 4.

\[ X = X + Xi \]  

(4)

The magnitude of this value is found by combining the real and imaginary portion of the number by taking the square root of the sum of the squares as shown in Equation 5. (Biran and Breiner, 1995)

\[ Magnitude = \sqrt{X^2 + Xi^2} \]  

(5)

The Phase can be calculated with the complex numbers shown in Equation 4. Equation 6 shows solution to the phase angle Equation 6. (Chopra, 2007)

\[ Phase(\varphi) = \tan^{-1} \frac{Xi}{X} \]  

(6)

The Coherence Function (CF) is defined as “the degree of noise contamination in the transfer function” (Ramsey, 1975). The CF is used to determine the quality of the data used in evaluating the Transfer Function. The CF describes the proportion of the output that is directly caused by the system input; it is a real function (Ramsey, 1975). The CF gives a measure of correlation between signal x and signal y (Department of Music, Stanford University, 2009). The CF ranges between values of zero and one and is generally denoted using the \( \gamma^2 \) symbol where

\[ (\gamma^2) = \frac{Response\ power\ caused\ by\ input}{Measured\ response\ power} \]  

(7)

and \( \gamma^2 \) can be calculated using Equation 8.
\[ \gamma^2 = \frac{|G_{xy}|^2}{G_{xx} \cdot G_{yy}} \text{ where } 0 \leq \gamma^2 \leq 1 \] 

\[ \bar{G}_{xy} \equiv \text{Average Cross Power Spectrum} \]

\[ G_{xx} \text{ and } G_{yy} \equiv \text{Average Auto Power Spectrum} \]

A coherence value of 1 indicates that the output was caused directly from the input, or by sources which are coherent with the measured input. While a coherence value of 0 indicate the output was not caused by the input signal. This means that no correlation exists between the output signal and the input signal. The CF can serve as an indicator of the quality of the TRF measurements.

The damping ratio of the bridge was estimated from experimental data using the Half-Power Bandwidth method. The FRF plot is used in evaluating the Half-Power damping estimation. For each peak, which corresponds to a resonant location on the FRF plot, the peak amplitude value at the resonant frequency \( (\omega_n) \) is divided by \( \sqrt{2} \) and the corresponding frequencies on each side \( (\omega_a \text{ and } \omega_b) \) are found. Figure 25 illustrates these variables, which are used to solve for the damping ratio \( (\xi) \).

The damping ratio is calculated by taking the higher frequency at the amplitude location divided by \( \sqrt{2} \) subtracted by the lower frequency and then taking this quantity divided by 2 times the natural frequency as seen in Equation 9.

\[ \xi = \frac{\omega_b - \omega_a}{2\omega} \]
The data recorded during testing of the LRB was saved, processed, and analyzed by researchers from USU.

Researchers organized the tests by day in the format of Day#_Test#, for example the first test of day 1 was labeled DY1_1. Table 3 contains detailed information regarding each test by day. Further discussion of each test including test parameters and modal properties obtained will be given later in this document.

The procedure used in analyzing the data is commonly referred to as the “Peak Picking Method” (Dominguez, 2007). This method is based on the principle that when the TRF reaches a peak this can be associated with a resonant frequency of the structure. Resonant frequencies may be located by observing the peaks in the TRF data. However, due to poor noise to signal ratio not all peaks represent locations of resonance. The Unwrapped Phase is also used further identify resonance locations.
### Table 3. Test Name and Details

NOTE: SSN= Stepped Sine Test, TRF= Transfer Function Test

<table>
<thead>
<tr>
<th>Test Day 1</th>
<th></th>
<th>Frequency Range (Hz)</th>
<th>Frequency Step (Hz)</th>
<th>Filter width (Hz)</th>
<th>Average s</th>
<th>Test Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td><strong>File Name</strong></td>
<td><strong>Frequency Range (Hz)</strong></td>
<td><strong>Frequency Step (Hz)</strong></td>
<td><strong>Filter width (Hz)</strong></td>
<td><strong>Average s</strong></td>
<td><strong>Test Quality</strong></td>
</tr>
<tr>
<td>SSN Run00002-Setup1 DY1_1</td>
<td>2.6-7.2</td>
<td>0.088</td>
<td>0.3</td>
<td>2</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>SSN Run00003-Setup1 DY1_2</td>
<td>7-18</td>
<td>0.073</td>
<td>0.3</td>
<td>2</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>SSN Run00004-Setup2 DY1_3</td>
<td>2.9-4.3</td>
<td>0.041</td>
<td>0.2</td>
<td>3</td>
<td>Good</td>
<td></td>
</tr>
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</table>

<table>
<thead>
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<th></th>
<th>Frequency Range (Hz)</th>
<th>Frequency Step (Hz)</th>
<th>Filter width (Hz)</th>
<th>Average s</th>
<th>Test Quality</th>
</tr>
</thead>
<tbody>
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<td><strong>Type</strong></td>
<td><strong>File Name</strong></td>
<td><strong>Frequency Range (Hz)</strong></td>
<td><strong>Frequency Step (Hz)</strong></td>
<td><strong>Filter width (Hz)</strong></td>
<td><strong>Average s</strong></td>
<td><strong>Test Quality</strong></td>
</tr>
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<td>2.9-3.8</td>
<td>0.045</td>
<td>0.2</td>
<td>3</td>
<td>Good</td>
<td></td>
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<td>SSN Run000020-DY2-2 set up #3</td>
<td>3.6-5.2</td>
<td>0.045</td>
<td>0.2</td>
<td>3</td>
<td>Good</td>
<td></td>
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<td>Type</td>
<td>File Name</td>
<td>Frequency Range (Hz)</td>
<td>Frequency Step (Hz)</td>
<td>Filter width (Hz)</td>
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</tr>
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<td>5-6.3</td>
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<td>0.2</td>
<td>3</td>
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<td>0.2</td>
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<td>0.2</td>
<td>3</td>
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</tr>
<tr>
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<td>Run000029-DY3-3 setup #3</td>
<td>9-11.22</td>
<td>0.045</td>
<td>0.2</td>
<td>3</td>
<td>Good</td>
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<td>SSN</td>
<td>Run000030-DY3-4 setup #3</td>
<td>11-13.2</td>
<td>0.045</td>
<td>0.2</td>
<td>3</td>
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<td>Type</td>
<td>File Name</td>
<td>Frequency Range (Hz)</td>
<td>Frequency Step (Hz)</td>
<td>Filter width (Hz)</td>
<td>Average s</td>
<td>Test Quality</td>
</tr>
<tr>
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<td>------------------------</td>
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<td>------------</td>
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</tr>
<tr>
<td>Ambient TRF</td>
<td>Run00004-DY4-1 setup #4</td>
<td>0-10</td>
<td>0.025</td>
<td>NA</td>
<td>90</td>
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</tr>
<tr>
<td>Ambient TRF</td>
<td>Run00005-DY4-2 setup #4</td>
<td>0-15</td>
<td>0.0375</td>
<td>NA</td>
<td>8</td>
<td>Good</td>
</tr>
<tr>
<td>Ambient TRF</td>
<td>Run00006-DY4-3 setup #4</td>
<td>0-15</td>
<td>0.01875</td>
<td>NA</td>
<td>8</td>
<td>Poor</td>
</tr>
<tr>
<td>Ambient TRF</td>
<td>Run00007-DY4-4 setup #4</td>
<td>0-15</td>
<td>0.01875</td>
<td>NA</td>
<td>6</td>
<td>Fair</td>
</tr>
<tr>
<td>Ambient TRF</td>
<td>Run00008-DY4-5 setup #4</td>
<td>0-15</td>
<td>0.01875</td>
<td>NA</td>
<td>6</td>
<td>Good</td>
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<tr>
<td>No Traffic TRF</td>
<td>Run00009-DY4-6 setup #4</td>
<td>0-15</td>
<td>0.01875</td>
<td>NA</td>
<td>6</td>
<td>Good</td>
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<tr>
<td>No Traffic</td>
<td>Run00010-DY4-7 setup</td>
<td>0-15</td>
<td>0.075</td>
<td>NA</td>
<td>6</td>
<td>Fair</td>
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<td>TRF</td>
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<td>0.01875</td>
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<td>6</td>
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<tr>
<td>No Traffic</td>
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<td></td>
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<tr>
<td>No Traffic</td>
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<td></td>
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<td>#4</td>
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<tr>
<td>No Traffic</td>
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<td>SSN</td>
<td>Run00002-DY4-1 setup</td>
<td>2.5-4.75</td>
<td>0.028125</td>
<td>0.4</td>
<td>Min</td>
<td>Very</td>
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<tr>
<td>SSN</td>
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<td>2.5-4.75</td>
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<td>3</td>
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<tr>
<td>SSN</td>
<td>Run00004-DY4-3 setup</td>
<td>3.070-3.127</td>
<td>0.0114</td>
<td>0.2</td>
<td>3</td>
<td>Poor</td>
</tr>
<tr>
<td></td>
<td>#4</td>
<td></td>
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</tr>
</tbody>
</table>
The Phase will transition through 180° while passing through resonance. When this transition occurs at a peak it is probable that a resonant frequency has been located. The Phase is also in or out of phase by 180° at all points along the structure which allows the mode shape of the structure to be determined. The coherence may also be used to further solidify the resonant location as the values should be near one at locations of resonance.

The analysis process will be demonstrated using test 1 of day 1 (DY1-1) as an example set. All other tests will be presented graphically and with summary tables only; readers should refer to test 1 of day 1 for clarification of the data analysis process. The letters A, B, and C used in the graphs and tables represent the sensors used in set-up # 1 as presented in Figure 15 and Table 3.

The preliminary analysis of the data was performed using Data Physic’s Signal Calc 730 and Microsoft Excel. Signal Calc has many useful analysis functions,
one such function is the capability to link cursors across multiple graphs. This feature was used to look at the change in phase across each peak in the TRF magnitude plot while also looking at the coherence. Locations where peaks and phase shifts occurred were noted and checked in subsequent tests for similar results. The data was also plotted in Excel and a spread sheet was set-up in order to calculate the phase shift for all the channels simultaneously to facilitate the analysis process. Further information and details regarding the excel programs can be found in Appendix B.

The test data collected during test DY1_1 was then converted from a “.ssn” (Singal Calc) file format to that of a “.mat” file which is used in Matlab. Matlab was used to obtain the damping ratio, analyzing, and plotting the results. The H1_1-8 and C1_1-8 files were imported into the “damping algorithm”; a Matlab script which calculates damping ratios, using the half-power bandwidth method. The script also plots the TRF in both Magnitude and Unwrapped Phase and the Coherence function. The Matlab script dampingalgorithm.m can be found in Appendix B. Figure 26 contains the results from test DY1-1 in graphical format, while Figure 27 contains the graphical and tabular representation of the damping ratio. Note in Figure 26 that there are four prevalent peaks on the middle graph (TRF-Magnitude). However, only three of the peaks meet the requirements of the phase transition of ~180° through the peak location. Further testing of the same frequency range also demonstrated the peak at 2.7 Hz was noise induced during the first test and not a location of resonance. Also note at the other three peaks a significant phase transition occurs. Table 4 contains the calculated damping ratios obtained using the half-Power bandwidth method, and Table 5 contains a summary of test DY1-1 results.
Figure 26. Test DY1-1 Top: TRF; Middle: Phase); Bottom: Coherence.

Figure 27. Sensor A graphically computed damping ratios.
Table 4. Calculated Damping Ratio (%) Half-Power Bandwidth Method

<table>
<thead>
<tr>
<th>Damping Ratio</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>2.5482</td>
<td>1.7944</td>
<td>2.1413</td>
</tr>
<tr>
<td>Mode 2</td>
<td>0.7344</td>
<td>0.7514</td>
<td>0.7375</td>
</tr>
<tr>
<td>Mode 3</td>
<td>2.2133</td>
<td>0.8989</td>
<td>3.1919</td>
</tr>
</tbody>
</table>

All other tests were analyzed in a manner similar to that of Test DY1-1; graphical and tabular results are found in Appendix C. Upon completion of the analysis process for each test a summary table indicating modal frequencies of the various types of test was compiled (Table 6).

Six locations of resonance or “modal frequencies” were located in this structure as shown again in Table 7.

The results of the dynamic testing and analysis will be used to calibrate an effective finite element model of the Lambert Road Bridge. These results should also be used in comparison of future tests.
Table 5. Natural Frequency and Damping of First Three Modes of Test DY1-1

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modal Frequency (ω)</th>
<th>AVG Phase (Φ)</th>
<th>Coherence</th>
<th>Damping (ξ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>3.22</td>
<td>175.8</td>
<td>70.56%</td>
<td>2.16%</td>
</tr>
<tr>
<td>Mode 2</td>
<td>3.66</td>
<td>221.8</td>
<td>51.45%</td>
<td>0.74%</td>
</tr>
<tr>
<td>Mode 3</td>
<td>4.11</td>
<td>185.3</td>
<td>75.63%</td>
<td>2.28%</td>
</tr>
</tbody>
</table>

Table 6. Modal Frequency Summary of LRB Testing

<table>
<thead>
<tr>
<th>TYPE</th>
<th>DAY/TEST</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
<th>Mode 5</th>
<th>Mode 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient TRF</td>
<td>TEST 4</td>
<td>3.08</td>
<td>3.65</td>
<td>4.10</td>
<td>8.03</td>
<td>9.83</td>
<td>NA</td>
</tr>
<tr>
<td>Ambient TRF</td>
<td>TEST 5</td>
<td>3.11</td>
<td>3.45</td>
<td>4.05</td>
<td>7.99</td>
<td>10.24</td>
<td>14.21</td>
</tr>
<tr>
<td>Ambient TRF</td>
<td>TEST 6</td>
<td>3.13</td>
<td>3.54</td>
<td>4.14</td>
<td>8.01</td>
<td>11.57</td>
<td>14.29</td>
</tr>
<tr>
<td>AVG Ambient</td>
<td></td>
<td>3.11</td>
<td>3.55</td>
<td>4.10</td>
<td>8.01</td>
<td>10.55</td>
<td>14.25</td>
</tr>
<tr>
<td>TRF No Traffic</td>
<td>TEST 7</td>
<td>3.11</td>
<td>3.68</td>
<td>4.07</td>
<td>7.99</td>
<td>10.10</td>
<td>14.03</td>
</tr>
<tr>
<td>TRF No Traffic</td>
<td>TEST 8</td>
<td>3.11</td>
<td>3.71</td>
<td>4.07</td>
<td>8.01</td>
<td>10.18</td>
<td>14.29</td>
</tr>
<tr>
<td>TRF No Traffic</td>
<td>TEST 9</td>
<td>3.08</td>
<td>NA</td>
<td>4.05</td>
<td>8.10</td>
<td>10.02</td>
<td>14.25</td>
</tr>
<tr>
<td>TRF No Traffic</td>
<td>TEST 10</td>
<td>3.23</td>
<td>3.80</td>
<td>4.20</td>
<td>8.10</td>
<td>10.20</td>
<td>14.32</td>
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<td>TRF No Traffic</td>
<td>TEST 11</td>
<td>3.17</td>
<td>3.50</td>
<td>4.07</td>
<td>7.93</td>
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<td>TRF No</td>
<td>TEST 12</td>
<td>2.98</td>
<td>3.58</td>
<td>4.07</td>
<td>7.99</td>
<td>10.07</td>
<td>13.88</td>
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### Table 6. Continued

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</tr>
<tr>
<td>AVG TRF</td>
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<td>4.10</td>
<td>8.11</td>
<td>10.43</td>
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<td>DAY 3</td>
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<td>3.79</td>
<td>4.21</td>
<td>7.99</td>
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<td>NA</td>
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<td>3.77</td>
<td>4.17</td>
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<td>AVG of all</td>
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<td>3.66</td>
<td>4.12</td>
<td>8.02</td>
<td>10.35</td>
<td>14.12</td>
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</tr>
</tbody>
</table>

### Table 7. Modal Final Results Obtained Through Dynamic Testing (Table 11)

| Modal Frequency | 3.11 | 3.66 | 4.12 | 8.02 | 10.35 | 14.12 |
Finite Element Modeling

A finite element model (FEM) of the LRB was constructed in SAP2000. Dereck Hodson was responsible for the modeling and refining of the model with respect to the results obtained in the Live Load Testing and Dynamic Testing.

The model was constructed using eight-node solid elements. The post tensioning strands were modeled using a tendon element. The boundary conditions and modulus of elasticity of the concrete were adjusted until the model corresponded with the results from the field testing. Figure 28 displays a 3D rendering of the FE Model.

The FEM yielded eight modal frequencies below 15Hz and the modes shapes of the LRB. Table 8 includes a compilation of the modal frequencies obtained from the FEM model.

Figure 28. 3D Rendering of solid 8 node finite element model.
As seen in Table 8 above there are more modal frequencies in the FEM than found during the experimental testing. During testing the bridge was only excited in the vertical direction; however the model describes modes in the vertical, transverse, and longitudinal directions. Mode 2 was questionable as to whether it was an actual resonant location or noise induced.

As seen in comparing the modal frequencies between the field-testing and the FEM model some errors exist between the theoretical and actual values. This is quite common and was to be expected. Table 9 compares the results from the theoretical and experimental results along with the percent difference.

As seen in Table 9, the percent difference between the mode shapes varies from 1% – 8% from the experimental to theoretical results. Other authors have found that the dynamic response of a structure can vary by as much as 5% due to temperature effects.
Table 9. Comparison of Experimental and Theoretical Modal Frequencies

<table>
<thead>
<tr>
<th>Experimental Frequency</th>
<th>Theoretical Frequency</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.11 (1)</td>
<td>3.30(1)</td>
<td>-6.2</td>
</tr>
<tr>
<td>3.66(2)</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>4.12(3)</td>
<td>4.44(2)</td>
<td>-7.9</td>
</tr>
<tr>
<td>NA</td>
<td>7.87(3)</td>
<td></td>
</tr>
<tr>
<td>8.02(4)</td>
<td>8.24(4)</td>
<td>-2.8</td>
</tr>
<tr>
<td>10.35(5)</td>
<td>10.48(5)</td>
<td>-1.3</td>
</tr>
<tr>
<td>NA</td>
<td>12.36(6)</td>
<td></td>
</tr>
<tr>
<td>NA</td>
<td>12.54(7)</td>
<td></td>
</tr>
<tr>
<td>14.12(6)</td>
<td>14.70(8)</td>
<td>-4.2</td>
</tr>
</tbody>
</table>

Modal shapes from the theoretical and experimental models will be compared using a Modal Assurance Criterion (MAC) Analysis. The MAC analysis serves to confirm whether two modal vectors correlate well; which also gives a measure of the accuracy of the FEM model. The MAC analysis will be explained and discussed in the subsequent section.

In summary a FEM was created for the LRB Bridge using SAP2000. The model was calibrated using experimental data obtained from dynamic and live load testing. The modal analysis of the model provided model frequencies which correlated with the first, third, fourth, fifth and sixth experimental modal frequencies. The MAC analysis will be used to check the degree to which the FEM model is able to accurately describe the response of the actual bridge.
MAC Analysis and Comparison

A Modal Assurance Criterion (MAC) analysis is commonly used as a means of quantitatively comparing the degree of correlation, or similarity between two given modal vectors. One common use of a MAC is to check the correlation between experimental and analytical models (Allemang, 2003). By comparing the mode shape of one model to that of the other, a quantitative measurement as to the similarity of the two mode shapes and natural frequencies can be obtained. Verification that the natural frequencies and mode shapes of the models are similar helps to establish the degree to which the analytical model is able to effectively capture the actual characteristics of a structure. MAC values are commonly presented in matrix form where values along the diagonal approach one and values off the diagonal approach zero, for well-correlated vectors. Off-diagonal values that do not approach zero may be due to spatial aliasing or similarities in the mode shape characteristics. Spatial aliasing is a result of under sampling of a system, or in other words, an insufficient number a data point are known to completely distinguish the mode shapes from one another.

Given two sets of modal shape vectors, \( \phi_A \) and \( \phi_B \) the MAC can be calculated as shown in Equation 10.

\[
\frac{\left| \sum_{q=1}^{N_o} \phi_A^T \phi_B \right|^2}{\sum_{q=1}^{N_o} \phi_A^T \phi_A \sum_{q=1}^{N_o} \phi_B^T \phi_B}
\] (10)

where
\( \phi_A = \) Vector containing mode shape from experimental data
\( \phi_B = \) vector containing mode shape from analytical data
A specialized application of the MAC concept is found in the auto-MAC. The auto-MAC is similar to the MAC in that modal vectors are compared to obtain the degree of correlation; however, in the case of the auto-MAC the mode shapes of a single model are compared to one another. The auto-MAC is useful in comparing different boundary conditions of the same system after damage has occurred, and in verifying that a sufficient number of degrees of freedom exist in order to fully distinguish the mode shapes from one another, or in other words in checking for spatial aliasing (Fotsch and Ewins, 2000).

The experimental mode shape was determined and normalized using sensor position F which remained constant throughout all tests. The magnitude and sine were derived from the TRF layout. The various test setups were normalized by finding the ratio between sensor placement F for setup 1 and sensor F for the other test setups. The ratio found for each individual setup was then multiplied to all sensors in that particular test set up, which allowed all sensors to be compared directly.

Both the MAC and auto-MAC were executed in MATLAB to further verify the correlation between experimental of analytical data, and to verify that sufficient data was collected to distinguish the individual mode shapes. The script can be found in Appendix B. Due to the channel capacity of the data acquisition system and other constraints spatial aliasing was of great concern. Also due to the high noise-to-signal content some uncertainty exists as to the existence of the 2\textsuperscript{nd} mode located during experimental testing. The auto-MAC of the experimental mode shapes allowed researchers to verify these two concerns. Table 10 and Figure 29 demonstrate the results from the auto-MAC correlation in both matrix and graphical form.
Some observations to note in Table 10 and Figure 29 are the high degree of correlation between modes two and three in the off diagonal position. At an off-diagonal MAC value of .869 the auto-MAC suggests the there is a very high degree of similarity between these two modes. Table 10 and Figure 29 also show that a high degree of correlation exists between modes two and three in the off diagonal position. With an off-diagonal MAC value of .869 the auto-MAC suggests the there is a very high degree of similarity between these two modes.

<table>
<thead>
<tr>
<th></th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
<th>Mode 5</th>
<th>Mode 6</th>
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<tr>
<td>Mode 1</td>
<td>1</td>
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<tr>
<td>Mode 2</td>
<td>0.0355</td>
<td>1</td>
<td></td>
<td></td>
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<tr>
<td>Mode 3</td>
<td>0.0051</td>
<td>0.8687</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode 4</td>
<td>0</td>
<td>0.2271</td>
<td>0.1053</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode 5</td>
<td>0.0574</td>
<td>0.1806</td>
<td>0.1488</td>
<td>0.029</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Mode 6</td>
<td>0.002</td>
<td>0.2471</td>
<td>0.1524</td>
<td>0.4151</td>
<td>0.0423</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 29. Auto-MAC experimental graphical matrix.
This correlation could be due to similar characteristic movement of both modes, or they could be the same mode shape. Figure 30 below compares visually the similarities between modes 2 and 3.

Due to the large signal to noise ratio during testing, in many cases it was challenging to differentiate actual resonance locations from noise induced. It is the opinion of the author, based on thorough investigation of the experimental data, that high degree of correlation is most likely due to the second scenario and modes 2 and 3 are representing the same mode shape which also correlates with the FEM solution. During review of the experimental data there were many circumstances in which the second modal frequency was present and many cases in which it was not. The information collected suggested that an actual resonance had been located; however, in light of the MAC results and the visual presentation seen in Figure 30 it appears that the initial conclusion was incorrect and what has been referred to herein as the second modal location is not an actual location of resonance.

It is also worth noting that the auto-MAC results follow the trends for MAC results previously mentioned. Namely, MAC values approaching unity along the diagonal and values approaching zero in off-diagonal locations with modes two and three.

Figure 30. Mode shape 2 vs. Mode shape 3 west and east perspectives.
being the exception. This indicates the spatial aliasing did not occur and that sufficient data was collected to distinguish the mode shapes from one another.

Based on the results of the experimental auto-MAC mode 2 has been removed from the list of mode shapes and frequencies. Table 11 displays the updated modal frequency locations.

The MAC analysis will reflect this modification. The analytical and experimental MAC matrix is presented in Table 11 with the analytical modes being presented in the columns and the experimental modes in the rows; Figure 31 is a graphical representation of the data found in Table 12.

### Table 11. Updated Modal Frequencies

<table>
<thead>
<tr>
<th>Modal Frequency</th>
<th>3.11</th>
<th>4.12</th>
<th>8.02</th>
<th>10.35</th>
<th>14.12</th>
</tr>
</thead>
</table>

### Table 12. Experimental vs. Analytical MAC Results

<table>
<thead>
<tr>
<th>Mode</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
<th>Mode 5</th>
<th>Mode 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>0.9896</td>
<td>0.0039</td>
<td>0.0492</td>
<td>0.0022</td>
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<td></td>
</tr>
<tr>
<td>Mode 2</td>
<td>0.9084</td>
<td>0.0629</td>
<td>0.1615</td>
<td>0.2098</td>
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<td></td>
</tr>
<tr>
<td>Mode 3</td>
<td>0.0326</td>
<td>0.0121</td>
<td>0.0365</td>
<td>0.0039</td>
<td>0.0681</td>
<td></td>
</tr>
<tr>
<td>Mode 4</td>
<td>0.0037</td>
<td>0.0032</td>
<td>0.6035</td>
<td>0.0656</td>
<td>0.0372</td>
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<tr>
<td>Mode 5</td>
<td>0.042</td>
<td>0.0198</td>
<td>0.012</td>
<td>0.1156</td>
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<td>Mode 6</td>
<td>0.0214</td>
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<td>0.0559</td>
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<td>0.0891</td>
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Correlation is based on the proximity of the numerical value to unity. Based on the results seen in other research projects a value of .6 or greater seems to suggest correlation in the vectors, this same assumption will be made herein. As seen in Table 12 and Figure 31 in comparing the analytical and experimental mode shapes the first 3 valid modes, being 1, 3, and 4 as previously stated, showed a high degree of correlation to the analytical mode shape 1, 2, and 4 as seen in the highlighted cells of Table 12. Also with the natural frequencies having a percent difference between 1-6%, it can be seen that the mode shapes and natural frequencies for the lowest three experimental vertical modes of the structure correlate with the FEM model. From this it can be inferred that the model is accurately able to describe the dynamic response of the structure. The higher modes, which are more difficult to excite, do not correlate to a high degree; however, due to the difficulty in exciting them and their low participation in the dynamic behavior of the structure, this is not of significant concern.
The first three vertical modes shapes are shown in Figures 32-34 below with the corresponding natural frequencies.

Figure 32. First vertical mode (3.30 Hz).

Figure 33. Second vertical mode (4.45 Hz).
The auto-MAC suggests that sufficient data was collected to distinguish individual modal shapes and also that mode shape 2 and 3 are actually representing the same mode. The MAC analysis was able to show that a high degree of correlation exist between the high participating modes of the experimental and analytical models. Due to the high degree of correlation the first three vertical modes were presented to a high degree of confidence as to their accuracy.
Long-term monitoring of a structure refers to the continual observation, by tracking of the structural response, at key locations due to ambient vibration and loading. Long term monitoring of large civil structures serves a wide variety of purposes and will assist in accomplishing the goals of the LTBP by providing scientific quality data of the structure under everyday conditions over a relatively long time period. Long-term testing allows researchers, engineers, and owners to track the health, or state, of a structure as it ages and to track the degradation processes occurring in and throughout the structure. It allows key factors leading to structure and component deterioration to be located and monitored over the life of the structure. It also allows the effects of cyclic loading due to diurnal and seasonal effects, as well as, high and low traffic volumes over a long time period to be monitored. Many researchers have shown that long-term monitoring of bridges can yield high quality quantitative data regarding the overall health and condition of the structure (Shoukey, Riad, and William, 2009; Zalt et. al., 2007; Wang, 2004; Cardini and Dewolf, 2009).

It was determined by the author in conjunction with the USU research team that the strains (stresses), rotations, dynamic response, and temperature should be monitored at key points along the structure. The key locations were determined based on the results of the dynamic and live load testing of the structure performed previously by USU LTBP researchers. The instrumentation layout drawings are included herein as Figures 35 and
Figure 35. Long-term instrumentation layout plan.

36 below. As seen in the figure instrument groups were placed at 0L, 0.3L, 0.6L, 1L, 1.4L, 1.7L, and 2L as measured from the northern abutment and where L is equal to half the length of the structure or 129 feet. Instruments were installed on the underside of the bridge as well as inside the cells as seen on the cross-section shown in Figure 36.

The Long-term sensors used in this project were of two sampling rates: dynamic (fast) and static (slow). Dynamic samplings rates are those intended to make many measurements per second, while static are intended to make a measurement at most once per several seconds. Dynamic instruments include the foil strain gages, velocity transducers and tilt meters. Static instruments include the vibrating wire strain gauge, thermocouples, and tilt meters. The two types of instruments, or sampling rates are designed to obtain two different types of data regarding the state, or health of the structure.
Figure 36. Cross-section of sensor of long-term instrument location.
The static measurements provide data that can be compared directly year to year
to track the aging process of the structure; while the other type (dynamic) can be
compared on a relative bases and used to track the short-term changes caused by vehicles
and ambient loading. The dynamic data can also be used to identify damage caused by
misuse of the bridge from the intended design, such as overloading. Consideration was
given to the nature of the testing in selecting a data acquisition system. The system was
required to accept both dynamic and static measurements simultaneously

A Campbell Scientific CR5000 data acquisition system was selected to collect,
record, and monitor the structural response. A photograph of the CR5000 data logger can
be seen in Figure 37. The CR5000 is able to run multiple sub-scans within the primary
scan of the main program, thus it is able to accommodate the dynamic and static scan
requirements of the system.

The basic CR5000 program was generated in “shortcut” and then modified in
program generator to obtain the final version which will be used in data collection. Both
Shortcut and Program Generator are programming software packages provided by
Campbell Scientific.

Figure 37. CR5000 data acquisition logger.
The final version of the long term monitoring program will be adapted from the Utah Pilot bridge code of which the present author and Steven Petroff, coordinator for the Utah Pilot bridge, developed with the help of Campbell Scientific group members.

**Foil Strain Gage**

A Hitec full bridge foil strain gage was selected to monitor the dynamic strains due to traffic and other ambient loading. Figure 38 shows an example of the foil strain gage used. The strain is calculated by observing the fluctuation of resistance across wire bridge circuit. The fluctuation in resistance occurs as the sensor elongates and shortens. This change in resistance is directly correlated to the elongation and shortening of the resistor wires. The strain is calculated from the change in resistance across the wire bridge using a calibration constant.

The raw data is given in micro-strain. This micro-strain can be converted to a strain and if the Moduls of Elasticity of the medium is known the stress can be calculated from hookes law ($\sigma=\varepsilon E$). The foil strain gauges provide information regarding the bridge response to dynamic excitation scenarios.

The FS gages are sampled at a dynamic sampling rate. The data will be recorded at an, as yet to be determined threshold trigger level based on event size. The FS gage is not ideal for long-term monitoring as it has a tendency to “drift” with time. This will require periodic “zeroing” of the sensor and eventual replacement of the sensor to maintain an acceptable level of data quality.
Vibrating-Wire Strain Gage

A vibrating-wire gage functions on the principle of string theory. A thin steel wire is stretched inside a steel tube to a known tension and fastened between to mounting blocks. The mounting blocks are attached to the surface of the object being monitored. As the object deforms the vibrating wire will deform in a like manner, and the tension in the steel wire will change. The fundamental or resonant frequency of the wire can be calculated from Equation 11.

\[
f = \frac{1}{2L_w} \sqrt{\frac{F}{m}}
\]  

(11)

where 

- \( f \) = Resonant frequency
- \( F \) = Tension in wire
- \( L_w \) = Length of Wire
The tension in the wire can be related to the strain by Equation 12

\[ F = \varepsilon_w E a \] (12)

where \( F \) = Tension in wire

\( E \) = Modulus of elasticity of steel \((30*10^6 \text{ ksi})\)

\( \varepsilon_w \) = Strain in the wire

\( a \) = Cross sectional area of the wire

By substituting Equation 12 into Equation 11 a relationship can be found between the tension in the wire and the strain in the wire as seen in Equation 13.

\[ \frac{(2L_w f)^2}{Ea} = \varepsilon_w \] (13)

Thus as resonant frequency of the vibrating wire is found by plucking the wire with an electromagnetic coil the tension and in turn strain in the wire and in turn the strain on the surface of the object can be obtained. The Geokon 4000 strain gage has been selected to provide the static long-term strain measurement for this project. A sample figure of the VW 4000 is provided in Figure 39 (Geokon, 2010a).

Figure 39. Geokon 4000 vibrating wire static measuring strain gage.
Velocity Transducer

A Mark Products Shallow Surface L-4 Seismometer (velocity transducer) will be used to capture the dynamic motions of the structure due to ambient vibrations. The velocity transducers are comprised of, in simplified terms, a magnet and a coil. As the sensor vibrates the interior magnet travels through the coil resulting in a flow of current. A calibration factor is used to correlate the change in voltage across the coil to a velocity (in/s) at which the structure is vibrating. The data acquisition system records the velocity at which the structure is vibrating. Figure 40 portrays an example photograph of a vertical Marks Product L-4 Seismometer.

Tilt Meter

The Geokon MemsTiltmeter 6160 is designed to capture short-term changes in tilt such as the passage of a large truck, as well as the long-term changes in tilt caused by

Figure 40. Marks Product L-4 shallow surface seismometer.
movement and settling of the structure. The micro-electrical-mechanical sensors (MEMS) are located inside the sealed Geokon tiltmeter. This sensor is designed to measure the inclination of the gage. Figure 41 displays a Geokon tiltmeter (Geokon, 2010b).

Thermo Couples

Type T thermocouple wire will be used to record temperatures along the cross-section of the structure. Type T thermocouples consist of a copper and nickel wire. The dissimilar metals create a small voltage when cooled or heated. The voltage can be converted to obtain the temperature.

Figure 41. Geokon 6160 tiltmeter.
Traffic Camera

An Axis traffic camera capable of low-resolution still-frame shots was used to understand traffic flow and in understanding cause of significant events and in data anomalies. It is proposed that strain threshold be used to trigger the traffic camera operation; the threshold limit is yet to be determined.

The use of still frame and short video of traffic will assist in bridge response analysis. A system must be established for collecting, saving and retrieving the data. A hard drive with sufficient capacity to allow data retrieval prior to system overwrite is critical. Understanding the traffic causing the events is essential in analyzing bridge response. As a weigh-in-motion sensor is extremely expensive to initially install and maintain it is not feasible to install at every bridge location. The traffic camera is the primary method of understanding the relative size and types of load crossing the structure.

A WIM is located several miles from the structure, which can be utilized to obtain a characterization of the traffic loading on the bridge.

The proposed location of the camera traffic tower can be seen in Figure 42. The final location of the tower is dependent upon approval from Caltrans district 3 encroachment permit office. The traffic tower will be of sufficient height to allow an uninterrupted view of the bridge deck and also protect against vandalism. It will also be equipped with an anti-climbing apparatus on the bottom 10 foot section.
Long-Term Monitoring System Protection and Preservation

Extreme care must be taken to protect and preserve the long-term system to ensure data quality and reliability. The sensors, instruments and cables must be guarded against wear and damage from environmental factors and vandalism. Each sensor was placed inside an 1/8 in. thick water tight steel enclosure, which had previously had the back panel section cut-out and removed to allow the sensor to be installed directly to the bridge surface. The sensors were mounted inside the steel boxes, but directly to the concrete surface, with conduit being attached to the structure from the box sensor to the main instrumentation box located on the central pier. Thus the sensor and cable is completely protected from the elements and vandals. An example of an exterior enclosure and conduit running along the exterior of the bridge and the main installation box located on the pier can be seen in Figure 43 with a tighter shot photograph of the central 12“X12”X6” FS gage enclosure being shown in Figure 44. The main installation box will house the CR5000 data logger and all other equipment used in storing and

Figure 42. Proposed tower location on west side of southbound lanes.
transferring the data. The main box will protect all the equipment from the elements and also from vandalism.

The sensors will be replaced as needed based on observation and analysis of the data. Sufficient redundancy exists in the system to verify proper functioning of the sensors.

Siemens America will be responsible of the storage of the raw data obtained during long-term monitoring. The analyzed data will also be sent to them for long-term storage. LTBP researchers will have access to both raw and analyzed data through coordination with the above-mentioned company. A cell phone modem will be available

Figure 43. A) Conduit installed on south span; B) main installation Box on central pier.
on site to download and transmit data at regular intervals. USU researchers will analyze the data as sufficient data is collected and becomes available.

Long-Term Sensor Field Installation

The USU LTBP research team carried out the installation of the long-term bridge monitoring equipment. An encroachment permit to permanently install instrumentation on a Caltrans structure was submitted and conditional permission was granted. Documentation was provided which outlined the location and placement of the sensors on the structure. A request was also submitted to install a 30 foot tower, 35 feet directly east and 40 feet directly south of southbound traffic lane. This request was denied due to special authorization procedures, which are required when placing a permanent object on the federal right of way. Per this unforeseen complication the installation process will not discuss the installation of the Traffic Camera or Tower in this document. A copy of
the encroachment permit for long-term sensor installation of everything except for the
traffic camera and tower is included as Appendix D.

The installation process began with the installation of the protective system,
which includes the PVC conduit and steel enclosures. The steel conduit straps and
closure boxes were installed with 2-in. concrete anchors. The bolts were installed by
drilling a ¼-in. pilot hole approximately 3-in. deep into the concrete and then the bolt was
hammered into the hole and a nut was tightened until snug with the contacting surface.

Upon completion of the conduit and box installation the cables were pulled
through the conduit from the sensor location to the main instrumentation box. The cable
was labeled prior to being pulled to indentify sensor location on the bridge and in the
instrumentation box. Cables were pulled in two groups; one group from the north span,
and one group from the south span. Figure 40 shows the pulled cables in the main box
with the separate groups being from the north and south spans.

The installation of the instruments followed the pulling of the cable. The Geokon
instruments, which included four vibrating wire strain gages and three tilt-meters,
contained detailed installation instructions in the manual provided with the sensor. These
instructions were followed during installation. The strain gage was installed on the
exterior underside of the box girder by drilling two ½-in. diameter holes 1 ½-in. into the
concrete. A rebar dowel was then attached to each side of the rod of the sensor and was
set using a standard two-part quick dry concrete epoxy. The tilt meter was installed by
drilling a ½-in. hole into the concrete pier 1-in. in depth. A concrete bolt set anchor was
the driven into the hole. The tilt meter was then attached using a common 3/8-in. bolt.

Readers are encouraged to see “Instruction manual - model 4000 - Vibrating
Wire Strain Gage (revision U)” and”Instruction manual-6160- MEMS Tilt-Meter (revision V) of the Geokon manuals for further information on the installation procedure.

Twelve Hi-tech FS gages were installed on the underside of the exterior concrete surface of the box-girder where the maximum strain was found during live load testing. Four additional FS gages were installed on the interior cell girder 6-in. below the deck and girder interface. The distributor recommends using M-bond A 10 epoxy for concrete installation. The surface was prepared for application of the sensor by grinding and
sanding the surface to ensure a level smooth surface. The surface of both the concrete and gage were then cleansed with a degreasing solution. The gages and concrete surface were then cleansed with an acidic solution and neutralized using a base solution. A thin coat of M-Bond-10 epoxy was applied to the exterior underside of the gage and the gages applied to the concrete surface. The recommended cure time for the M bond is 6 hours at 5-15 psi. This cure time was accomplished using a strain gage installation kit developed by USU researchers. The strain installation kit consists of a piece of steel bar stock cut to the dimensions of the gage, and lined with a thin piece of foam of the same dimension. A clear piece a packing tap was used to wrap both pieces forming one unit. A 7/8-in. threaded steel rod and nut and a 3/8-in. wood plank 12-in. long. The sensors was attached in the center of the prepared surface longitudinally in line with the bridge centerline on the concrete under-surface and held in place by installers. The foam side of the bar stock was placed over the sensor, the nut/rod was placed on the steel side of the bar stock. The wood plank was placed over the ledges on the steel protective enclosure and directly below that sensor and rod. The rod was then unscrewed from the bolt until contact was made with the plank below. The rod was extended until sufficient pressure was placed on the sensor. The strain installation kit remained attached to the sensor until the epoxy was completely cured. The following Figure 46 illustrates the strain gage kit being used to install a FS gage.

USU researchers also developed and manufactured an installation kit for the Mark Products L4 seismometers. The installation kit consisted of two aluminum plates and four threaded rods with accompanying washers and nuts. The upper plate was installed
directly to the concrete using the anchor bolts as previously mentioned. The upper plate had four threaded holes, one in each corner, into which a threaded rod was inserted as to be flush with the upper surface. Permanent loc-tite was used to ensure the rods would not loosen with time. The sensor was then place right side up with the top surface flat against the upper plate and in between the four threaded rods. The bottom plate was then attached as to be flush with the bottom of the sensor, it had also had four over-sized hole drilled in it at the exact location of the upper plate holes as to align with one another. The over sized holes allowed for the sensor to be adjusted and placed into a vertical position. Figure 47 shows an example of how the sensor would be installed using the USU manufactured installation kit.

Installation of the of the thermo couples was done by soldering the nickel and copper ends together and placing them in the steel enclosure near the sensors.
The CR5000 data acquisition system was installed in main enclosure. A contractor was hired by USU to provide AC power inside the enclosure. This power will be used to power all data acquisition systems and accessories.

The USU LTBP research team installed the long-term monitoring instrumentation to the Lambert Rd Bridge near Elk Grove California. All manufacturer’s guidelines were followed to ensure proper functioning of the sensors and reliable data.

In cases where no orientation was provided or available researchers developed installation procedures, which would ensure proper functioning of the sensors and longevity in use. The tower and camera will be installed at a future date, as the traffic camera is an essential piece of the monitoring system.

Figure 47. Marks Product L4 seismometer and installation kit.
CONCLUSION AND RECOMMENDATIONS

The LTBP program was launched by the FHWA to collect scientific quality data regarding a wide variety of bridge types currently in use in the national bridge network. Dynamic modal analysis and long-term monitoring of the structures will help meet the goals of this project by providing a means of tracking deterioration. The dynamic modal analysis and modeling of the Lambert Road Bridge has provided the global “insitu” conditions of the bridge for future comparisons and evaluations. The magnitude of the damage in the structure can be directly correlated to changes in global modal properties. The modal analysis of the structure revealed the first five vertical modes. The locations of resonance and damping are provided in Table 13 and in Appendix C. These locations should be compared with future tests to evaluate softening or weakening of the structure.

Table 13. Experimental Results for Dynamic Testing of the Lambert Road Bridge

<table>
<thead>
<tr>
<th>TYPE</th>
<th>DAY/TEST</th>
<th>Mode1</th>
<th>Mode 3</th>
<th>Mode 4</th>
<th>Mode 5</th>
<th>Mode6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient TRF</td>
<td>TEST 4</td>
<td>3.08</td>
<td>4.10</td>
<td>8.03</td>
<td>9.83</td>
<td>NA</td>
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<td>Ambient TRF</td>
<td>TEST 5</td>
<td>3.11</td>
<td>4.05</td>
<td>7.99</td>
<td>10.24</td>
<td>14.21</td>
</tr>
<tr>
<td>Ambient TRF</td>
<td>TEST 6</td>
<td>3.13</td>
<td>4.14</td>
<td>8.01</td>
<td>11.57</td>
<td>14.29</td>
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<tr>
<td>AVG</td>
<td></td>
<td>3.11</td>
<td>4.10</td>
<td>8.01</td>
<td>10.55</td>
<td>14.25</td>
</tr>
<tr>
<td>TRF No Traffic</td>
<td>TEST 7</td>
<td>3.11</td>
<td>4.07</td>
<td>7.99</td>
<td>10.10</td>
<td>14.03</td>
</tr>
<tr>
<td>TRF No Traffic</td>
<td>TEST 8</td>
<td>3.11</td>
<td>4.07</td>
<td>8.01</td>
<td>10.18</td>
<td>14.29</td>
</tr>
<tr>
<td>Table 13. Continued</td>
<td>TEST 9</td>
<td>3.08</td>
<td>4.05</td>
<td>8.10</td>
<td>10.02</td>
<td>14.25</td>
</tr>
<tr>
<td>TRF No Traffic</td>
<td>TEST 10</td>
<td>3.23</td>
<td>4.20</td>
<td>8.10</td>
<td>10.20</td>
<td>14.32</td>
</tr>
</tbody>
</table>
A very high noise-to-signal ratio was observed during dynamic testing. This ratio was due to live traffic conditions on the bridge during testing. Data quality and results could be improved by improving the noise to signal quality. This can be accomplished by removing the noise or by increasing the signal. It is not feasible to close traffic on a major thoroughfare into Sacramento and therefore reducing the noise level will be very difficult. However, it may be feasible to increase the signal by increasing the level of shaking. Two shakers could and should be used in future tests, or some form a shaking which is able to provide more input into the structure. Filtering of the data is also very important to reduce the amount of exterior noise. The tighter filter was observed to provide a better to noise to signal ration during testing. It would also be advisable in

### Table 13. Continued

<table>
<thead>
<tr>
<th></th>
<th>TEST 11</th>
<th>TEST 12</th>
<th>TEST 13</th>
<th>TEST 14</th>
<th>AVG</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TRF No Traffic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>7.93</td>
<td>10.05</td>
<td>14.10</td>
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<td>4.07</td>
<td>7.99</td>
<td>10.07</td>
<td>13.88</td>
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<td>7.95</td>
<td>10.03</td>
<td>NA</td>
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<tr>
<td>TEST 14</td>
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<td>8.06</td>
<td>9.98</td>
<td>13.91</td>
</tr>
<tr>
<td><strong>AVG</strong></td>
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<td>8.02</td>
<td>10.08</td>
<td>14.11</td>
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<td><strong>SSN Test</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DAY 1</td>
<td>3.22</td>
<td>4.10</td>
<td>8.11</td>
<td>10.43</td>
<td>14.01</td>
</tr>
<tr>
<td>DAY 2</td>
<td>3.07</td>
<td>4.18</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>DAY 3</td>
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<td>4.21</td>
<td>7.99</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td><strong>AVG</strong></td>
<td>3.12</td>
<td>4.17</td>
<td>8.05</td>
<td>10.43</td>
<td>14.01</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3.11</strong></td>
<td><strong>4.12</strong></td>
<td><strong>8.02</strong></td>
<td><strong>10.35</strong></td>
<td><strong>14.12</strong></td>
</tr>
</tbody>
</table>
future tests to obtain data regarding the transverse and longitudinal modes, which would serve to provide a great understanding of the dynamic response of the structure.

An analytical model of the bridge was created using SAP 2000. The model was constructed of eight-node solid elements. A modal analysis of the model was conducted in SAP with results being compared to the experimental data, as seen in Table 9, which is presented here again as Table 14.

The model was validated by means of a Modal Assurance Criterion (MAC). Mode shapes from both models were compared and the model was adjusted until satisfying results were obtained. The model was able to correctly predict the first 3 vertical modes of the bridge. The first vertical mode of the model was found to correlate very well with the first experimental mode with a MAC value of .98 and a percent difference in frequency of 6%. The second vertical mode also correlated well with the second experimental mode with a MAC value of .9 and a percent difference in frequency of 8%. The third experimental mode correlates well with the fourth analytical mode.

<table>
<thead>
<tr>
<th>Experimental Frequency</th>
<th>Theoretical Frequency</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.11 (1)</td>
<td>3.30 (1)</td>
<td>-6.2604502</td>
</tr>
<tr>
<td>4.12 (2)</td>
<td>4.44 (2)</td>
<td>-7.9296117</td>
</tr>
<tr>
<td>NA</td>
<td>7.87 (3)</td>
<td></td>
</tr>
<tr>
<td>8.02 (3)</td>
<td>8.24 (4)</td>
<td>-2.8266833</td>
</tr>
<tr>
<td>10.35 (4)</td>
<td>10.4 (5)</td>
<td>-1.3236715</td>
</tr>
<tr>
<td>NA</td>
<td>12.36 (6)</td>
<td></td>
</tr>
<tr>
<td>NA</td>
<td>12.54 (7)</td>
<td></td>
</tr>
<tr>
<td>14.12 (5)</td>
<td>14.70 (8)</td>
<td>-4.1572238</td>
</tr>
</tbody>
</table>
The MAC value obtained in this correlation was .61 and the frequencies were within 3% of one another. It should be noted that the SAP model was correlated to both the Dynamic Modal properties and Live-Load response data. Therefore a modification in the model to improve the dynamic response often had adverse effects on the live-load response and vice versa. One observation worth noting is that the experimental frequencies are consistently lower than the FEM model frequencies. This could be remedied in part, with no adverse effect to the live load data, by increasing the density of the concrete in the model. The basic equation used in calculating the frequency indicated in Equation 14.

\[
F = \frac{K}{\sqrt{M \times \frac{1}{2\pi}}} 
\]  

(14)

where:  
\( F \) = Frequency  
\( K \) = Stiffness of the structure  
\( M \) = Mass  

Increasing the density of the concrete effectively increases the mass of the bridge. According to Equation 14 this would result in a decrease in the frequency response of the model, which would have no effect on the live-load response of the structure as the live load is not dependent upon the mass. This would decrease the percent difference between the model and the experimental data allowing for better correlation of the models.

Working with SAP it was observed that a solid element model is extremely cumbersome and an extremely large amount of processing capacity was required. A
more simple modeling approach may be advisable in cases where processing capacity is not available.

The long-term monitoring of the structure was designed to capture response at key locations during ambient loading cycles. The key locations were determined based on dynamic, live-load and modeling of the bridge. Strains, stresses, rotations and temperature will be monitored at these key locations. Velocity transducers were also included in the long-term monitoring system to provide a global means of tracking the deterioration process through ambient modal analysis. Extreme care was taken during installation to follow manufacturer recommendations and in maintaining high standards of workmanship to maintain data quality. USU researchers created several installation kits during the installation process. These kits proved to make installation extremely quick and painless. However, continued observation of the sensors used in conjunction with these installation kits is advisable as no previous case studies are available to check the durability of the methods. Extreme care was taken to provide ample protection from natural and other modes of damage to the system. Sensors were completely encapsulated in steel enclosures with cable being transported inside PVC conduit.

Care must also be taken to begin encroachment submittals with plenty of lead-time as it was found to take a considerable amount of time and preparation on the part of the researchers and agencies involved.
REFERENCES


APPENDICES
Appendix A
Dynamic Testing Plan and Drawings
Lambert Road Bridge
Dynamic Testing Plan

Timothy Paul Thurgood
11/7/2009
Dynamic Testing Plan
Lambert Road Bridge

Dynamic testing of the Lambert Road Bridge on Interstate 5, 30 miles south of Sacramento, California will be implemented using the following equipment:

- 3 vertical L-4 Velocity Transducers (VT)
- 3 horizontal L-4 Velocity Transducers
- 1 Electro-Magnetic Shaker
- 1 Quattro 4 channel-Data Acquisition (DAQ) System w/ Signal Calc software (by Data Physics)
- Cable of sufficient length to connect each sensor to the DAQ system

The dynamic testing will consist of three phases: 1. Broad Frequency Sweep, 2. Narrow Frequency Sweep, and Mode Shapes. A brief discussion of the stepped sine analysis procedure will be discussed prior to outlining the three phases.

1.0 Analysis Procedure

A stepped sine analysis will be used for the dynamic testing of the Lambert Bridge. Stepped sine is a form of testing in which the DAQ is programmed to provide a signal to the shaker that will step through a user-specified range of frequencies in a given length of time. The amplitude of the response (in/s) versus the current frequency is plotted at each time/frequency step. This plot is commonly referred to as a Frequency Response Function (FRF). Coherence Function and FRF with Amplitude in degrees will also be used to locate resonant frequencies and mode shapes. Figure 1 displays a completed stepped sine analysis for a three degree of freedom (DOF) system.
As seen in the middle graph of Figure A1 the three peaks correspond to the three resonant frequencies for the three DOF system. The phase shift in the bottom graph from positive 180° to negative 180° or vice-versa also indicates that the system has passed through a resonant frequency.

Stepped sine is very useful in environments where a large amount of noise will be present. Noise, here in, refers to any frequency not corresponding to the frequency at which that shaker is vibrating. The Lambert Road Bridge, at the time of dynamic testing, will be open to truck and car usage. It is assumed that the traffic present, as well as other sources, on the bridge during testing will introduce a large amount of noise into the bridge system. Stepped sine analysis has many features which make this method conducive to noisy environments. The user has control of the range of data received from the sensors. For example, if the shaker is vibrating at 10 Hz the user can specify that only oscillations in the range of 9.5 Hz-10.5 Hz be accepted in the data. This filtering of data along with averaging is very useful in reducing noise content in the measurements.

2.0 Phases

Phase 1: Broad Frequency Sweep
Three VTs will be placed on the deck in three locations, as shown in Figure A2 and with distances in Table A1, in order to capture the vibrations introduced by the Electro-Magnetic shaker. Dynamic A stepped sine analysis covering a broad range of frequencies from 2.5 Hz to 20 Hz will be applied to the bridge. The frequency will be increased in increments of approximately 0.3 Hz. A filter of 0.2 Hz will be applied for noise reduction. It is anticipated that 100 data points will be taken in this range. This number may be adjusted in the field if under-sampling is seen. Researchers may also repeat this process with sensors in a new location depending on the data from the first sampling. The same process and setup will be applied to the other span of the bridge. The same process will also be used during horizontal shaking.

Figure A2. Initial accelerometer setup.
Phase 2: Narrow Frequency sweep
The information obtained from phase 1 will be analyzed in the field and possible resonant frequencies will located. A narrow stepped analysis from 1hz-2hz on either side of the suspected resonant frequency will be used to further evaluate the exact frequency of resonance. A total of 50 points will be taken in the 2hz span allowing the resonant frequency to be determined to within approximately .04hz. Due to time constraints and the difficulty in exciting higher resonant frequencies only the first 8-10 total, including vertical and horizontal, resonant frequencies will be located.

Phase 3: Mode Shapes
For the final phase of the Dynamic testing a Zoomed Analysis (Fct) procedure will be implemented. An Fct allows the user to specify a central frequency and a frequency window in which data will be collected. The resonant frequency of each given mode will be used as the central frequency. A window of 2hz above resonance and 2hz below, 4hz total, will be used to focus the entire bandwidth of the DAQ system on the area surrounding the resonance frequencies. This procedure like the stepped sine allows much of the noise to excluded excluding much.

A single frequency sine wave will be generated at each of the individual resonant frequencies using the electro-magnetic shaker. The VTs will be moved to various locations around the bridge and the amplitude in in/s will be noted at each location. This amplitude will be converted into a displacement during post-processing in order to obtain displacements. The displacements will be used to establish the mode shapes of the bridge.

Table A1. Accelerometer distances as shown in Figure 2

<table>
<thead>
<tr>
<th>Accelerometer Line</th>
<th>Distance From End of Bridge (in)</th>
<th>Distance From West side Barrier (in)</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>B</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>E</td>
<td>10</td>
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</tr>
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<td>F</td>
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<td>G</td>
<td>14</td>
<td>0</td>
</tr>
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<td>H</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>I</td>
<td>18</td>
<td>0</td>
</tr>
<tr>
<td>J</td>
<td>20</td>
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<td>K</td>
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<td>0</td>
</tr>
<tr>
<td>L</td>
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<td>0</td>
</tr>
<tr>
<td>M</td>
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</tr>
<tr>
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</tr>
<tr>
<td>O</td>
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<td>0</td>
</tr>
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<td>P</td>
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<td>0</td>
</tr>
<tr>
<td>Q</td>
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<td>0</td>
</tr>
<tr>
<td>R</td>
<td>36</td>
<td>0</td>
</tr>
<tr>
<td>S</td>
<td>38</td>
<td>0</td>
</tr>
<tr>
<td>T</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>U</td>
<td>42</td>
<td>0</td>
</tr>
</tbody>
</table>
Appendix B
Dynamic And Mac Analysis Programs
Figure B-1: Excel spread sheet used to calculate phase difference (Test Day 1).
Figure B-2 Excel spreadsheet used to calculate the phase difference (Test day 2-3).
Damping Algorithm.m

clear all

%% Load data from mfile and plot
load('DY2_1') % exported matlab file from data physics
Nsensors=8; % input the number of sensors used here
avg=1;
for i = 2:Nsensors
    s=('H1_' int2str(i));
    TRF=eval(s);
    eval(['storeTRF int2str(i) ' =TRF;']);
    z=('C1_' int2str(i));
    COH=eval(z);
    eval(['storeCOH int2str(i) ' =COH;']);
end

%% plot magnitude
figure
% TRF(:,2)=filter(ones(1,avg)/avg,1,TRF(:,2));
plot(TRF(:,1),abs(TRF(:,2)));xlabel('Hz');ylabel('in/s/V');title ('Magnitude s')

%% Find Local Maximums/ Damping Ratio
% from graph

dfstep=TRF(2,1)-TRF(1,1); % determine delta frequency step
q=num2str(TRF(2,1)-TRF(1,1));
df=('frequency step = ' q);
User_Request=('Please click bracketing pairs for freq_range (press enter when done): ')
[freq,mag]=ginput(20); % bracketed pairs from plot stored in freq and mag

for h=1:length(freq)
    X(h)=round((freq(h)-TRF(1,1))/dfstep)+1; % find the point corresponding to the bracketed pairs
end

count=0;
for c=1:2:length(freq)
    count=count+1;
    [peak(count,i-1),location]=max(abs(TRF(X(c):X(c+1),2))); % find the peak between selected pairs
    loc(count,i-1)=location+X(c)-1; % find the location of the peak
    halfpamplitude(count,i-1)=1/sqrt(2)*peak(count,i-1); % half power amplitude based on peak
    % Linear interpolation variables
    xlow=(TRF(X(c):loc(count,i-1),1));
    xhigh=(TRF(loc(count,i-1):X(c+1),1));
    ylow=abs(TRF(X(c):loc(count,i-1),2));
    yhigh=abs(TRF(loc(count,i-1):X(c+1),2));

    lina(count,i-1)=interp1(ylow,xlow,halfpamplitude(count,i-1)); % from left to right
    linb(count,i-1)=interp1(yhigh,xhigh,halfpamplitude(count,i-1)); % from right to left

    zeta(count,i-1)=(linb(count,i-1)-linb(count,i-1))/2/TRF(loc(count,i-1))*100; % damping ratio as percentage
    hold on;
    plot(lina(count,i-1),halfpamplitude(count,i-1), 'x')
    plot(linb(count,i-1),halfpamplitude(count,i-1), 'x')
    fill([lina(count,i-1),lina(count,i-1),linb(count,i-1),linb(count,i-1)], [0,halfpamplitude(count,i-1),halfpamplitude(count,i-1),0], 'g')
    hold off
end
end

% % % Zeta average for each mode by sensor

zetavg=sum(zeta,2)/(Nsensors-1) % finds the average zeta for each mode of this test

%%% plot all sensors on the same graph
figure
for i =2:Nsensors
    if i==2
        subplot(3,1,1)
        hold on
        tempx=eval(['storeTRF int2str(i) (:, int2str(1) )']);
        tempy=eval(['storeTRF int2str(i) (:, int2str(2) )']);
        tempy=filter(ones(1,avg)/avg,1,tempy);
        plot(tempx,abs(tempy),'b-');xlabel('Hz');ylabel('in/s/V');title ('Magnitude')
        hold off
        subplot(3,1,2)
        hold on
        tempx=eval(['storeTRF int2str(i) (:, int2str(1) )']);
        tempy=eval(['storeTRF int2str(i) (:, int2str(2) )']);
        tempy=filter(ones(1,avg)/avg,1,tempy);
        plot(tempx,unwrap(angle(tempy))*180/pi,'b-');xlabel('Hz');ylabel('DEG');title ('Unwrapped Phase')
        hold off
        subplot(3,1,3)
        hold on
        tempx=eval(['storeCOH int2str(i) (:, int2str(1) )']);
        tempy=eval(['storeCOH int2str(i) (:, int2str(2) )']);
        tempy=filter(ones(1,avg)/avg,1,tempy);
        plot(tempx,tempy,'b-');xlabel('Hz');ylabel('REAL');title ('Coherence Function')
        hold off
    elseif i==3
        subplot(3,1,1)
        hold on
        tempx=eval(['storeTRF int2str(i) (:, int2str(1) )']);
        tempy=eval(['storeTRF int2str(i) (:, int2str(2) )']);
        plot(tempx,abs(tempy),'g-');hold off
        subplot(3,1,2)
        hold on
        tempx=eval(['storeTRF int2str(i) (:, int2str(1) )']);
        tempy=eval(['storeTRF int2str(i) (:, int2str(2) )']);
        plot(tempx,unwrap(angle(tempy))*180/pi,'g-');hold off
        subplot(3,1,3)
        hold on
        tempx=eval(['storeCOH int2str(i) (:, int2str(1) )']);
        tempy=filter(ones(1,avg)/avg,1,tempy);
        plot(tempx,abs(tempy),'g-');hold off
        subplot(3,1,2)
        hold on
        tempx=eval(['storeTRF int2str(i) (:, int2str(1) )']);
        tempy=eval(['storeTRF int2str(i) (:, int2str(2) )']);
        plot(tempx,unwrap(angle(tempy))*180/pi,'g-');hold off
        subplot(3,1,3)
        hold on
        tempx=eval(['storeCOH int2str(i) (:, int2str(1) )']);
        tempy=filter(ones(1,avg)/avg,1,tempy);
        plot(tempx,abs(tempy),'g-');hold off
        subplot(3,1,2)
        hold on
        tempx=eval(['storeTRF int2str(i) (:, int2str(1) )']);
        tempy=eval(['storeTRF int2str(i) (:, int2str(2) )']);
        plot(tempx,unwrap(angle(tempy))*180/pi,'g-');hold off
        subplot(3,1,3)
        hold on
        tempx=eval(['storeCOH int2str(i) (:, int2str(1) )']);
        tempy=filter(ones(1,avg)/avg,1,tempy);
        plot(tempx,abs(tempy),'g-');hold off
        subplot(3,1,2)
        hold on
        tempx=eval(['storeTRF int2str(i) (:, int2str(1) )']);
        tempy=eval(['storeTRF int2str(i) (:, int2str(2) )']);
        plot(tempx,unwrap(angle(tempy))*180/pi,'g-');hold off
        subplot(3,1,3)
        hold on
        tempx=eval(['storeCOH int2str(i) (:, int2str(1) )']);
        tempy=filter(ones(1,avg)/avg,1,tempy);
        plot(tempx,abs(tempy),'g-');hold off
        subplot(3,1,2)
        hold on
        tempx=eval(['storeTRF int2str(i) (:, int2str(1) )']);
        tempy=eval(['storeTRF int2str(i) (:, int2str(2) )']);
        plot(tempx,unwrap(angle(tempy))*180/pi,'g-');hold off
        subplot(3,1,3)
        hold on
        tempx=eval(['storeCOH int2str(i) (:, int2str(1) )']);
        tempy=filter(ones(1,avg)/avg,1,tempy);
        plot(tempx,abs(tempy),'g-');hold off
    else
        % plot Coherence
        subplot(3,1,1)
        hold on
        tempx=eval(['storeTRF int2str(i) (:, int2str(1) )']);
        tempy=eval(['storeTRF int2str(i) (:, int2str(2) )']);
        plot(tempx,abs(tempy),'b-');xlabel('Hz');ylabel('REAL');title ('Coherence Function')
tempy = eval(['storeCOH int2str(i) '(:, ' int2str(2) ')']);
tempy = filter(ones(1, avg)/avg, 1, tempy);
plot(tempx, tempy, 'g-');
hold off
elseif i == 4
    subplot(3, 1, 1)
    hold on
    tempx = eval(['storeTRF int2str(i) '(:, ' int2str(1) ')']);
tempy = eval(['storeTRF int2str(i) '(:, ' int2str(2) ')']);
    tempy = filter(ones(1, avg)/avg, 1, tempy);
    plot(tempx, abs(tempy), 'r-');
    hold off
    % plot Unwrapped Phase
    subplot(3, 1, 2)
    hold on
    tempx = eval(['storeTRF int2str(i) '(:, ' int2str(1) ')']);
tempy = eval(['storeTRF int2str(i) '(:, ' int2str(2) ')']);
tempy = filter(ones(1, avg)/avg, 1, tempy);
    plot(tempx, unwrap(angle(tempy))*180/pi, 'r-');
    hold off
    % plot Coherence
    subplot(3, 1, 3); hold on
    tempx = eval(['storeCOH int2str(i) '(:, ' int2str(1) ')']);
tempy = eval(['storeCOH int2str(i) '(:, ' int2str(2) ')']);
tempy = filter(ones(1, avg)/avg, 1, tempy);
    plot(tempx, tempy, 'r-');
    hold off
end
if i == 5
    subplot(3, 1, 1)
    hold on
    tempx = eval(['storeTRF int2str(i) '(:, ' int2str(1) ')']);
tempy = eval(['storeTRF int2str(i) '(:, ' int2str(2) ')']);
    tempy = filter(ones(1, avg)/avg, 1, tempy);
    plot(tempx, abs(tempy), 'black');
    hold off
    % plot Unwrapped Phase
    subplot(3, 1, 2)
    hold on
    tempx = eval(['storeTRF int2str(i) '(:, ' int2str(1) ')']);
tempy = eval(['storeTRF int2str(i) '(:, ' int2str(2) ')']);
tempy = filter(ones(1, avg)/avg, 1, tempy);
    plot(tempx, unwrap(angle(tempy))*180/pi, 'black');
    hold off
    % plot Coherence
    subplot(3, 1, 3); hold on
    tempx = eval(['storeCOH int2str(i) '(:, ' int2str(1) ')']);
tempy = eval(['storeCOH int2str(i) '(:, ' int2str(2) ')']);
tempy = filter(ones(1, avg)/avg, 1, tempy);
    plot(tempx, tempy, 'black');
    hold off
end
if i==6
    subplot(3,1,1)
    hold on
    tempx=eval(['storeTRF int2str(i) '(:, int2str(1) ')']);
    tempy=eval(['storeTRF int2str(i) '(:, int2str(2) ')']);
    tempy=filter(ones(1,avg)/avg,1,tempy);
    plot(tempx,abs(tempy),'magenta');
    hold off
    subplot(3,1,2)
    hold on
    tempx=eval(['storeTRF int2str(i) '(:, int2str(1) ')']);
    tempy=eval(['storeTRF int2str(i) '(:, int2str(2) ')']);
    tempy=filter(ones(1,avg)/avg,1,tempy);
    plot(tempx,unwrap(angle(tempy))*180/pi,'magenta');
    hold off
    subplot(3,1,3)
    hold on
    tempx=eval(['storeCOH int2str(i) '(:, int2str(1) ')']);
    tempy=eval(['storeCOH int2str(i) '(:, int2str(2) ')']);
    tempy=filter(ones(1,avg)/avg,1,tempy);
    plot(tempx,tempy,'magenta');
    hold off
end
if i==7
    subplot(3,1,1)
    hold on
    tempx=eval(['storeTRF int2str(i) '(:, int2str(1) ')']);
    tempy=eval(['storeTRF int2str(i) '(:, int2str(2) ')']);
    plot(tempx,abs(tempy),'y');
    hold off
    subplot(3,1,2)
    hold on
    tempx=eval(['storeTRF int2str(i) '(:, int2str(1) ')']);
    tempy=eval(['storeTRF int2str(i) '(:, int2str(2) ')']);
    tempy=filter(ones(1,avg)/avg,1,tempy);
    plot(tempx,unwrap(angle(tempy))*180/pi,'y');
    hold off
    subplot(3,1,3)
    hold on
    tempx=eval(['storeCOH int2str(i) '(:, int2str(1) ')']);
    tempy=eval(['storeCOH int2str(i) '(:, int2str(2) ')']);
    tempy=filter(ones(1,avg)/avg,1,tempy);
    plot(tempx,tempy,'y');
    hold off
end
if i==8
    subplot(3,1,1)
    hold on
    tempx=eval(['storeTRF int2str(i) '(:, int2str(1) ')']);
    tempy=eval(['storeTRF int2str(i) '(:, int2str(2) ')']);
    plot(tempx,unwrap(angle(tempy))*180/pi,'y');
    hold off
    subplot(3,1,2)
    hold on
    tempx=eval(['storeCOH int2str(i) '(:, int2str(1) ')']);
    tempy=eval(['storeCOH int2str(i) '(:, int2str(2) ')']);
    tempy=filter(ones(1,avg)/avg,1,tempy);
    plot(tempx,tempy,'y');
    hold off
end
tempx=eval(['storeTRF int2str(i) '(:, int2str(1))']);
tempy=eval(['storeTRF int2str(i) '(:, int2str(2))']);

%   tempy=filter(ones(1,avg)/avg,1,tempy);

plot(tempx,abs(tempy),'cyan');legend('A', 'B', 'C', 'D', 'E', 'F', 'G')
hold off

%plot Unwrapped Phase    
subplot(3,1,2)
hold on

   tempx=eval(['storeTRF int2str(i) '(:, int2str(1))']);
tempy=eval(['storeTRF int2str(i) '(:, int2str(2))']);
tempy=filter(ones(1,avg)/avg,1,tempy);

plot(tempx,unwrap(angle(tempy))*180/pi,'cyan');legend('A', 'B', 'C', 'D', 'E', 'F', 'G')

%plot Coherence
subplot(3,1,3);hold on

   tempx=eval(['storeCOH int2str(i) '(:, int2str(1))']);
tempy=eval(['storeCOH int2str(i) '(:, int2str(2))']);
tempy=filter(ones(1,avg)/avg,1,tempy);

plot(tempx,tempy,'cyan');legend('A', 'B', 'C', 'D', 'E', 'F', 'G')
hold off

end
end
MAC Analysis script in MATLAB
MAC.m
% This script compares the mode shapes of the experimental data
% Collected with Data Physics against itself, and the theoretical data
% from the FEM against itself and also compares them against each other.

clear all
%A= Modes for experimental data
A=[-1 1 1 -1 1;
-1.09777481 1.506569772 0.960358443 0.929680287 -0.59035247274971;
-1.068077099 1.16503971 2.146446861 -0.598908621 1.8631061056863;
1.246051264 0.521353314 -0.036153640 0.007336018 1.22461936772979;
1.14243793 1.394312921 0.849499169 0.247782166 0.932722048581724;
-0.870321607 0.715324833 -0.235954446 0.014206957 1.30354494028618;
1.126543178 1.737827999 0.84291204 -0.612068837 0.917433239814474;
-1.158560975 1.483322373 -1.9961396 1.580090741 -0.915390752767998;
1.45998387 1.121822798 -0.473454809 0.04870109 1.651470909729;
1.39133934 1.05341658 0.469761036 -0.076390821 -0.287930362957099];

B=[1 1 1 1 1 1 1 1;
1.18743767 1.345453278 0.856856859 1.021271288 0.355038522 0.569676719 0.830065315 0.42802006266695;
1.212083065 1.341468413 3.054511556 3.359677339 0.112053438 0.505297841 3.167400956 1.82692132570152;
-1.307032996 0.992855795 5.387034798 -1.300426053 -1.802958874 0.866375098 -5.208966432 9.4566856734936;
1.203610347 0.759987246 -6.237728967 1.330394914 1.295040856 0.724057709 5.039930506 -3.54691260306794;
1.073937663 1.398472142 -2.896879697 -2.857022757 -0.807587917 -0.814208736 -0.378283176 1.45104371398834;
-1.420880376 1.276732118 6.128286375 -1.337249136 0.725276049 -0.359880662 -1.43533285 -1.11187617006194;
1.237376165 1.498249612 -2.952466281 -3.041823385 0.528879401 0.541580665 -3.185884983 1.71336268000604;
-1.499776042 1.290639646 6.125245672 -1.383217533 -0.346525456 0.205905143 -3.271986309 0.698514228974222;
-1.202907858 1.024419831 -4.927351994 1.366875951 1.704828332 -0.610108885 0.352824369 2.47122674848648];
% Modes from FEM

%% AutoMac compares the modes of the Experimental against themselves.
for i=1:(size(A,2))
    for j=1:(size(A,2))
        a=A(:,i);
        b=A(:,j);
        a1=(a'*b)^2;%(sum(A(:,i)*A(:,j)))^2
        b1=(a'*a)*(b'*b);%sum(A(:,i)'*A(:,i))*sum(A(:,j)'*A(:,j))
        amacexp(i,j)=a1/b1;
    end
end
amatexp
%
%% AutoMac compares the modes of the FEM against themselves.
for i=1:(size(B,2))

for j=1:(size(B,2))
    a=B(:,i);
    b=B(:,j);
    a1=(a'*b)^2;%(sum(A(:,i)'*A(:,j)))^2
    b1= (a'*a)*(b'*b);%sum(A(:,i)'*A(:,i))*sum(A(:,j)'*A(:,j))
    amacFEM(j,i)=a1/b1;
end
end
amacFEM

%% MAC compares the compares the modes of the experimental vs the
% modes of the FEM.
for i=1:min(size(A,2))
    for j=1:max(size(B,2))
        a=A(:,i);
        b=B(:,j);
        a1=(a'*b)^2;%(sum(A(:,i)'*A(:,j)))^2
        b1=(a'*a)*(b'*b);%sum(A(:,i)'*A(:,i))*sum(A(:,j)'*A(:,j))
        mac(j,i)=a1/b1;
    end
end
mac
Appendix C
Dynamic Test Results
Test DY1-1
Test Range 2.6-18 Hz with 175 points recorded between limits. Frequency step of .088hz. Two averages recorded per measurement. Fixed Band Filter of .3Hz. Set-up # 1 used. Test was interrupted at 7.2 Hz.

![Diagram of Test DY1-1](Image)

Figure C1 Test DY1_1.

**Table C1 DY1_1**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modal Frequency ($\omega$)</th>
<th>AVG Phase Transition ($\Phi$)</th>
<th>AVG Coherence</th>
<th>AVG Damping ($\xi$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>3.22</td>
<td>175.8</td>
<td>70.56%</td>
<td>2.16%</td>
</tr>
<tr>
<td>Mode 2</td>
<td>3.66</td>
<td>221.8</td>
<td>51.45%</td>
<td>0.74%</td>
</tr>
<tr>
<td>Mode 3</td>
<td>4.11</td>
<td>185.3</td>
<td>75.63%</td>
<td>2.28%</td>
</tr>
</tbody>
</table>
Test DY1-2
Test Range 7-18 Hz with 150 points recorded between limits. Frequency step of .073hz. Two averages recorded per measurement. Fixed Band Filter of .3Hz. Set-up # 2 used. Test was a continuation of DY1-1

![Graphs showing Magnitude, Unwrapped Phase, and Coherence Function](image)

Figure C2 DY1_2.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency ($\omega$)</th>
<th>AVG Phase Transition ($\Phi$)</th>
<th>AVG Coherence (%)</th>
<th>AVG Damping ($\xi$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 4</td>
<td>8.034</td>
<td>146.2</td>
<td>99.93%</td>
<td>3.38%</td>
</tr>
<tr>
<td>Mode 5</td>
<td>10.25</td>
<td>97.1</td>
<td>85.93%</td>
<td>0.60%</td>
</tr>
<tr>
<td>Mode 6</td>
<td>14.01</td>
<td>133.0</td>
<td>83.00%</td>
<td>0.31%</td>
</tr>
</tbody>
</table>
Test DY1-3
Test Range 2.9-9 Hz with 100 points recorded between limits. Frequency step of .041hz. Three averages recorded per measurement. Fixed Band Filter of .2Hz. Set-up # 2 used. Test was interrupted at 4.3 Hz.

Figure C3 DY1_3.

Table C3 DY1_3

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modal Frequency (ω)</th>
<th>AVG Phase Transition (Φ)</th>
<th>AVG Coherence</th>
<th>AVG Damping (ξ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>3.066</td>
<td>181.6</td>
<td>34.11%</td>
<td>1.606%</td>
</tr>
<tr>
<td>Mode 3</td>
<td>4.184</td>
<td>182.3</td>
<td>32.35%</td>
<td>1.046%</td>
</tr>
</tbody>
</table>
Test DY2-1
Test Range 2.9-3.8 Hz with 20 points recorded between limits. Frequency step of .045hz. Three averages recorded per measurement. Fixed Band Filter of .2Hz. Set-up # 3 used.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (ω)</th>
<th>AVG Phase Transition (Φ)</th>
<th>AVG Coherence</th>
<th>AVG Damping (ξ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>3.089</td>
<td>172.9</td>
<td>84.05%</td>
<td>1.45%</td>
</tr>
<tr>
<td>Mode 2</td>
<td>3.705</td>
<td>173.26</td>
<td>35.08%</td>
<td>0.77%</td>
</tr>
</tbody>
</table>

Figure C4 DY2_1.
Test DY2-2
Test Range 3.6-5.2 Hz with 35 points recorded between limits. Frequency step of .045hz. Three averages recorded per measurement. Fixed Band Filter of .2Hz. Set-up # 3 used.

Figure C5 DY2_2.

Table C5 DY2_2

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modal Frequency ($\omega$)</th>
<th>AVG Phase Transition ($\Phi$)</th>
<th>AVG Coherence</th>
<th>AVG Damping ($\xi$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>3.788</td>
<td><strong>259.41</strong></td>
<td><strong>31.65%</strong></td>
<td><strong>0.5%</strong></td>
</tr>
<tr>
<td>Mode 2</td>
<td>4.212</td>
<td><strong>148.01</strong></td>
<td><strong>92.96%</strong></td>
<td><strong>1.86%</strong></td>
</tr>
</tbody>
</table>
Test DY2-3
Test Range 5-7.2 Hz with 35 points recorded between limits. Frequency step of .045hz. Three averages recorded per measurement. Fixed Band Filter of .2Hz. Set-up # 3 used. No Modal Properties were found in this Test.

Figure C6 DY2_3.

Table C6 DY2_3

| Mode 1 | NA | NA | NA | NA |
Test DY3-1
Test Range 6.3-7.2 Hz with 20 points recorded between limits. Frequency step of .045hz. Three averages recorded per measurement. Fixed Band Filter of .2Hz. Set-up #3 used. No Modal Properties were found in this Test.

Table C7 DY3_1

<table>
<thead>
<tr>
<th>Mode 1</th>
<th>Modal Frequency (ω)</th>
<th>AVG Phase Transition (Φ)</th>
<th>AVG Coherence</th>
<th>AVG Damping (ξ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

Figure C7 DY3_1.
Test DY3-2
Test Range 7-9.2 Hz with 45 points recorded between limits. Frequency step of .045hz. Three averages recorded per measurement. Fixed Band Filter of .2Hz. Set-up # 3 used. No Modal Properties were found in this Test.

Figure C8 DY3_2.

Table C8 DY3_2

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modal Frequency ($\omega$)</th>
<th>AVG Phase Transition ($\Phi$)</th>
<th>AVG Coherence</th>
<th>AVG Damping ($\xi$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.988</td>
<td>115.2%</td>
<td>92.31%</td>
<td>1.53</td>
</tr>
</tbody>
</table>
Test DY3-3
Test Range 9-11.2 Hz with 45 points recorded between limits. Frequency step of .045hz. Three averages recorded per measurement. Fixed Band Filter of .2Hz. Set-up # 3 used. No Modal Properties were found in this Test.

Figure C9 DY3_3.

Table C9 DY3_3

<table>
<thead>
<tr>
<th>Mode 1</th>
<th>NA</th>
<th>NA</th>
<th>NA</th>
<th>NA</th>
</tr>
</thead>
</table>

Modal Frequency ($\omega$)  AVG Phase Transition ($\Phi$)  AVG Coherence  AVG Damping ($\xi$)
Test DY3-4

Test Range 11-13.2 Hz with 45 points recorded between limits. Frequency step of .045hz. Three averages recorded per measurement. Fixed Band Filter of .2Hz. Set-up # 3 used. No Modal Properties were found in this Test.

Figure C10 DY3_4.

Table C10 DY3_4

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modal Frequency ($\omega$)</th>
<th>AVG Phase Transition ($\Phi$)</th>
<th>AVG Coherence</th>
<th>AVG Damping ($\xi$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>
Test TRFDY4-1
Ambient Vibration Test 0-10Hz. Frequency step of .025hz. 90 averages recorded per measurement. Set-up # 4 used. White noise was used as the reference channel.

Figure C11 TRFDY4_1.

Table C11 TRFDY4_1

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modal Frequency (ω)</th>
<th>AVG Phase Transition (Φ)</th>
<th>AVG Coherence</th>
<th>AVG Damping (ξ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>3.08</td>
<td>NA</td>
<td>NA</td>
<td>1.27</td>
</tr>
<tr>
<td>Mode 2</td>
<td>3.65</td>
<td>NA</td>
<td>NA</td>
<td>0.85</td>
</tr>
<tr>
<td>Mode 3</td>
<td>4.10</td>
<td>NA</td>
<td>NA</td>
<td>1.29</td>
</tr>
<tr>
<td>Mode 4</td>
<td>8.03</td>
<td>NA</td>
<td>NA</td>
<td>0.51</td>
</tr>
<tr>
<td>Mode 5</td>
<td>9.83</td>
<td>NA</td>
<td>NA</td>
<td>0.43</td>
</tr>
</tbody>
</table>
Test TRFDY4-2
Ambient Vibration Test 0-15Hz. Frequency step of .025hz. 6 averages recorded per measurement. Set-up # 4 used. White noise was used as the reference channel. The curve was smoothed using 3 averages to accentuate the peaks.

Figure C12 TRFDY4_2.

Table C12 TRFDY4_2

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modal Frequency(ω)</th>
<th>AVG Phase Transition (Φ)</th>
<th>AVG Coherence</th>
<th>AVG Damping (ξ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>3.11</td>
<td>NA</td>
<td>NA</td>
<td>1.79</td>
</tr>
<tr>
<td>Mode 2</td>
<td>3.45</td>
<td>NA</td>
<td>NA</td>
<td>1.18</td>
</tr>
<tr>
<td>Mode 3</td>
<td>4.05</td>
<td>NA</td>
<td>NA</td>
<td>1.41</td>
</tr>
<tr>
<td>Mode 4</td>
<td>7.99</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Mode 5</td>
<td>10.24</td>
<td>NA</td>
<td>NA</td>
<td>.9581</td>
</tr>
<tr>
<td>Mode 6</td>
<td>14.21</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>
Test TRFDY4-3
Ambient Vibration Test 0-15Hz. Frequency step of .025hz. 90 averages recorded per measurement. Set-up # 4 used. White noise was used as the reference channel. The curve was smoothed using 3 averages to accentuate the peaks.

Figure C13 TRFDY4_3.

Table C13 TRFDY4_3

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modal Frequency(ω)</th>
<th>AVG Phase Transition (Φ)</th>
<th>AVG Coherence</th>
<th>AVG Damping (ξ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>3.13</td>
<td>NA</td>
<td>NA</td>
<td>1.5574</td>
</tr>
<tr>
<td>Mode 2</td>
<td>3.54</td>
<td>NA</td>
<td>NA</td>
<td>1.5512</td>
</tr>
<tr>
<td>Mode 3</td>
<td>4.14</td>
<td>NA</td>
<td>NA</td>
<td>1.0595</td>
</tr>
<tr>
<td>Mode 4</td>
<td>8.01</td>
<td>NA</td>
<td>NA</td>
<td>.6309</td>
</tr>
<tr>
<td>Mode 5</td>
<td>11.57</td>
<td>NA</td>
<td>NA</td>
<td>.5898</td>
</tr>
<tr>
<td>Mode 6</td>
<td>14.29</td>
<td>NA</td>
<td>NA</td>
<td>.2073</td>
</tr>
</tbody>
</table>
Test TRFDY4-4
Ambient Vibration Test 0-15Hz. Frequency step of .01875hz. 6 averages recorded per measurement.  Set-up # 4 used.  White noise was used as the reference channel. The curve was smoothed using 5 averages to accentuate the peaks.

Table C14 TRFDY4_4

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modal Frequency($\omega$)</th>
<th>AVG Phase Transition ($\Phi$)</th>
<th>AVG Coherence</th>
<th>AVG Damping ($\xi$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>3.13</td>
<td>NA</td>
<td>NA</td>
<td>1.2912</td>
</tr>
<tr>
<td>Mode 2</td>
<td>3.54</td>
<td>NA</td>
<td>NA</td>
<td>1.1849</td>
</tr>
<tr>
<td>Mode 3</td>
<td>4.14</td>
<td>NA</td>
<td>NA</td>
<td>.7427</td>
</tr>
<tr>
<td>Mode 4</td>
<td>8.01</td>
<td>NA</td>
<td>NA</td>
<td>1.2704</td>
</tr>
<tr>
<td>Mode 5</td>
<td>11.57</td>
<td>NA</td>
<td>NA</td>
<td>.5898</td>
</tr>
<tr>
<td>Mode 6</td>
<td>14.29</td>
<td>NA</td>
<td>NA</td>
<td>.4700</td>
</tr>
</tbody>
</table>
Test TRFDY4-5
Ambient Vibration Test 0-15Hz. Frequency step of .01875hz. 6 averages recorded per measurement. Set-up # 4 used. White noise was used as the reference channel. The curve was smoothed using 3 averages to accentuate the peaks.

![Magnitude](image1)

![Unwrapped Phase](image2)

![Coherence Function](image3)

Figure C15 TRFDY4_5.

Table C15 TRFDY4_5

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modal Frequency(ω)</th>
<th>AVG Phase Transition (Φ)</th>
<th>AVG Coherence</th>
<th>AVG Damping (ξ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>3.13</td>
<td>NA</td>
<td>NA</td>
<td>.7546</td>
</tr>
<tr>
<td>Mode 2</td>
<td>3.54</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Mode 3</td>
<td>4.14</td>
<td>NA</td>
<td>NA</td>
<td>1.2212</td>
</tr>
<tr>
<td>Mode 4</td>
<td>8.01</td>
<td>NA</td>
<td>NA</td>
<td>0.9028</td>
</tr>
<tr>
<td>Mode 5</td>
<td>11.57</td>
<td>NA</td>
<td>NA</td>
<td>0.5976</td>
</tr>
<tr>
<td>Mode 6</td>
<td>14.29</td>
<td>NA</td>
<td>NA</td>
<td>0.3684</td>
</tr>
</tbody>
</table>
Test TRFDY4-6
No Traffic Vibration Test 0-15Hz. Frequency step of .01875hz. 6 averages recorded per measurement. Set-up # 4 used. White noise was used as the reference channel. The curve was smoothed using 3 averages to accentuate the peaks.

![Magnitude Graph]

![Unwrapped Phase Graph]

![Coherence Function Graph]

Figure C16 TRFDY4_6.

Table C16 TRFDY4_6

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modal Frequency(ω)</th>
<th>AVG Phase Transition (Φ)</th>
<th>AVG Coherence</th>
<th>AVG Damping (ξ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>3.08</td>
<td>NA</td>
<td>NA</td>
<td>.7546</td>
</tr>
<tr>
<td>Mode 2</td>
<td>3.525</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Mode 3</td>
<td>4.05</td>
<td>NA</td>
<td>NA</td>
<td>1.2212</td>
</tr>
<tr>
<td>Mode 4</td>
<td>8.10</td>
<td>NA</td>
<td>NA</td>
<td>0.9028</td>
</tr>
<tr>
<td>Mode 5</td>
<td>10.02</td>
<td>NA</td>
<td>NA</td>
<td>0.5976</td>
</tr>
<tr>
<td>Mode 6</td>
<td>14.25</td>
<td>NA</td>
<td>NA</td>
<td>0.3684</td>
</tr>
</tbody>
</table>
Test TRFDY4-7
No Traffic Vibration Test 0-15Hz. Frequency step of .075hz. 6 averages recorded per measurement. Set-up # 4 used. The curve was smoothed using 2 averages to accentuate the peaks.

![Graphs showing Magnitude, Unwrapped Phase, and Coherence Function]

**Figure C17 TRFDY4_7.**

**Table C17 TRFDY4_7**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modal Frequency(ω)</th>
<th>AVG Phase Transition (Φ)</th>
<th>AVG Coherence</th>
<th>AVG Damping (ξ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>3.225</td>
<td>NA</td>
<td>NA</td>
<td>2.137</td>
</tr>
<tr>
<td>Mode 2</td>
<td>3.525</td>
<td>NA</td>
<td>NA</td>
<td>3.218</td>
</tr>
<tr>
<td>Mode 3</td>
<td>4.20</td>
<td>NA</td>
<td>NA</td>
<td>3.8206</td>
</tr>
<tr>
<td>Mode 4</td>
<td>8.10</td>
<td>NA</td>
<td>NA</td>
<td>2.0526</td>
</tr>
<tr>
<td>Mode 5</td>
<td>10.20</td>
<td>NA</td>
<td>NA</td>
<td>2.6069</td>
</tr>
<tr>
<td>Mode 6</td>
<td>14.32</td>
<td>NA</td>
<td>NA</td>
<td>2.2868</td>
</tr>
</tbody>
</table>
Test TRFDY4-8
No Traffic Vibration Test 0-15Hz. Frequency step of .01875hz. 6 averages recorded per measurement. Set-up # 4 used.

![Graphs showing magnitude, unwrapped phase, and coherence function for different modal frequencies.]

Figure C18 TRFDY4_8.

Table C18 TRFDY4_8

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modal Frequency((\omega))</th>
<th>AVG Phase Transition ((\Phi))</th>
<th>AVG Coherence</th>
<th>AVG Damping ((\xi))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>3.17</td>
<td>NA</td>
<td>NA</td>
<td>2.341</td>
</tr>
<tr>
<td>Mode 2</td>
<td>3.50</td>
<td>NA</td>
<td>NA</td>
<td>0.8657</td>
</tr>
<tr>
<td>Mode 3</td>
<td>4.07</td>
<td>NA</td>
<td>NA</td>
<td>1.824</td>
</tr>
<tr>
<td>Mode 4</td>
<td>7.93</td>
<td>NA</td>
<td>NA</td>
<td>1.37</td>
</tr>
<tr>
<td>Mode 5</td>
<td>10.05</td>
<td>NA</td>
<td>NA</td>
<td>0.851</td>
</tr>
<tr>
<td>Mode 6</td>
<td>14.10</td>
<td>NA</td>
<td>NA</td>
<td>1.0304</td>
</tr>
</tbody>
</table>
Test TRFDY4-9
No Traffic Vibration Test 0-15Hz. Frequency step of .01875 Hz. 6 averages recorded per measurement. Set-up # 4 used.

Table C19 TRFDY4_9

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modal Frequency (ω)</th>
<th>AVG Phase Transition (Φ)</th>
<th>AVG Coherence</th>
<th>AVG Damping (ξ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>2.98</td>
<td>NA</td>
<td>NA</td>
<td>2.6436</td>
</tr>
<tr>
<td>Mode 2</td>
<td>3.58</td>
<td>NA</td>
<td>NA</td>
<td>0.8657</td>
</tr>
<tr>
<td>Mode 3</td>
<td>4.07</td>
<td>NA</td>
<td>NA</td>
<td>1.048</td>
</tr>
<tr>
<td>Mode 4</td>
<td>7.99</td>
<td>NA</td>
<td>NA</td>
<td>.988</td>
</tr>
<tr>
<td>Mode 5</td>
<td>10.07</td>
<td>NA</td>
<td>NA</td>
<td>1.341</td>
</tr>
<tr>
<td>Mode 6</td>
<td>13.88</td>
<td>NA</td>
<td>NA</td>
<td>0.4224</td>
</tr>
</tbody>
</table>
Test TRFDY4-10
No Traffic Vibration Test 0-15Hz. Frequency step of .01875 Hz. 6 averages recorded per measurement.  Set-up # 4 used.

![Magnitude](image1)

![Unwrapped Phase](image2)

![Coherence Function](image3)

Figure C20 TRFDY4_10.

Table C20 TRFDY4_10

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modal Frequency((\omega))</th>
<th>AVG Phase Transition ((\Phi))</th>
<th>AVG Coherence</th>
<th>AVG Damping ((\xi))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Mode 2</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Mode 3</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Mode 4</td>
<td>7.95</td>
<td>NA</td>
<td>NA</td>
<td>1.00</td>
</tr>
<tr>
<td>Mode 5</td>
<td>10.07</td>
<td>NA</td>
<td>NA</td>
<td>1.341</td>
</tr>
<tr>
<td>Mode 6</td>
<td>13.88</td>
<td>NA</td>
<td>NA</td>
<td>2.4107</td>
</tr>
</tbody>
</table>
Test TRFDY4-11
No Traffic Vibration Test 0-15Hz. Frequency step of .01875 Hz. 6 averages recorded per measurement. Set-up # 4 used. The curve was smoothed using 3 averages to accentuate the peaks.

Figure C21 TRFDY4_11.

Table C21 TRFDY4_11

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modal Frequency(ω)</th>
<th>AVG Phase Transition (Φ)</th>
<th>AVG Coherence</th>
<th>AVG Damping (ξ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>3.04</td>
<td>NA</td>
<td>NA</td>
<td>1.2615</td>
</tr>
<tr>
<td>Mode 2</td>
<td>3.68</td>
<td>NA</td>
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</tr>
<tr>
<td>Mode 3</td>
<td>4.05</td>
<td>NA</td>
<td>NA</td>
<td>2.60</td>
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<tr>
<td>Mode 4</td>
<td>8.06</td>
<td>NA</td>
<td>NA</td>
<td>1.61</td>
</tr>
<tr>
<td>Mode 5</td>
<td>9.98</td>
<td>NA</td>
<td>NA</td>
<td>2.29</td>
</tr>
<tr>
<td>Mode 6</td>
<td>13.91</td>
<td>NA</td>
<td>NA</td>
<td>1.58</td>
</tr>
</tbody>
</table>
Test DY4-1
SSN Test 2.5-4.75Hz. Frequency step of .028125 Hz. Min Coh 0.6 Set-up # 4 used. The min Coherence feature was used in this test. This means that an avg was taken until the min coherence of .6 was reached; however, this feature did not function well for this testing setup and the data is very poor. No modal information was obtained from this test.

Figure C22 DY4_1.

Table C22 DY4_1

<table>
<thead>
<tr>
<th>Modal Frequency(ω)</th>
<th>AVG Phase Transition (Φ)</th>
<th>AVG Coherence</th>
<th>AVG Damping (ξ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>4.5</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
Test DY4-2
SSN Test 7.9-8.1. Frequency step of .02Hz. 3 averages recorded per measurement.
Set-up # 4 used. Fixed Band-Width Filter of .3 Hz was used.

![Magnitude](image1)

![Unwrapped Phase](image2)

![Coherence Function](image3)

Figure C23 DY4_2.

Table C23 DY4_2

<table>
<thead>
<tr>
<th>Mode 1</th>
<th>Modal Frequency(ω)</th>
<th>AVG Phase Transition (Φ)</th>
<th>AVG Coherence</th>
<th>AVG Damping (ξ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7.967</td>
<td>NA</td>
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<td>NA</td>
</tr>
</tbody>
</table>
Test DY4Horizontal-1
SSN Test 2.5-4.5. Frequency step of .025Hz. 3 averages recorded per measurement.
Set-up # 5 used. Fixed Band-Width Filter of .4 Hz was used. Filter was too broad poor
data obtained. No modal properties obtained.

<table>
<thead>
<tr>
<th>Modal Frequency(ω)</th>
<th>AVG Phase Transition (Φ)</th>
<th>AVG Coherence</th>
<th>AVG Damping (ξ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
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<tr>
<td>3</td>
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</tr>
<tr>
<td>4.5</td>
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</tr>
</tbody>
</table>

Figure C24 DY4_2.

Table C24 DY4_2
Appendix D
Encroachment Permit For Long-Term Installation
STATE OF CALIFORNIA - DEPARTMENT OF TRANSPORTATION
ENCROACHMENT PERMIT
TR-0120 (REV 6/2000)

In compliance with (Check one):
☐ Your application of April 7, 2010
☐ Utility Notice No. of
☐ Agreement No. of
☐ RW Contract No. of

TO: Utah State University
Civil and Environmental Engineering
4110 Old Main Hill
Logan UT 84322
Attn: Timothy Thurgood
(435)797-1646

and subject to the following, PERMISSION IS HEREBY GRANTED to:
Install structure's health monitoring equipment on Caltrans Structure #24-2087L on Interstate 5 as per attached plans and the following conditions:
1. The cabinet, hardware, and rigid steel conduit mounted to the bridge column shall be painted to match the color of the concrete.
2. All electrical work shall conform to the National Electrical Code (NEC).
3. Details and specifications for the steel access openings and concrete removal shall be provided.
4. Hoffman PVC enclosure boxes for the tiltmeters will not be allowed to mechanically mount onto the bridge girders because the bridge girders are cast-in-place prestressed girders.
Continue on Page 2.

THIS PERMIT IS NOT A PROPERTY RIGHT AND DOES NOT TRANSFER WITH THE PROPERTY TO A NEW OWNER.

The following attachments are also included as part of this permit (Check applicable):
☐ Yes ☐ No General Provisions
☐ Yes ☐ No Utility Maintenance Provisions
☐ Yes ☐ No Special Provisions
☐ Yes ☐ No A Cal-OSHA permit if required: Permit No.
☐ Yes ☐ No As-Built Plans Submittal Route Slip for Locally Advertised Projects
☐ Yes ☐ No Storm Water Pollution Protection Plan

☐ Yes ☐ No The information in the environmental documentation has been reviewed and considered prior to approval of this permit.

This permit is void unless the work is completed before December 1, 2010
This permit is to be strictly construed and no other work other than specifically mentioned is hereby authorized.
No project work shall be commenced until all other necessary permits and environmental clearances have been obtained

Earl Kaslan- Structure Maintenance
(916)227-8205 Office, (916)799-5057 Cell

cc: Kevin Keady- Structure (916)212-8165 Cell
Mall Karim- Permit Inspector (916)709-1744 Cell
Rusty Groat, Maint. Sunrise Region

APPROVED:

JODY JONES, District Director
SHAUN A. RICE, Chief-Encroachment Permits Branch

ADA Notice For individuals with sensory disabilities, this document is available in alternate formats. For information call (916) 653-3667 or TDD (916) 654-3880 or write Records and Forms Management, 1120 N Street, MS-69, Sacramento, CA 95814.
PERMISIIONS Conditions Continued:

Permittee shall contact Earl Kasian Structure Maintenance, Cell (916) 799-5057, SEVEN (7) working days prior to commencing work, to arrange a pre-job meeting. A 24-hour notification before restarting work shall be strictly adhered to. All work shall be conducted and completed to the satisfaction of Caltrans representative. Immediately following completion of the work permitted herein, the Permittee shall fill out and mail the Notice of Completion attached to this Permit.