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# MODAL ANALYSIS AND MODELING OF HIGHWAY BRIDGES

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## SUMMARY

Two bridges along the I-15 corridor in Salt Lake City, Utah were tested using forced and ambient vibrations. The forced vibration testing was done using an eccentric mass shaker and a 1800 kg drop weight both on and adjacent to the bridge structure. Ambient vibration excitation was provided by wind, traffic, and other urban vibrational sources.

Dynamic modeling was performed using commercially available finite element software. Modal parameters were determined from the experimental testing and these parameters were utilized for the calibration of the FEM models.

Ambient vibration data was collected over a sustained time for one of the bridges so that statistical information could be determined regarding the variability in the data.

The analytical models correlate very well with the field collected data in both the vertical and horizontal modes. Both ambient vibration and forced vibration sources are adequate for determining modal; parameters, and each have advantages.

## INTRODUCTION

Two highway bridges were tested as part of this study. Bridge 1 (Figs. 1 and 2) was tested using an eccentric mass shaker mounted to the bridge. Bridge 2 (Fig. 3) was tested using a 4000 lb drop weight. Ambient vibration data was also collected from each bridge.

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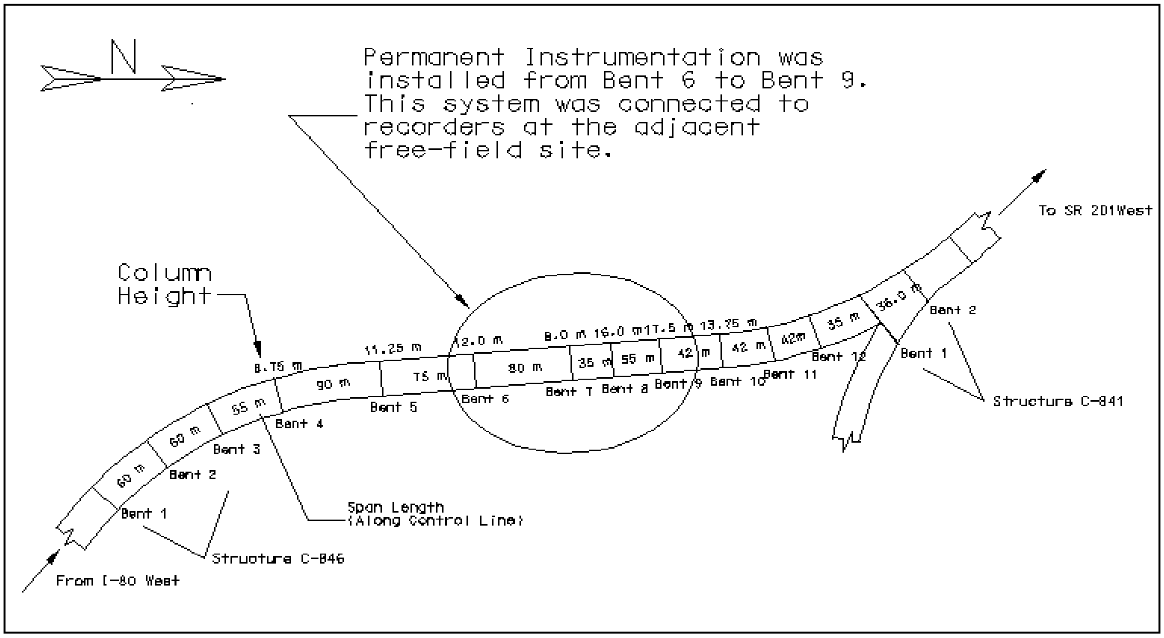


**Figure 1. Bridge 1 Site Plan**

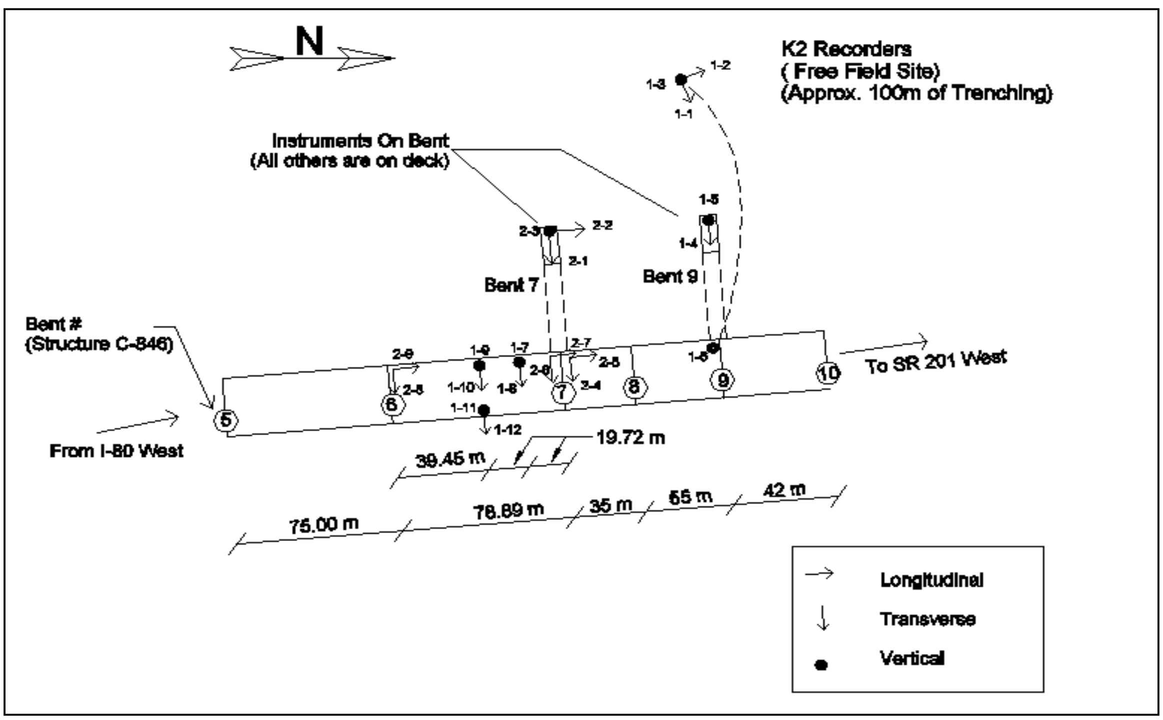


**Figure 2. Permanent Instrument Layout, Bridge 1**

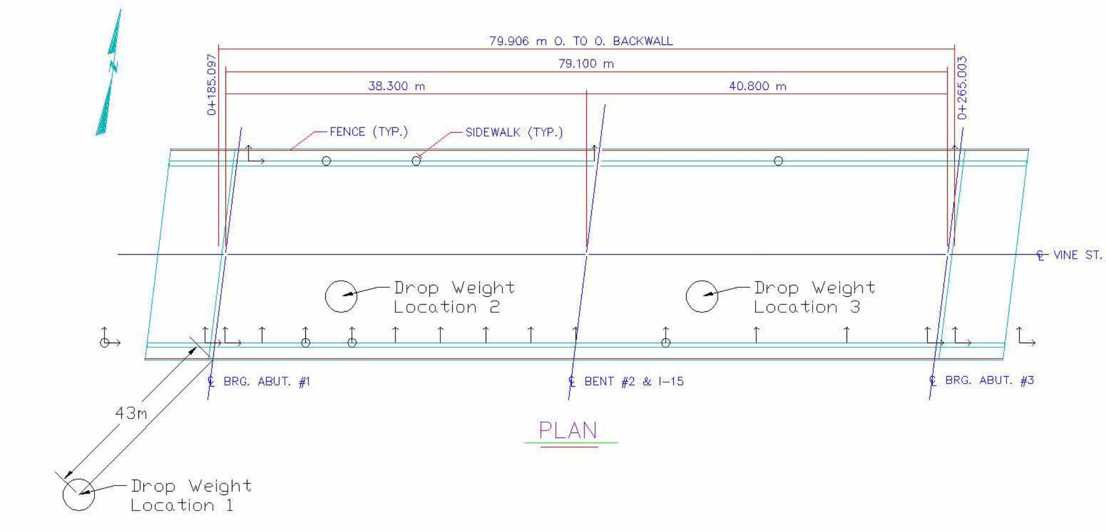


**Figure 3. Bridge 2**

**Bridge 1**

The first bridge tested was UDOT bridge C-846 (Bridge 1). Instrumentation deployed on this bridge included 36 channels of 1 Hz velocity transducers installed on the under side of the bridge deck, on bridge bents, and on several beams and columns. In addition to this instrumentation, the bridge was instrumented with 10 removable accelerometers and 21 channels of strong motion force balanced accelerometers permanently attached to the structure. Of these 21 channels, 18 channels are located on the deck and bents of the bridge with 3 channels and the recorders located at a free-field site about 140 meters away from the bridge. Also included at the free field site are 12 down-hole channels. This bridge is the first bridge instrumented with strong motion instrumentation within the state of Utah. All instrumentation was operational with traffic on all lanes.

This permanent instrumentation will fill the multiple purposes of long term monitoring of the bridge by researchers at Utah State University, real time data flow to the University of Utah Seismographic Station as part of the Advanced National Seismic System (ANSS), and recording of the bridge response due to a local earthquake in the Salt Lake City vicinity. The orientation of the structure and the locations of the permanent instrumentation are shown in figures 1 and 2.

Several reasons exist for selecting this structure for long term health monitoring in the state of Utah. This bridge is new (constructed in 2001), as a part of the I-15 reconstruction through Salt Lake City, Utah. It is a crucial interchange in the transportation system of the state and is a long-span flyover type structure. It is also located only 6 kilometers from the Wasatch Fault. This site is of great geotechnical interest due to its location on very soft deep Lake Bonneville sediments in the valley.

The temporary instrument array was designed in three phases, primarily to improve the coverage of vertical motion in the test section of the bridge. A total of 46 additional instruments were used in the three stages. Several velocity transducers were placed next to the permanent accelerometers so that the arrays could be normalized to each other. A group of instruments, placed eight meters north of the eastern column of Bent 7, were used as free-field instruments for the third stage.

The complete bridge was modeled using commercially available software. The modal frequencies obtained from the FEM model were compared to the natural frequencies obtained from field testing.

**Bridge 2**

The second bridge tested was UDOT bridge C-814 (Bridge 2). It was tested by using a drop weight, and ambient vibrations. It is a two span bridge with a skew of 7 degrees and approximately 2 meters of elevation difference between the two abutments. The bridge is 80 meters long, and 18 meters wide. It was chosen, because of its simplicity, and relatively large length to width ratio. The orientation and instrument locations of this structure are shown in figure 3.

Thirty four channels of data were recorded during both ambient and forced vibration testing. Seven of those channels were longitudinal, seven vertical, and twenty transverse. The bridge was excited from ambient vibration, and a 1800 kg drop weight. The drop weight was located in three different locations. The first location was 43 meters from the south-west corner of the bridge, the second location was at the third point of the first span, and the third location was at the third point of the second span.

## ANALYSIS

**Bridge 1**

During a one year period both forced vibration testing and ambient vibration testing were conducted on the subject bridge.

The forced vibration testing was conducted during a four-week period in May of 2001. This testing was conducted using an eccentric-mass shaking machine that was mounted on the east extension of bent 7 (Fig 2). The forcing, ranging from 0.5 to 20 hertz and was applied at 45 degrees to the longitudinal axis of the bridge. During the forced vibration and a portion of the ambient vibration testing, all of the permanent and the temporary instrumentation were in place. All instruments, the shaker, and cabling were installed such that testing could be accomplished while the bridge was fully opened to traffic.

Ambient vibration testing was performed approximately every 2 weeks for about one year. This testing gave a long-term picture of the variability of the modes and their accompanying frequencies. The main source of excitation was live traffic. Data was collected during various times of the day and at different seasons of the year.

Bridge modeling was accomplished through the use of shell and frame elements. A total of 1407 frame elements were used for the bents and bent caps as well as the intermediate cross-bracing between girders, while shell elements were used to represent the deck, flanges, webs, and web and bearing stiffeners.
Shell elements were used for the plate girders, as opposed to frame elements, due to the large variations of the geometry of the girders. Bents and bent caps were more easily and definitively described using frame elements. Twenty-nine thousand shell elements were used to model the plate girders, and concrete deck.

Table 1 is a summary of the mean natural frequencies for the first 26 modes, recorded from both the forced and the ambient vibration. As indicated in the table, 184 samples were included in the forced data, 24 samples in the ambient data, for a total of 208 samples from the field. In addition, the normalized variation is calculated for each mode, which is the standard deviation in the values divided by the mean value, and then presented as a percentile.

**Table 1. Natural Frequencies and Variation in the Data, C-846**

| Mode # | Mean Nat. Frequency Forced (184) | Ambient (24) | Computer Model | Normalized Variation Forced | Ambient |
|---|---|---|---|---|---|
| 1 | 1.114 | 1.099 | 1.287 | 4.13% | 1.24% |
| 2 | 1.310 | 1.342 | 1.405 | 3.12% | 1.21% |
| 3 | 1.488 | 1.452 | 1.420 | 1.26% | 1.14% |
| 4 | 1.582 | 1.589 | 1.795 | 1.82% | 2.86% |
| 5 | 1.760 | 1.757 | 2.507 | 1.55% | 2.67% |
| 6 | 1.924 | 1.916 | 2.570 | 0.98% | 1.60% |
| 7 | 2.248 | 2.214 | 2.861 | 1.62% | 1.08% |
| 8 | 2.369 | 2.367 | 3.491 | 1.48% | 1.68% |
| 9 | 2.701 | 2.683 | 3.690 | 4.14% | 2.39% |
| 10 | 3.067 | 3.053 | 3.782 | 1.85% | 2.76% |
| 11 | 3.317 | 3.299 | | 1.33% | 1.65% |
| 12 | 3.488 | 3.467 | | 1.35% | 1.69% |
| 13 | 3.722 | 3.840 | | 3.26% | 3.27% |
| 14 | 4.254 | 4.166 | | 2.35% | 3.13% |
| 15 | 4.719 | 4.765 | | 1.50% | 1.81% |
| 16 | 5.169 | 5.131 | | 1.98% | 2.07% |
| 17 | 5.582 | 5.507 | | 0.90% | 1.46% |
| 18 | 6.150 | 6.110 | | 3.57% | 3.96% |
| 19 | 7.302 | 7.339 | | 3.01% | 3.31% |
| 20 | 8.944 | 9.274 | | 2.79% | 3.57% |
| 21 | 10.697 | 10.564 | | 2.69% | 1.75% |
| 22 | 11.750 | 12.043 | | 2.61% | 2.77% |
| 23 | 12.999 | 12.719 | | 2.86% | 3.05% |
| 24 | 14.286 | 14.265 | | 2.66% | 2.38% |
| 25 | 15.587 | 16.016 | | 2.62% | 1.91% |
| 26 | 17.084 | 17.363 | | 2.22% | 2.59% |

Also included in Table 1 are the modal frequencies for the first ten modes as determined from the computer model. The horizontal modes were selected based on a mass participation ratio of ten percent or greater. The vertical modes were selected based on a mass participation ratio of three percent or greater. Based on these criteria, ten modes were chosen from the first thirty produced by the computer model. Figure 4 is a plot of the mean values of frequency from forced vibration, from ambient vibration, and from the computer model. Figure 5 is a plot of the variations in the mean values from the multiple sampling, which occurred in both the forced and ambient vibration testing.

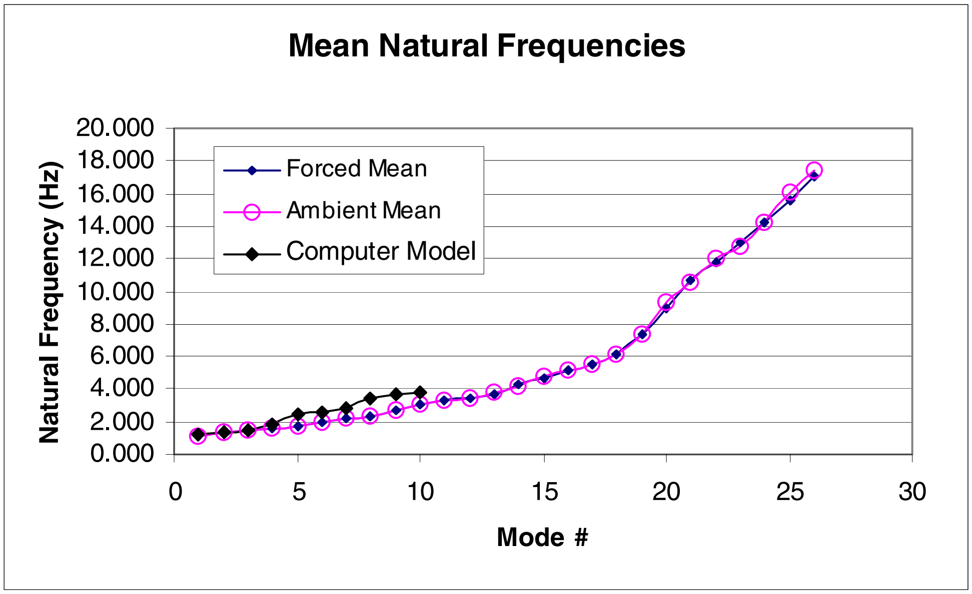


**Figure** 4. **Mean natural frequencies from both forced and ambient data**

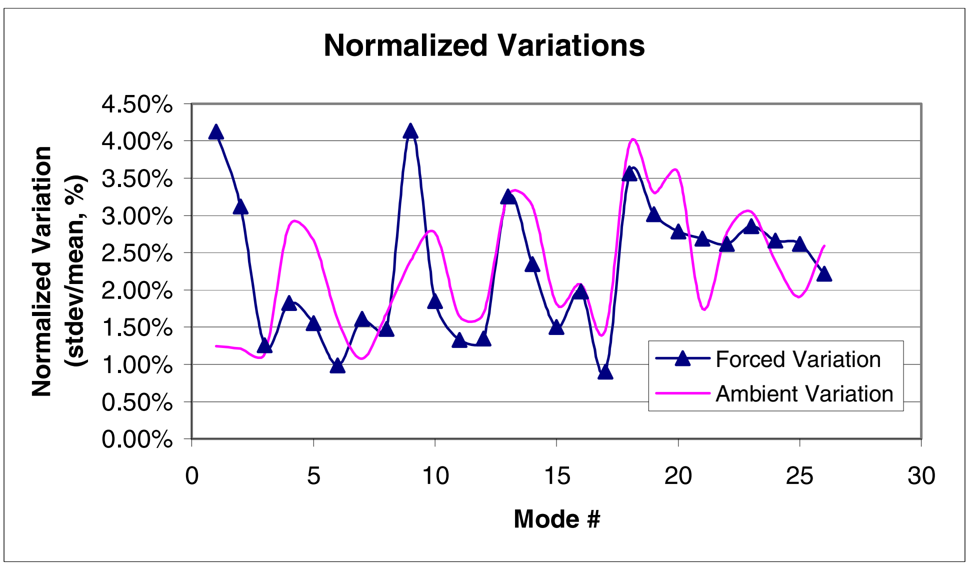


**Figure 5. Variability in the data, comparing forced and ambient vibration testing**

**Bridge 2**
The testing on bridge 2 was conducted on August 13th 2003. The drop weight tests were done several times at each location. The data was recorded using a PC based Data Acquisition system, and a Data Analyzer. The analyzer allowed for real-time results of up to 4 channels, while the Data Acquisition system allowed for a large number of channels to be recorded.

Bridge 2 was also modeled by using a combination of shell and frame elements. Approximately 20,000 shell elements were used, and 671 frame elements were used in creating the model.

Table 2 is a summary of the mean natural frequencies for the lower modes, recorded from both the forced and the ambient vibration. Also included in Table 2 are the modal frequencies for corresponding modes as determined from the computer model. The horizontal and vertical modes were selected based on a mass participation ratio of one percent or greater.

**Table 2. Natural Frequencies, C-814**

| Mode # | Mean Nat. Frequency | | | | | | |
|---|---|---|---|---|---|---|---|
| | Forced | Ambient | | | Computer Model | | |
| | | Longitudinal | Transverse | Vertical | Longitudinal | Transverse | Vertical |
| 1 | | | | | 1.84 | | 1.84 |
| 2 | 2.59 | 2.69 | | 2.69 | | | |
| 3 | 2.77 | | 2.85 | 2.85 | | | 2.94 |
| 4 | | | | | | 3.13 | |
| 5 | 3.72 | 3.88 | | | 4.40 | | |
| 6 | 3.91 | | | 4.01 | | | |
| 7 | 5.02 | 5.05 | 5.05 | 5.05 | 4.48 | | |
| 8 | 5.66 | 5.77 | | 5.77 | | | |
| 9 | | | | | 6.43 | 6.43 | |
| 10 | | | 6.56 | 6.56 | 6.60 | 6.60 | |
| 11 | 8.36 | | | | | | |
| 12 | 9.53 | | 9.59 | 9.59 | | | 8.03 |
| 13 | | | 10.01 | 10.01 | | | 12.75 |
| 14 | | 11.63 | 11.63 | | | | |
| 15 | | 11.92 | | | | | |
| 16 | | 13.59 | 13.59 | 13.59 | | | 14.12 |
| 17 | | | | | | | 16.38 |

## CONCLUSIONS AND RECOMMENDATIONS

Two different approaches were used in natural frequency calculation. One method used normalized displacement plots while the other used singular value graphs. It was observed that the average natural frequencies and variations could be found with good accuracy using either the forced vibration or ambient vibration testing method. This is very important considering long-term monitoring of the structure will be analyzed using this Frequency Domain Decomposition (FDD) method.

Natural frequencies determined using forced vibration (eccentric mass shaking, bridge 1) testing corresponds very well with frequencies determined using ambient vibration techniques.

The variability in the frequencies is about the same for both forced vibration (eccentric mass shaking, bridge 1) and ambient vibration testing. Figure 5 indicates a maximum variation for forced vibration of about 4.1 % and about 4.0 % for ambient vibration.

Drop weight testing using the trailer mounted drop weight for the source was effective for modal testing on the bridge. The results reflect testing where the weight was dropped on the bridge. Dropping the weight on the ground away from the bridge did not generate large enough signals to be measured on the bridge using standard techniques.

Testing of these recently constructed bridges made it possible to see how environmental conditions and testing procedures affected the modal parameters. Variations in the natural frequencies from field measurements were found to be from 0.9 to 4.1 percent. These variations were due, in part, to testing procedures and due, in part, to temperature fluctuations. During testing, temperatures ranged between 12 $^{o}$C and 24 $^{o}$C. This magnitude of temperature fluctuation is comparable to research done by Roberts and Pearson (1998) where they noted that changes in the eigen frequencies due to environmental conditions were as much as 3 to 4 percent for a 9-span, 840 meter long bridge.

Early modeling of these bridges yielded excellent results, indicating that with care in modeling and the proper use of boundary conditions, the modal frequencies can be used to make reasonable estimates.
To improve the efficiency of future vibration data analysis it would be necessary to record more temperature readings for each collected data file in order to properly characterize variations due to environmental conditions. A wide range of temperatures is recommended in order to see if the bridge response is significantly different for extreme temperatures. The incorporation of this extra parameter could further reduce modal variations, thus allowing detection of smaller levels of damage.

In order to study the long-term affects of temperature, traffic, and other unknown sources on the bridge a repetitious monitoring system is required. The same process that was established for processing ambient data during the initial testing is recommended for analyzing future ambient vibration data of the permanent instruments. Each analyzed file will be used to refine each natural frequency's average and variation found from the initial forced and ambient vibration testing.

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