Vibrational Testing, Modeling and Monitoring of Two Highway Bridges

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SUMMARY:
Researchers at Utah State University (USU) have completed initial diagnostic testing on two highway bridges using modal testing. The tests involved ambient and forced vibration techniques using a temporary instrumentation system. A finite element model (FEM) was created and calibrated using data from the initial testing and was found to have excellent correlation.
Based on the FEM and initial testing results, an instrumentation plan for a long-term monitoring system was designed for each bridge. Both bridges were installed with velocity transducers for measuring vibration response. Initial results from the long-term monitoring systems show excellent comparison with initial testing results and FEM analysis.
This paper outlines initial testing, FEM creation, long-term instrument installation, and data analysis of the continuous monitoring systems. Initial results for correlations with traffic and vehicle types are presented.

Keywords: vibrations, structural health monitoring, modelling, bridge, instrumentation

1. INTRODUCTION

Seismic structural design relies on the ability of engineers to anticipate excitation and predict seismic structural response. Vibration instrumentation is essential in developing the art and science of creating a more accurate model for predicting seismic structural response. These models are created by testing full scale structures. Modal analysis is a reliable method for determining the seismic response of a full-scale structure.

Researchers at Utah State University (USU) have completed initial diagnostic testing on two highway bridges using modal testing. The tests involved ambient and forced vibration techniques using a temporary instrumentation system. The temporary instrumentation system was composed of velocity transducers (commonly known as geophones). Excitation for the forced vibration tests was provided by an electromagnetic shaker. Ambient vibration excitation consisted of vehicle traffic on the bridge, environmental conditions, and nearby traffic. Following the initial testing, a finite element model (FEM) was created for each bridge. The FEM was validated using data from the initial testing and was found to have excellent correlation.

Referencing the results of the FEM and initial testing led to an instrumentation plan for a long-term monitoring system on each bridge. The monitoring systems for each bridge are slightly different, but similar in that they achieve a parallel outcome. Both bridges use velocity transducers as the primary sensor for measuring the vibrational response of the structure. Monitoring is ongoing, and will continue for many years. Initial results from the long-term monitoring systems show excellent comparison with initial testing results and FEM analysis.

The first bridge selected is an overpass structure carrying I-15 northbound over Cannery Street near Perry, Utah; approximately 100km north of Salt Lake City, Utah, USA. This bridge is an integral abutment, single span concrete bridge with overall length of 24.4m. The superstructure is composed of 5 pre-cast, pre-stressed, AASHTO Type IV girders supporting a 203mm reinforced concrete deck.

The second bridge is a two-span, cast-in-place, post tensioned, concrete box girder bridge carrying I-5 over Lambert Road, approximately 35km south of Sacramento California, USA. Each span is 39.62m long for an overall length of 79.24m. The deck is 203mm thick of reinforced concrete.

2. LITERATURE REVIEW

Dynamic testing, or modal analysis, is a procedure that extracts natural frequencies, mode shapes, and modal damping from multi-degree of freedom systems. This method of structural analysis can be used for both short-term and long-term applications. Brownjohn et al. (2011) presents 31 cases of long-term dynamic monitoring of structures through the entire world. Hsieh et al. (2006) provides a brief overview of vibrational monitoring with case studies provided to explain points of interest.

Dynamic testing requires forcing energy to be applied to the structure. This generally occurs under one of two forms, or in some cases both, which are ambient or forced excitation. Experts in the field of dynamic testing will argue that one form is better than another, while others apply both excitation methods in their studies. For example, Patjawit et al. (2005) argues that ambient excitation may not be sufficient to infer structural condition. Conte et al. (2008) further explains that forced excitation is better than ambient excitation because (1) the input excitations are well-defined and (2) the excitations can be used to optimize the response of modes of interest. Raghavendrachar et al. (1992) explained that impact testing is not as susceptible to nonlinearities as ambient testing is. In support of Ambient excitation, Gul et al. (2008) emphasizes that ambient vibration testing is a practical method for large civil structures where input excitation cannot be applied or measured properly. Peeters and Roeck (2001) conducted modal testing on the Z24-Bridge in Switzerland and noted that there was no possibility of continuously exciting the bridge with a known force; thus requiring ambient excitation. Grimmelsman et al. (2007) chose ambient vibration to ensure that results from the testing provided an objective measure of *in situ* characteristics of the bridge. Regardless of the method used, many studies using either or both method have resulted in a demonstration that dynamic testing is the best method for determining modal characteristics of a bridge. Some examples include: Huang (2005), Wahab and Roeck (1998), Lee et al. (1987), Morassi and Tonon (2007), and Paultre et al. (1995).

Due to the direct relationship of stiffness, mass and damping to modal properties of a structure, dynamic properties can be used to determine deterioration, damage, or change in state. Bolton et al. (2005) conducted a modal test on a bridge structure immediately before and after a large seismic event. The seismic event caused damage to the bridge structure which was visible through visual and modal analysis. Bolton reported an average change in modal frequency of 18.8%. Mertlich et al. (2007) varied the boundary condition on a curved girder bridge by inducing controlled damage to the structure. Under the change in boundary conditions, a change in modal frequency of up to 34% was found. In a similar test, Halling et al. (2001) carried a bridge structure through multiple damage and repair states and conducted modal analysis tests at each state. Each damage state resulted in a lowering of modal frequency and each repair resulted in an increase of modal frequency. Dean (2011) demonstrated the ability to track changes in modal properties of a concrete girder bridge as a function of changing mass. The change in mass was due to removal of an existing asphalt overlay on the bridge and subsequent replacement of a new, thinner layer of asphalt. As theoretically predicted, when the stiffness was held constant and the mass decreased, the modal frequencies of the bridge increased. Conversely, as the mass of the bridge increased, placement of the new asphalt layer, the frequencies decreased. Therefore, it is clear that modal analysis can be used as a method to track structural health of a bridge structure through damage states.

An important factor when using modal properties to determine damage, is the effect that temperature has on modal properties. On a test of a steel girder highway bridge, Zhao and DeWolf (2002) showed that with a baseline temperature, chosen to be 12.8˚C (55˚F), that decreases in temperature result in an increase in frequency with little change occurring before the temperature drops below -1.1˚ (30˚F). Peeters and Roeck (2001) found similar results, noting that modal frequencies change the most at 0˚C (32˚ F). This behavior is predicted to be a combination of the asphalt wearing surface contributing to structural stiffness and changes in boundary conditions due to soil property changes at the time of freezing. Sohn et al. (1999) found that changes in frequencies are linearly correlated with temperature readings across the bridge. Cornwell et al. (1999) reported that the first, second, and third modal frequencies varied by approximately 4.7%, 6.6%, and 5.0%, respectively over a 24 hour period. Sometimes, the effect that damage has on modal properties is less than that of environmental properties, such as temperature. Huth et al. (2005) performed modal analysis on the Romeo Bridge of the Obkirchen Highway Viaduct in Lucerne, Switzerland. He found that the Romeo Bridge is subjected to variations of natural frequencies of 0.3, 0.35, and 0.5Hz. for the first, second and third modes due to temperature changes; which is much greater than the changes due to damage.

3. BRIDGE DESCRIPTION

3.1. Cannery Street Overcrossing

The Cannery Street Overcrossing, UDOT structure number 1F 205, is located approximately 100km north of Salt Lake City, Utah and was constructed in 1976. It carries Northbound Interstate 15, with annual average daily traffic of 20,000 vehicles over Cannery Street. The structure is a single-span bridge with integral abutments. The bridge measures approximately 23.4 m (80 ft) long. The bridge is 13.41-m (44-ft) wide, accommodating a 12.34-m (40-ft 6-in.) wide roadway made up of a 1.6-m (5-ft 3-in.) left shoulder, two 3.66-m (12-ft) lanes and a 3.43-m (11-ft 3-in.) right shoulder. The bridge is made of a 203 mm (8-in.) thick concrete deck supported by 5 pre-cast pre-stressed AASHTO Type IV concrete girders. Figure 1 shows the Cannery Street Overpass.

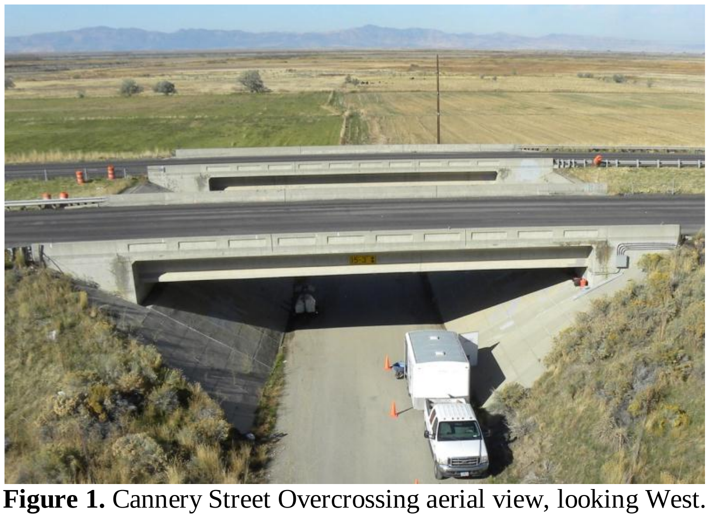

Figure 1. Cannery Street Overcrossing aerial view, looking West.

3.2. Lambert Road Overcrossing

The Lambert Road Overcrossing is located approximately 24 km (15 mi.) south of Sacramento, California. It was designed as a cast-in-place, post tensioned, box-girder bridge. Construction of the bridge was completed in 1975. The bridge carries two lanes of southbound traffic on Interstate 5 and has an average daily traffic of 25,000 vehicles. The overall length of the bridge is 78.7 m (258 ft) which is comprised of two equal spans at an 8° skew. The width of the deck (including barrier railings) is 12.8 m (42 ft). The deck was constructed as a 203 mm (8 in.) thick reinforced concrete slab. The overall depth of the bridge superstructure is 1.7 m (66 in.). The superstructure was constructed as a four cell configuration with girder spacing of 2.74 m (9 ft). The webs of the girders are 0.3 m (1 ft) thick. The deck overhang distance from the edge of the bridge deck to the centerline of the exterior girder is 0.91 m (3 ft). Figure 2 shows an elevation view of the Lambert Road Bridge.

Figure 2. Aerial/Elevation view of Lambert Road Overcrossing

4. INITIAL LOAD TESTING

4.1. Dynamic Load Testing

Dynamic testing allows for determination of bridge characteristics that static and semi-static load testing methods typically do not. Of primary interest in the dynamic test are modal frequencies, mode shapes, and damping ratios. A dynamic excitation is simply one that has a rapidly repeating signal. Dynamic excitation can range from controlled input through a shaker or a drop weight device. Other excitation comes from natural or randomly induced forces, such as vehicles and wind.

An electromagnetic harmonic force shaker was used to provide the forced excitation for the dynamic tests. Velocity transducers and a high speed data acquisition unit was used to collect and process the bridge response. The data acquisition unit and software package allowed for onboard FFT, windowing, anti-aliasing, and multiple other test parameter settings to be controlled.

Ambient excitation forcing was also used to excite the bridges structures. The data acquisition used for ambient data collection did not have onboard controls as the forced excitation unit. The necessary controls for FFT, windowing, anti-aliasing, etcetera, were established through customized analysis scripts written in MATLAB. Large data sets were gathered during ambient testing to allow for many averages during post-processing for a better frequency response.

4.1.1. Cannery Street Overcrossing Dynamic Results

Post processing and analysis of the collected data revealed six visible modes. Additional modes may exist, but were difficult to determine the because of the heavy vehicle interference with the shaker input and the inability of ambient vibration to excite higher modes.

4.1.2. Lambert Road Overcrossing Dynamic Results

Because of the noise created by the heavy traffic, a forced vibration stepped-sine analysis test (SSN) was implemented. The SSN test worked by inducing a single sine wave at a user-defined frequency and duration while the velocity transducers recorded the response of the bridge. Once the bridge reached a steady state condition, the frequency was changed and the process was repeated. During the testing of the bridge, the data underwent further averaging and filtering to monitor the data quality. The initial dynamic test consisted of using a broad frequency sweep. After this broad frequency sweep, subsequent tests focused on suspected resonant frequencies for modal confirmation. Based on the measured results, the first five modal frequencies were determined.

4.2. Live-Load Testing

Live load testing provides additional information for the establishment of a baseline of bridge performance for future comparison with continuous monitoring data and future load tests. Live-load testing data provides an excellent source of information for refining a finite element model used to analytically quantify bridge response.

4.2.1. Cannery Street Overcrossing Live Load Test

A total of 20 surface mounted stain sensors and 7 deflectometers, or vertical displacement sensors, were used. Sensors were placed at four cross-sectional locations along the structure. Strain sensors were placed in two of these cross-sections with two sensors per girder; one at the extreme underside fibre of the girder and one at the top of the web. Deflectometers were placed at the other two cross-sections, 0.5L and 0.6L, where L is the clear span of the bridge.

A total of six predetermined load paths were used during the test. The loading vehicles followed these paths along the length of the bridge. Five of the load paths were quasi-static, where the trucks moved across the bridge at walking speeds, and the sixth load path was a high-speed test. The five quasi-static load paths were chosen to induce maximum load in the exterior girder, first interior girder, single truck in the right lane, a multiple presence factor (one truck in each lane), and one truck following the other in the right lane. The high-speed test placed the truck in the right lane, the typical lane for large trucks on this section of highway.

4.2.2. Lambert Road Overcrossing Live Load Test

The bridge was instrumented with 53 instruments (42 strain transducers, 10 displacement sensors, and 1 uniaxial rotation sensor). Sensors were placed near both abutments and on both sides of the pier so that the support conditions could be obtained. The sensors were also placed near midspan for each span so that the maximum response of the bridge could be obtained.

To ensure that quality data was being collected, in some instances the trucks were driven over the same load path twice to see if reproducible results could be obtained. Results from these same run repetitions show nearly the same response with insignificant differences in the magnitude of the measured strain. In all cases where a load path was repeated more than once, when the truck was off the bridge the strain, as well as other measurements, returned to zero indicating that the bridge was behaving linearly elastically.

5. FINITE ELEMENT MODELLING

The formulation of a Finite Element Model (FEM) is a very important part of understanding bridge response and the data collected. There are various reasons for creating an FEM. One reason is to document the current state of the bridge through an analytical model, thus establishing a quantitative baseline for future comparison.

For both bridges, the finite element model was created in SAP2000 Version 14. Each model was created using solid elements for both the deck and the girders. It is preferred that solid elements are compact and regularly shaped to improve accuracy. Because of the geometric design of the structures, the elements were shaped as closely to square as possible. In the finite-element model, it was assumed that the deck, parapets, girders, and bottom of the box girder were rigidly attached to each other.

Replication of prestressing and post-tensions strands is achieved through the use of an element called a tendon. When applying the prestressing load, SAP2000 allows for a point load or a stress. Since losses have already occurred friction and anchorage were set to zero. Additional loss parameters including Elastic Shortening Stress, Creep Stress, Shrinkage Stress, and Steel Relaxation Stress are inputs that were set at zero.

End restraints have a significant effect on the structural response of the bridge, especially modal parameters. The design of both bridges employed integral abutments that act somewhere between a fixed-fixed and a pin-pin support condition. This behavior is modeled with the use of horizontal and vertical springs at the girder and deck level. The magnitude and placement of the springs were changed until a good correlation between the strains, displacements, rotations, and mode shapes and corresponding frequencies between the FEM and test measurements was obtained.

To model material properties, the bridges were separated into multiple sections where material properties were allowed to vary during the refinement process. The deck and girders were separated into multiple sections to allow for multiple values of material properties to be included. Additional sections were created for the parapets and midspan diaphragm. Figure 3 shows the 5 deck, 5 girder, and parapet sections on a 3D representation from SAP2000 for the Cannery Street Overcrossing.

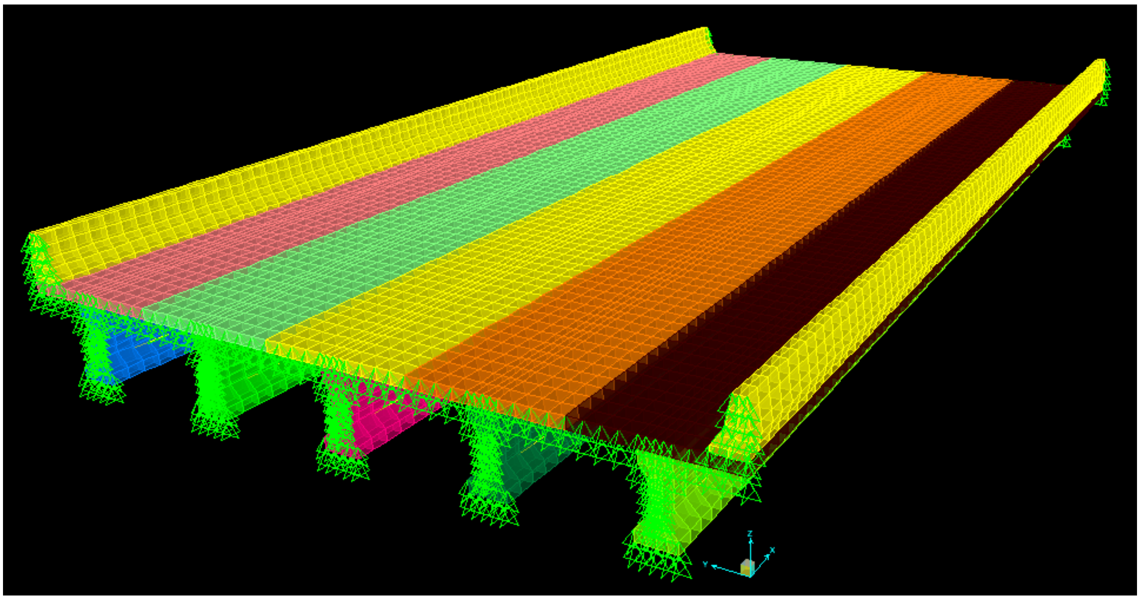

Figure 3. 3D Representation of Cannery Street Overcrossing Bridge. Colors represent material sections.

For refinement purposes, data collected from both the Dynamic and Live-Load Tests were used. Wheel loads were represented by single point loads, applied at the assumed centroid of the wheel.
The truck position was mapped continuously as it crossed the bridge during the live-load test. For modeling simplicity, the truck was moved at increments of 1.2m (4 ft) along the length of the bridge. Multiple load cases replicating the position of the truck in time were used in the FEM. When checking the accuracy of the FEM, all load cases were run simultaneously. This allowed for a comparison of the load path between the FEM and Live-Load data.

6. STRUCTURAL HEALTH MONITORING (SHM) SYSTEM

Based on the understanding of the bridge structure gained from the initial load testing and the FEM, an instrumentation plan for long-term structural health monitoring was created. A benefit of long-term monitoring is the fact that data received from the instrumentation is continuous and with the use of remote connections does not require researchers to be physically at the bridge to collect data. Once installed, the sensors provide continuous information on traffic conditions, seasonal and daily temperature changes, as well as the ability to capture extreme or unusual events, such as an earthquake or collision.

6.1. Cannery Street Overcrossing SHM System

The SHM system of the Cannery Street Overcrossing has a total of 36 structural sensors. They consist of tiltmeters (4), foil strain gauges (5), vibrating wire strain gauges (2), velocity transducers (3), and thermocouples (21). The thermocouples are placed near the other structural instruments either to provide temperature compensation or to simply understand the temperature gradients of the structural elements.

6.2. Lambert Road Overcrossing SHM System

The Lambert Road Overcrossing has a total of 51 structural sensors installed; tiltmeters (3), foil strain gauges (16), vibrating wire strain gauges (4), velocity transducers (4), and thermocouples (24). The thermocouples are placed near other structural instruments either to provide temperature compensation or to simply understand the temperature gradients of the structural elements.

7. COMPARISON OF INITIAL TESTING, FEM, AND SHM SYSTEMS

All comparisons will show how the Initial Testing, FEM, and SHM Systems correspond to provide very similar results.

7.1. Modal Frequency

Initial testing of the Cannery Street Overcrossing revealed a total of six modes. The SHM system permanently installed on the bridge is able to track and monitor the same six modes through time. As previously mentioned, a finite-element model was created to document the initial testing and to use for future analytical studies. Once the permanent instrumentation was installed, analysis was conducted to determine the modal properties as measured by the SHM system. Table 1 shows a comparison of the initial testing, FEM, and long-term testing results.

Table 1. Comparison of Initial Testing, FEM, and SHM System, Cannery St.

Mode	C1 Initial Test	C2 SHM System	C3 FEM	C1/C2	C1/C3
1	6.45	6.47	6.52	1.00	0.99
2	7.62	7.84	6.91	0.97	1.10
3	9.52	9.33	9.32	1.02	1.02

The columns representing the Initial Test, SHM System, and FEM results are labelled, C1, C2, and C3 for ease in understanding the comparison method. The two right most columns compare the SHM system and FEM to the Initial Test. This is conducted by fixing the Initial Test in the numerator and dividing by either the SHM System results or the FEM results. A value of 1.0 represents an exact match. A value greater than 1.0 indicates that the Initial Test is greater in the comparison. A number less than 1.0 indicates that the Initial Test is lower in the comparison. As can be seen through Table 1, excellent comparison is found among the Initial Test, the SHM System, and the FEM.

Ongoing work is being done to demonstrate the capabilities of the SHM system to detect structural changes due to temperature, mass, and other parameters that affect modal properties. The FEM is also being used to verify the SHM system results and to analytically compare all results.

7.2. Strain

A detailed comparison of strain results between the initial test and finite element model has been completed for the Lambert Road Overcrossing. Prior to using a finite element model to predict future use, it is essential that it be calibrated, or refined, by comparing it to strains, deflection, and rotations gathered from a controlled field test. Recall that the FEM for this bridge was created using solid elements. Solid elements do not output strain directly, but they do provide stress as an output. By extracting the stress at the location of interest for comparison, it is possible to back-calculate strain through the use of Hooke's Law if the modulus of elasticity is known. For the FEM created, the modulus was an input parameter and therefore known. A single node was used to represent a strain transducer. Typically, four solid elements connect to a single node, or joint. The stresses of the four solids surrounding the single node were retrieved and averaged to determine the stress at that point. By repeating this process for all locations of interest for comparison, the strain from the field test results and the finite element model could be compared.

Figure 4 shows a comparison of strain in the north span, where the gauge is located at approximately midspan. The plot y-axis shows microstrain. The x-axis shows position, representing the position of the truck. Since the strain gauge is fixed in one location, the strain variation is a function of the location of the truck on the bridge. Therefore, this plot shows the magnitude of strain at that one location as the truck moves across the length of the bridge. As shown, the peak response at the location of this strain gauge is at approximately 30 m (90 ft.) which represents approximately 13.5 microstrain. In Figure 4, the red black line with black squares represents the FEM results, the solid red line represents the initial test results.

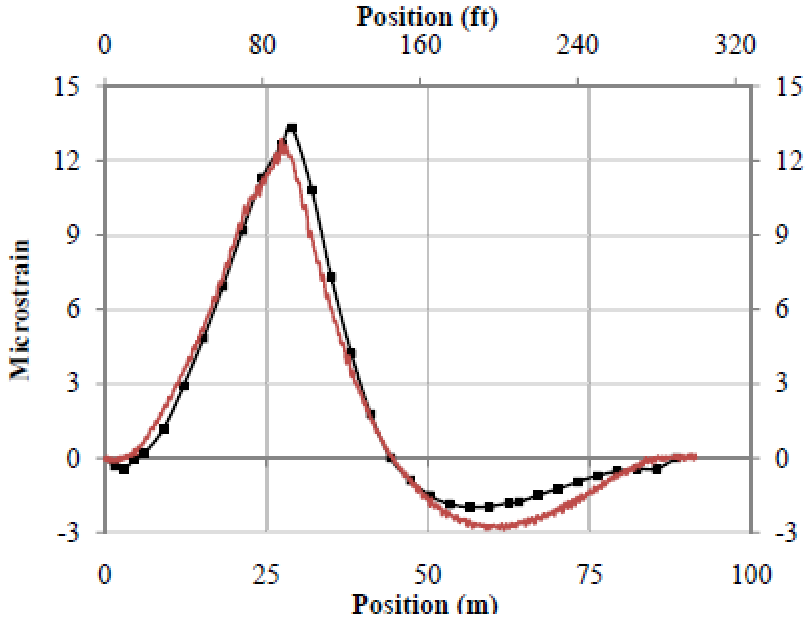

Figure 4. Strain response comparing Initial Testing and FEM results.

7.3. Tilt

During the initial test on the Cannery Street Overcrossing, there were not tilt, or rotation, measurements taken. However, on the Lambert Road Overcrossing, one uniaxial titlmeter was installed. Additional to calibrating the FEM to strain, the model was also calibrated to rotation. The rotation values from both the FEM and the initial test are very low with the peak rotation value of approximately 0.00015 radians (0.0086 degrees). Figure 5 shows a comparison of the rotation between the FEM and Initial Test.

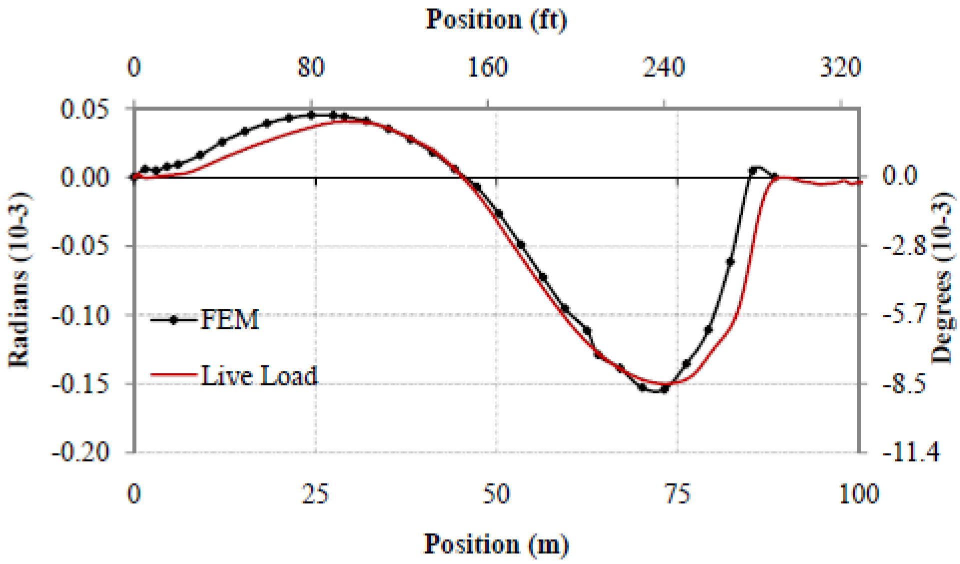

Figure 5. Rotation comparison between the FEM, and the Initial Live Load Test.

5. CONCLUSION

- To document the current status of the Cannery Street Overcrossing and the Lambert Road Overcrossing, initial testing was performed on both bridges. Initial testing included both a Dynamic Load test where modal frequencies and modal shapes were determined for each structure. Additionally, a Live-Load test was performed that gathered strain, deflection, and rotation data to further aid in calibrating a finite-element model.
- At the completion of the initial testing for each bridge, a unique finite-element model was created for each bridge. Due to the structure type, some form of reinforced, post/ or pre tensioned concrete bridge, the two models used solid elements to replicate the as-built structure. Refinement process, included using data from both the Dynamic and Live-Load testing, provided models that compare very closely with the initial testing.
- To continuously monitor the behaviour and possible changes of the structures, separate permanent, structural health monitoring systems were created for each bridge. On the Cannery Street Overcrossing, a total of 36 sensors were installed. The break down of sensors is: tiltmeters (4), foil strain gauges (5), vibrating wire strain gauges (2), velocity transducers (3), and thermocouples (21). For the Lambert Road Overcrossing, a total of 51 sensors were installed. The breakdown of sensors is: tiltmeters (3), foil strain gauges (16), vibrating wire strain gauges (4), velocity transducers (4), and thermocouples (24).
- To demonstrate the ability of the permanently installed SHM system to monitor the changes in the bridge structure over time, a comparison between the Initial Test, FEM results, and SHM system was shown for the first three modes. The SHM system is capable of providing the same results of the initial testing within 0-3%, which is an excellent correlation and provides confidence that future changes in bridge performance will be detected by the SHM system.
- To demonstrate the accuracy of a refined FEM, results from the Lambert Road Overcrossing for strain and tilt were shown. Even with relatively low strain values, an excellent correlation between the field data and analytical model output was achieved. Similarly, the rotation values determined by the uniaxial tiltmeter were duplicated in the model. This demonstrates that by using field data, a model can be trained to replicate structural response for additional analytical studies that otherwise would not be able to be done.

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