Non-destructive structural assessment of BRIDGEs using in-service dynamic response

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Abstract: Mainmark have introduced the STRAAM system of full scale structural integrity assessment and continuous monitoring for bridges into Australia and New Zealand. Advances in measuring extremely low amplitude vibrations combined with methods for extracting the unique dynamic signature have now enabled the rapid measurement of the response of steel and concrete structures. The STRAAM method utilizes the normal traffic conditions and wind loads on the structure to measure the frequency response of the structure. This allows the quick calibration of Finite Element Models that can be used to accurately assess the strength of the structure. Furthermore, this information allows asset owners to efficiently track changes in the capacity of their structures due to aging, impact, earthquake or flood activity through changes in the vibration of the structure and associated natural frequencies, mode shapes and damping ratios.

This paper discusses the results obtained from field measurements of two Australian bridges.

Keywords: Bridge Assessment, Structural Integrity, Monitoring, Testing, Dynamics, Non-linear Damping, FEM Calibration.

1. STRAAM

Mainmark have partnered with STRAAM from New York to introduce the STRAAM structural risk and management system for structures into Australia and New Zealand. The STRAAM system allows for rapid, non-invasive assessment of a structure's current status.

1.1 Non-intrusive non-destructive methodology

The testing of steel and concrete bridges using high technology has become fast, cheap and precise. At the same time, it is non-intrusive and gives both basic information and information that would be difficult to obtain by conventionally assessments. This state of affairs has been caused by the use of induced vibration testing of a series of bridges both in Europe and the USA. Details of on-site testing of several bridges is given here together with the methodology for fast testing using high precision accelerometers. The calibration of the non-intrusive simple methodology against the induced vibration approach is detailed here. As a result, it has made it possible to use the simple methodology associated with naturally occurring excitation to decode the state of health of the bridge structure.

The methodology for the induced vibration testing can be described as follows (Ellis et al):

1. Vibrators were located at the mid-point. The frequency of excitation was incremented sequentially and a response/frequency curve was obtained;
2. A frequency of resonance was selected and the vibrators were set to operate at this frequency;
3. An accelerometer was taken to various locations of interest, in turn, and the vibration amplitude was measured at each position, both longitudinally and across the bridge deck;
4. The vibrators were suddenly switched off, and the ensuing decay of oscillation was used to estimate the damping ratio for this mode of vibration;
5. Steps 2, 3 and 4 were repeated for each resonance in turn;
6. The vibrators were turned through 90° and Step 1 was repeated for across-valley vibration. No resonances were found in this case;
7. The vibrators were redeployed and Steps 1-5 inclusive were repeated for further modes of vibration;
8. Step 7 was repeated with a further redeployment of the vibrators
9. A recording of the ambient response was made for a period of about 12 hours.

A certain amount of background vibration was observed which, on occasions, made the measuring of the lower frequency responses rather difficult.

For the use of ambient excitation step 9 only is required, although the necessary recording time is dictated by the lowest frequency of resonance of the structure.

1.2 The philosophy of assessment of state of health from dynamic measurements

The use of very precise measurements of the dynamic properties of bridges has led to a rationale for the management of such facilities with a methodology that is capable of augmenting and upgrading visual inspections (Jeary et al). The overall analogy is with that of the use of an electrocardiograph to detect abnormalities in a human subject. The vibration of the structure is analogous to the rhythm of a person's

The rationale for the methodology involves the retrieval of the system properties of the bridge and the formalized search for indications of the initiation of any of the possible failure modes for the type of bridge.

The equations of dynamic motion for a structural system are defined using Newton's second law of motion and applying this to individual modes of vibration. Under these circumstances for each mode 'r' the equation to describe motion can be expressed as:

$$m_r = \frac{\hat{F}_r}{\hat{x}_r\, 8\, \zeta_r\, \pi^2\, f_{r^2}}$$

Where, for mode 'r' for an applied modal force of F_r, the displacement is x_r, the frequency of resonance is f_r and the damping ratio is $\zeta_{r.}$

In practice, we are more interested in the displacement per unit force and the damping parameter. The use of a measurement of displacement per unit force allows comparison with the requirements of design and construction, and the damping parameter gives a measurement of the energy dissipation by the structure. Since, for any single mode, the modal mass m_r does not change in the elastic regime, then measurements of the frequency of resonance and the non-linear damping characteristic contain all of the information that is necessary to compare the demand to capacity ratio (or assess the magnitude of an event that would make the structure exit the elastic range, and all types of energy loss by the structure (such as that caused by damage, water leakage and breaching of a clay core). All of these parameters apply to a single mode of vibration, and so the deflected mode shape that is characteristic of mode 'r' also has to be assessed. Each type of bridge has characteristic modes of vibration, and the application of this methodology can be applied to all types of bridges (including stone, steel or concrete, single span and multiple span, box and girder). In all cases these types have been tested in the field and examples are given below.

The methodology requires a force to be applied to the bridge. Because a series of bridges were tested using induced vibration testing (with a large vibrator system), and these results were correlated against the response of bridges from naturally occurring forces, then the non-intrusive methodology has been calibrated in the most precise way possible. Examples of naturally occurring forces include wind, traffic and micro-seismic activity. Because of the precision of the instrumentation used it is no longer necessary to wait for an event such as an earthquake for the state of health of the structure to be assessed. In this way regular or continuous monitoring can also be used to show the gradual ageing process for the structure. Such detailed information allows the management of facilities and the planning of necessary maintenance that is informed by measurement. This type of measurement is capable of discerning information about problem areas of a bridge that are not apparent to a visual observation, and therefore offers a significant advantage over a more conventional type of inspection. This type of measurement can also be performed quite quickly (as little as a few hours for a single span bridge) and is economically efficient.

In practice the force can be applied from natural sources such as air movement, traffic or other human agency.

The following describes the response of as single degree of freedom (mode 'r').

$$\boldsymbol{X_r} = \frac{F_r}{8 f_r^2 \zeta_r M_r \pi^2}$$

Where for mode 'r'

M is the participating mass
f is the frequency of resonance
F is the force
Ç is the damping ratio of mode r

Thus the displacement per unit force can be defined as:

$$\frac{X_r}{F_r} = \frac{1}{8 \zeta_r f_r^2 M_r \pi^2}$$

- The displacement per unit force is inversely proportional to the damping times the stiffness.
- If the modal mass is unchanging, and the mode shape is unchanging then for a given frequency and damping for a mode 'r' the displacement per unit force will remain unchanged up to the elastic limit.
- In practice there may be small changes in the frequency of resonance (as a function of amplitude – not as a function of time). There will be changes to damping with amplitude. However, we can compensate for such effects by measuring the non-linear damping.

There are several system-level parameters which aid in the conversion from dynamic response (acceleration records) to Dynamic Signature, and identification of damage in a structure during a STRAAM structural assessment:

1. Gross migration of frequency of resonance away from the expected response. In particular, the loss of stiffness in each mode of vibration can be estimated by comparing the differences in measured frequencies of resonance from the expected values. Lower frequencies indicate a loss of stiffness in a particular mode of vibration.

2. Spectral bifurcations whereby a principal mode of vibration shows signs of splitting into several modes of vibration. This indicates that the structure is forming mechanisms and that local resonances are forming.
3. Changes in modal amplitude ratios can be tracked over time to show indications of changes to particular modes of vibration which can indicate that parts of the structure are responding differently from previously. Inferences of damage or strengthening can be made utilizing these changes along with other observations.
4. Energy dissipation as measured through the nonlinear damping parameter. Damping values which are higher than expected are clear indications that energy is being dissipated through cracking, rubbing of structural members or unexpected soil-structure interaction (foundation damage). This measure generally requires a long duration of measurement such as that obtained with continuous monitoring in order to establish the full amplitude dependent damping behavior.

1.3 Digital Signal Processing (Baseline Spectral Response Analysis)

The on-site measurements of acceleration are processed using standard and proprietary digital signal processing (DSP) techniques to facilitate the extraction of relevant dynamic properties of the structural system. The main output of the DSP process is the decomposition of the time-series acceleration data into its frequency content (Power Spectral Density). The spectrum is interpreted to identify the modes of vibration (frequencies of resonance, amplitudes and modal ratios) of the structure. This forms the baseline Dynamic Signature and is essentially a fingerprint of how the structure is currently behaving with resonances appearing as isolated peaks in the plots. This baseline Dynamic Signature provides the datum with which future dynamic responses can be compared for assessment of changes to the structure's performance.

1.4 The Methodology

STRAAM uses a systematic approach, called the STRAAM Protocol, to understand how a structure behaves and for developing the best approach of monitoring the structure for an assessment and then long term monitoring.

The STRAAM Protocol involves several steps necessary to establish the baseline Dynamic Signature of the structure including:

1. Step 1 (Site Survey, Photos, Drawings, Reports) is to gather field information so that the monitoring plan will achieve the project goals efficiently. This was accomplished through discussion with Schnabel and the transfer of design drawings and photos.
2. Step 2 (Structural Model and Frequency Range Identification) we will use the existing FEM (or create our own if needed) to understand the expected response, mode shapes and frequency ranges for the structure. Additionally, it can help locate areas of the structure which will provide the greatest response for our instruments. This is all integrated into an advanced monitoring plan that is designed to best achieve the project goals. We performed the FEM on this dam to determine the frequency range of each mode of vibration.
3. Step 3 (Data collection/ Signal Conditioning) we proceed to the field to capture response information from the structure in an efficient and effective manner. We performed field measurements on January 12, 2012. Measurements were taken over a 5 hour period from approximately 10am to 3pm. The instruments were located based on results of the FEM, which allowed us to determine a good location to capture the desired response. When monitoring, we recorded acceleration (along the X, Y and Z axis), tilt (along the X and Y axis), and temperature at a rate of 200 samples per second for the acceleration, 10 samples per second for the tilt, and 1 sample per second for the temperature. The sensitivity of the instruments allows STRAAM to capture low amplitude response information to be used for analysis.
4. We then proceeded with steps 4-7 of the STRAAM Protocol where we process the data into the response spectra and compare the dynamic resonant frequencies in various modes and various conditions. This iterative process completely correlates the measured response with the expected response from the model.

2. Bridge 1

The first bridge is a 22.8 meter span precast concrete super tee bridge. The bridge is on a busy metropolitan road and the assessment was undertaken to demonstrate the STRAAM assessment to the local road authority. The bridge was selected as it had a single lane closure for works on the approach slab. Using the existing road closure minimised the impact on local road users.

Figure 1. Bridge 1.

Figure 2. Underside of Bridge 1.

The field testing component of the bridge was conducted on 21 February 2017. The data acquisition phase took approximately two hours on site. This included the setup of the sensors and data acquisition components, recording of the vibration responses, and subsequent removal of the test equipment. Accelerometers were deployed at different locations on the bridge to measure vibration responses in the longitudinal, transverse and vertical directions.

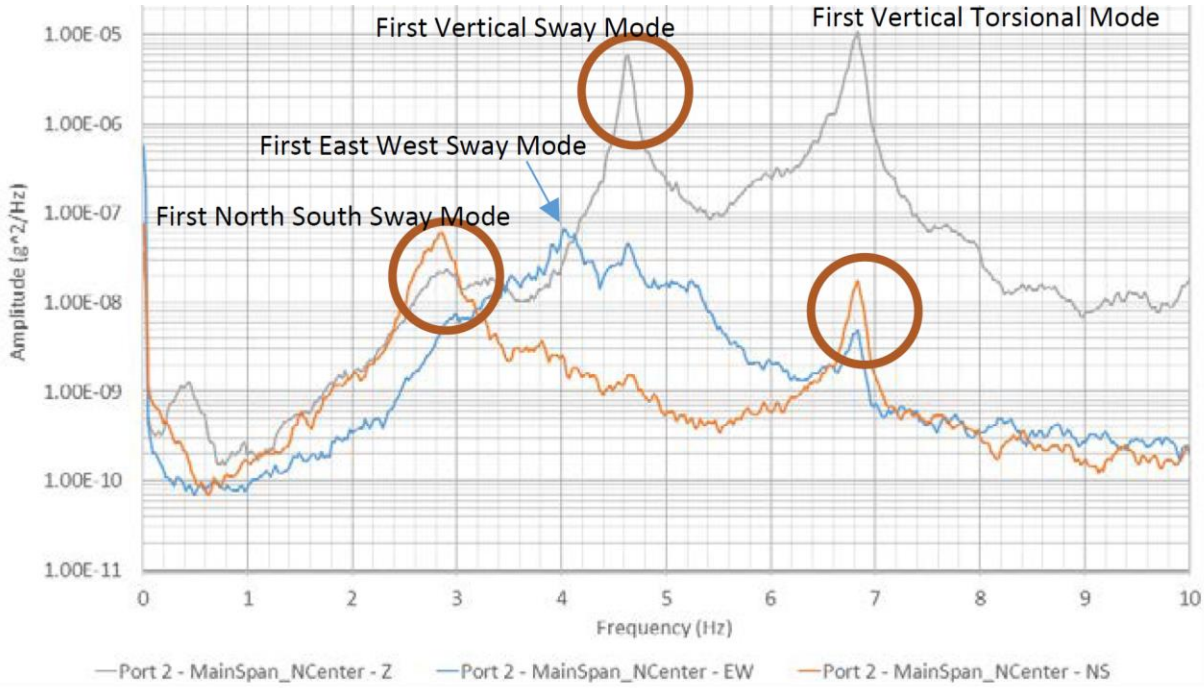

Figure 3. Spectral response of bridge, each peak corresponds to a natural frequency

The assessment found some small anomalies in the response of the bridge. This can be seen in the comparison of deflection of the north and south parapets; with the North parapet deflecting approximately 50% more than the South parapet.

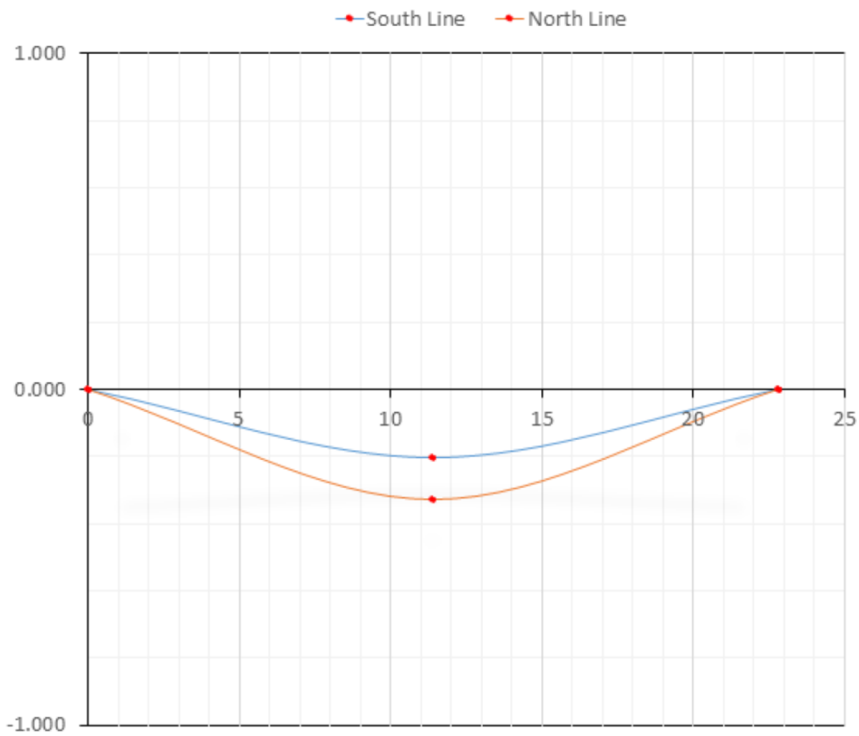

Figure 4. Bridge parapet deflection at first mode of vibration; 2.881 Hz.

Once the data had been collected from site it was cleaned to remove background noise and then analyzed by a random decrement algorithm to determine the harmonic frequencies for the structure in the X. Y and Z directions.

Table 1. Bridge calibration of FEM to measured frequencies.

Mode	Measured Frequency	RNFEM Frequency	% difference
NS1	2.88	3.02	4.6
EW1	4.00	3.90	2.6
V1	4.61	4.61	0.0
V2	4.63	5.18	10.6

The assessment allowed the calibration of a finite element model of the bridge, which can be used as a tool for future changes, the effects of maintenance and the period checking of the bridge for changes.

The calibrated finite model was used to assess the performance of the bridge to original design parameters. In addition, various load combinations were evaluated to gain an understanding of the current load capacity of the bridge.

The following is a series of simulated deflections when a truck (or trucks) are stationary on the bridge. The bridge is 22.8 metres in length and 9.5 metres in breadth. The results of these simulations are summarized as follows.

Table 2. Bridge calculated deflections.

Loading condition	file	displacement (mm)	Posn Node #
single T44	DCB5	6.4	30
two T44's opposite lanes	DCB6	6.3, 6.6	30,21
queue T44's one lane	DCB7	8.4	30,31
queue T44’s two lanes	DCB8	8.2	21,20,31,30
B Double 1 lane	DCB9	8.2	21,30
B Double 2 lanes	DCB10	8.2	20,21, 30,31

The maximum deflection of 8.4 mm is well within the AASHTO span/375 requirement.

The STRAAM assessment of the bridge memorialized a baseline for the structure and determined:

- The bridge is in good condition.
- The small anomalies observed suggest different aging effects at the abutments.
- The FEM has been calibrated for the existing condition of the bridge and is a resource for assessing current and future loading conditions.
- The response of the bridge is within design loads and AASHTO recommendations.

3. Bridge 2

Bridge 2 is a two lane, single cell box girder bridge. It has two spans, with a central pier. The west span is 42.5 meters and the east span is 18.5 meters. Concern has been raised as the west abutment has subsided approximately 100 mm and the east abutment has subsided approximately 50 mm. Prior to commencing repairs to the bridge, a bridge inspection was undertaken and the current structure condition has been memorialized.

Figure 5. Bridge 2

A Dynamic Signature consists of determining the bridge's frequencies of resonance, mode shapes and damping properties through collecting on-site measurements of acceleration from ambient excitation. Mainmark collected approximately three hours of data on November 13th 2017. Five tri-axial accelerometers were used in conjunction with STRAAM's Structurocardiograph (SKG) to capture the unique Dynamic Signature of the bridge. The STRAAM system collects acceleration data at 200 samples per second. The accelerometers were placed on various locations on the deck. The positions of the measurements on the bridge are shown in the following figure. The positions are labelled with a prefix of 'R' denoting a reference position, or 'T' representing a position used for 'traveller' measurements. Measurements in the reference positions took approximately three hours, whilst traveler positions continued for 30-45 minute depending on operation requirements. The time of measurement is predicated on the requirements for analysis that allow the reduction of statistical errors associate with the retrieval of parameters from randomly induced data.

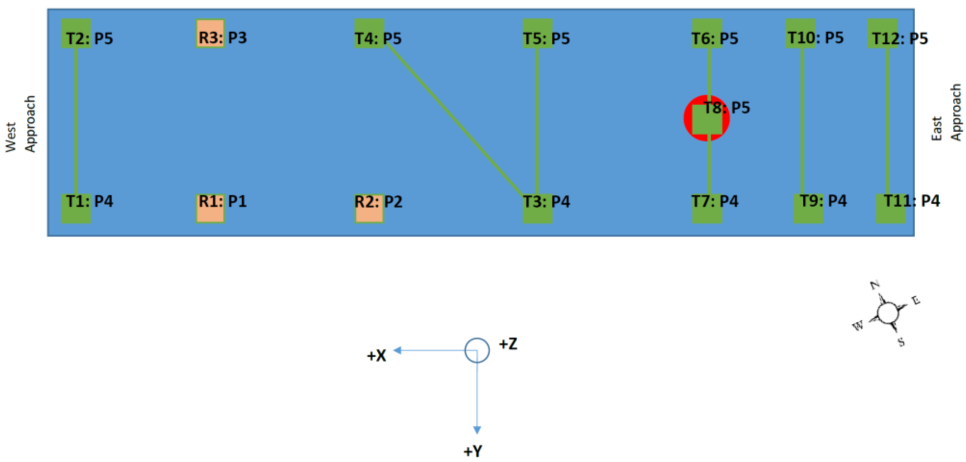

Figure 6. Bridge 2 accelerometer locations

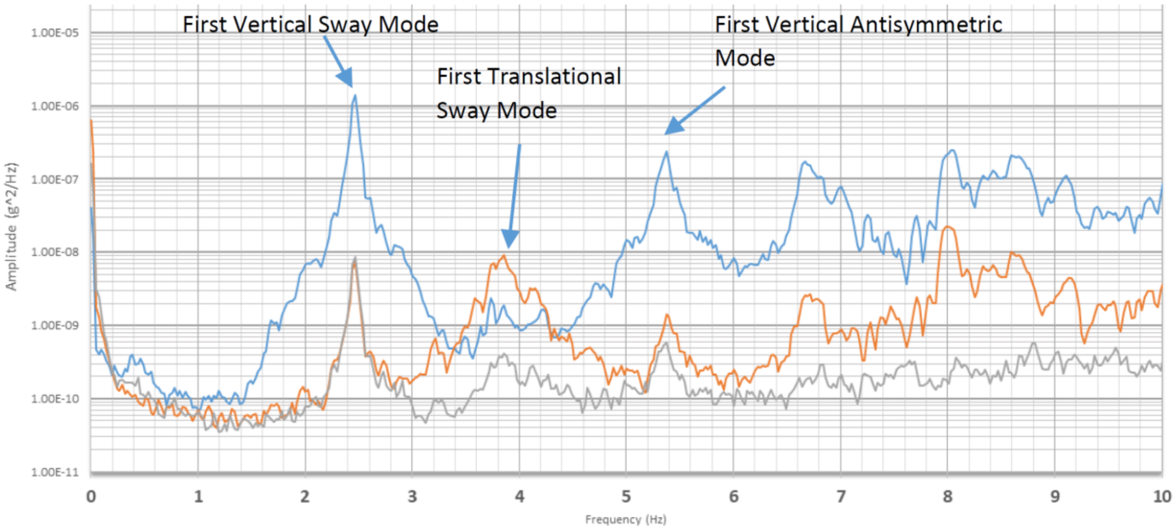

Figure 7. Bridge 2 baselines and fundamental frequencies

Establishing the baseline for the bridge prior to the works is critical to ensuring the works do not compromise further the structure. The variables that determine the harmonic frequencies are mass, geometry and stiffness. During the raising of the abutments towards their original position the harmonic frequencies should not shift; as the base variables are not impacted by the lifting operation. In addition, strain gauges on the bridge should record a decrease in strain over the pier location. The response of the structure during the works will be monitored in real time to ensure the lifting does not cause damage to the bridge.

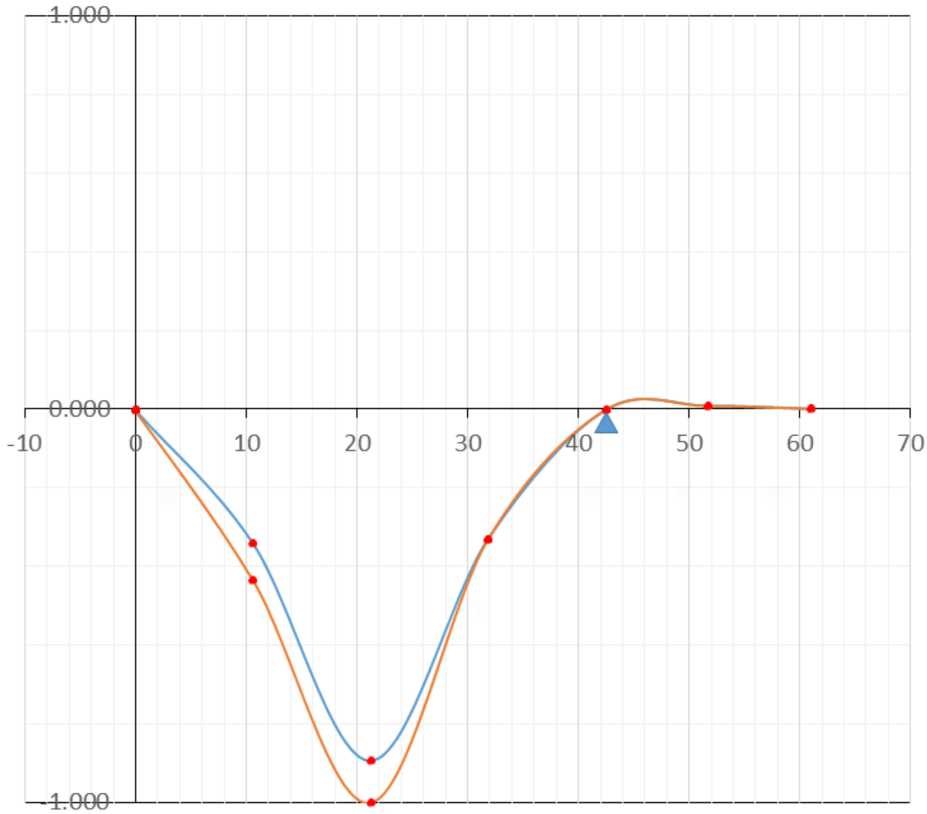

Figure 8. Bridge 2 parapet deflections

The measured deflection of the bridge under load illustrates the influence on the west span loads on the east abutment. The original design allowed for this by concrete filling the box at the east abutment. However the settlement of the abutments has negated some of the benefit provided by the concrete filled boxes.

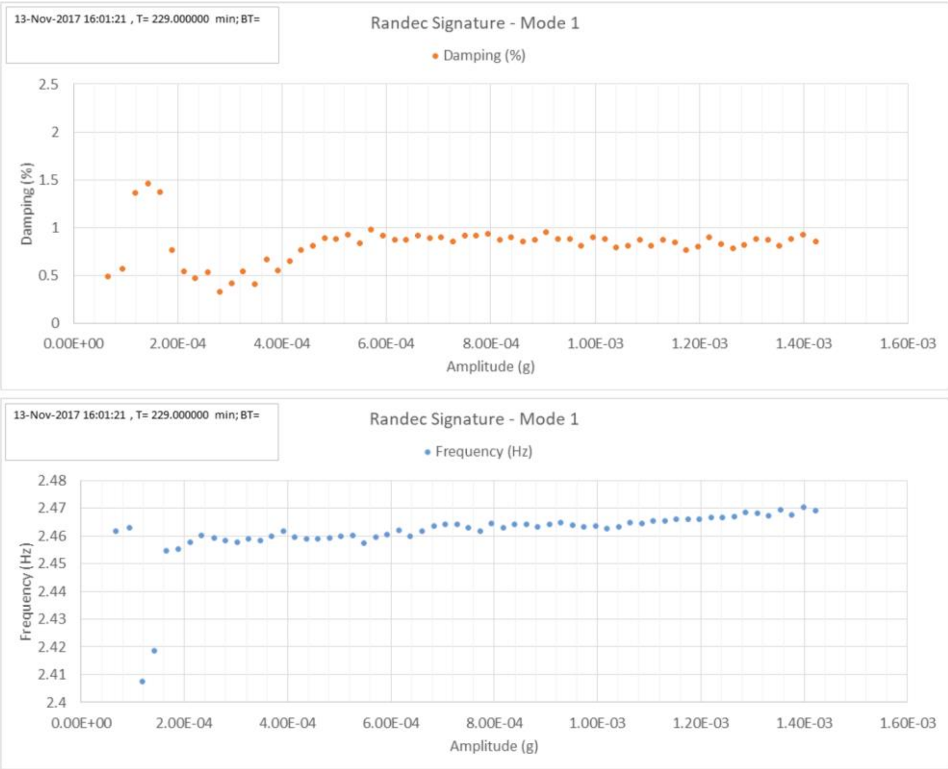

Figure 9. Bridge 2 damping coefficients

The damping ratio of approximately 1% of critical shows that the bridge is in relatively good condition despite the amount of settling. An anomaly occurs at lower amplitude with a sudden reduction in frequency and increase in damping. This anomaly will be compared with future measurements, and is most likely associated with the differential movement at the eastern abutment.

In conclusion, the baseline response of the bridge has been detailed. The following points should be noted:

1. Except for the differential settlement of the abutments, there are a minimal number of anomalies present in the recordings that indicate significate structural damage.

2. The first three modes of vibration have been characterized above and will be used as a baseline to compare with future measurements.

3. The Randec Signature presented in Mode 1 shows an anomaly at low amplitude. This sudden reduction in frequency and increase in damping generally indicates energy dissipation associated with the interaction of the bridge with abutments. As the improvements to the structure conducted by Mainmark progress, changes to this anomaly will be tracked and reported on.

4. Summary

The STRAAM system provided by Mainmark allows rapid, non-evasive, real time assessment of the condition of the bridge structure. Accelerometers and strain gauge measurements are used to provide a baseline record of the structure. Periodic assessment of the structure and comparison of the baselines over time provides quantifiable evidence of any deterioration in the structure.

The outputs of the accelerometers and strain gauges are used to calibrate a finite element model of the bridge, thus providing an accurate view of the current status of the bridge. Once the model of the bridge is calibrated to the measured behavior of the structure, it can be used to assess operational conditions and changes to use.

5. References

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