Validation of finite element light rail bridge model using dynamic bridge deflection measurement

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ABSTRACT: Use of finite element modelling (FEM) to predict structural behaviour under static and dynamic loading conditions is a well-established aspect of the bridge design process. A finite element model for the design of the new Grand Parade Bridge in Cherrywood, South County Dublin, was developed by Arup, to understand how the bridge extension would change the behaviour of the existing light rail bridge and how Luas operations would affect the structural dynamic behaviour of the proposed pedestrianised area. As with any FEM, a number of assumptions are made in creating the bridge model. In order to validate the FEM precise dynamic measurements of the existing structure under live load were undertaken. Murphy Surveys used a microwave interferometer to measure the dynamic deflection of the bridge at a number of locations on the viaduct spans of interest. The main advantages of this passive monitoring method include that no installation of sensors on the bridge is necessary (meaning no need to get access or power to the bridge), it outputs displacement directly and in real-time, and has a stated accuracy of 0.01 mm at an acquisition frequency of up to 100 Hz, making it suitable for dynamic measurement. This paper describes the finite element model of the bridge, the assumptions made in the FEM, the measurement method and test results, demonstrating the good agreement between predicted and observed behaviour.

KEY WORDS: Validation; Finite Element Model; Dynamic Monitoring, Interferometry, Structural Dynamics.

1 INTRODUCTION

The creation of a finite element model for any structure involves making multiple assumptions. An experienced engineer uses established guidance, design codes and standards to set modelling parameters, element size, degrees of freedom, material properties, load conditions, and safety factors. The model serves to predict the behaviour of a structure, however, owing to the number of predictions made there will generally be differences between the predicted and actual behaviour [1].

Arup was appointed to undertake the design of the Grand Parade Bridge. This bridge forms part of the Cherrywood Town Centre Development and will carry Grand Parade with vehicle, pedestrian and cycle access, which runs adjacent to the existing Luas track, over the R118 Wyattville Link Road. The existing bridge is a steel-concrete composite structure.

This new structure will be constructed by means of widening the existing Luas Bridge at this location. To achieve this an integral connection between the existing and new bridge is provided. Understanding of the condition and structural behaviour of the existing bridge is essential prior to detailed design and incorporation into the proposed new bridge [2]. The importance of this practice has been described in different studies [3]–[6].

The monitoring application presented in this paper and its subsequent outcomes are a result of the structural assessment of the existing structure, shown in Figure 1, carried out as part of the planning approval process before progressing with the detailed design and building works of the Grand Parade Bridge.

Figure 1. Existing Grand Parade Luas Bridge

Murphy Surveys Ltd proposed a dynamic monitoring solution to assist Arup with the validation of their developed finite element model of the existing structure. A microwave interferometer was used to measure vertical deflections of the bridge deck in real time during tram crossing events. The instrument emits a high-frequency wave and measures the phase difference in reflected backscatter from the structure, allowing the determination of deflection and frequency of vibration of the subject.

The results of the dynamic monitoring measurement were processed and compared to outputs from the bridge model. This assessment allows for the validation of Arup's developed finite element model of the existing structure and its associated assumptions, which are described later in this paper.

2 METHOD OF MEASUREMENT

An IDS GeoRadar IBIS-FS interferometric radar, shown in Figure 2, was used for the dynamic measurement. This allows the engineer to gain an understanding of the static and dynamic performance of the structure under ambient and live loading conditions respectively.

Figure 2. IDS GeoRadar IBIS-FS Interferometric Radar

The instrument measures and infers:
- Vertical and Horizontal Displacement (sub-millimeter accuracy from up to 500 m range)
- Resonant frequencies (Sample frequency of up to 100 Hz, meaning most bridge frequencies of interest (<50 Hz) can be characterised)
- Vertical and Horizontal Modes of Oscillation

Benefits of this solution include:
- Remote, non-intrusive installation – no need to access the bridge or affect Luas operations;
- No requirement for fixed point reflectors
- Quick to set up
- Real-time feedback and analysis of results (displacements, frequencies);
- Multiple observation points from single set-up;
- No restriction on operational hours (works in all light conditions)

The instrument uses Radar (RAdio Detection And Ranging) to measure the phase difference between emitted and back-scattered electromagnetic waves. The displacement of an object is inferred from the measured phase difference. The device scans at up to 100 Hz enabling it to be used to measure the dynamic behaviour of objects. In this way, it is ideally suited to measure the dynamic behaviour of large civil engineering structures such as dams, cuttings, embankments, bridges, wind turbines, tall buildings, open pit mines, etc.

The IBIS-FS uses a Modulated Frequency Continuous Wave (MFCW) operating at 17.1 GHz. Exploiting the MFCW technique, the IBIS-FS builds a one-dimensional image, called a range profile where the targets in the detection area of the device are resolved within a range resolution of 0.75 m, independent of distance and related to bandwidth, called a ‘range bin’ (see Figure 3).

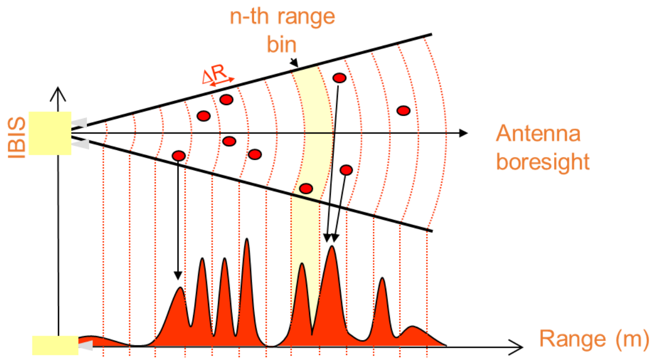

Figure 3. IBIS-FS Method of Measurement - Range Resolution

Each sample at every range bin has associated amplitude and phase information. The differential interferometric calculation provides the resulting object displacement along the line of sight, d_p, by comparing the detected phase difference ($\varphi_2 - \varphi_1$) of reflected waves (at wavelength, λ) from the object, Equation (1).

$$d_p = -\frac{\lambda}{4\pi}(\varphi_2 - \varphi_1) \qquad (1)$$

Since the displacement, d_p, is measured along the line of sight of the device, the geometry of the device set up relative to the bridge is measured to enable the calculation of the actual vertical displacement of the object. The vertical height, h, from the instrument radar head to the height of the object being measured and the line of sight distance or range, R, from the radar head to the object are used to calculate the vertical displacement, d. Equation (2).

$$d = d_p \times \frac{R}{h} \qquad (2)$$

To interpret the results it is necessary to identify the measurement areas through an analysis of the Signal Noise Ratio (SNR) of the recorded signal. Where the SNR is high there is good reflection from a prominent object in the detection area of the device. Once the ranges of interest are identified the IBIS DataViewer post-processing software enables the export of the displacement data for the relevant ranges. With an understanding of the dimensions of the structre, the ranges of interest can be associated with structural elements.

3 DYNAMIC MONITORING MEASUREMENT CAMPAIGN

3.1 Bridge Deflection Measurement

The dynamic monitoring measurement campaign was carried out by Murphy Surveys on Wednesday 25th September between 9:30 – 15:30. Weather conditions were favourable. It was clear, sunny, with light winds and an average temperature of 16°C. Traffic management was in place for the duration of the monitoring.Seven individual set-ups were used to capture the dynamic response of both bridge spans from multiple angles. The dynamic bridge response to 42 tram crossing events was captured during the testing campaign. The data from set-up 3 is presented in this paper and compared with output from the FEM. Six tram crossing events were caputred at this instrument set-up, three inbound and three outbound trams.

The purpose of set up 3 was to capture the mid-span deflection of Span 1 on the loaded (western) side of the bridge. The radar was positioned in the central median to the west side of Span 1, as shown in the schematic in Figure 11 and the photograph in Figure 5. The radar head was pointed towards beam B1_3 and beam B1_4. This position corresponds to the alignment of the tram tracks on the deck above this location.

Figure 4. Instrument set up 3

Table 1 lists the tram crossing events recorded at set up 3. The inbound trams crossed the bridge on the wetstern side of the bridge while the outbound trams crossed the bridge in the centre of the span as shown in Figure 11.

Table 1. Tram crossing events at set up 3

Number	Tram Direction	Time
1	Outbound Tram	11:22:51
2	Inbound Tram	11:31:50
3	Outbound Tram	11:33:10
4	Inbound Tram	11:44:45
5	Outbound Tram	11:47:31
6	Inbound Tram	11:57:51

As discussed in Section 2, the emitted electromagnetic waves are back-scattered off prominient features on the strucutre. A signal to noise ratio plot is shown in Figure 5. SNR peaks are noted at ranges of 9 m, 11 m and 15 m. These ranges are shown in Figure 4 and correspond to the intersection of beam B1_2 and S1-T2, beam B1.3 and mid-span of beam B1_4 respectively.

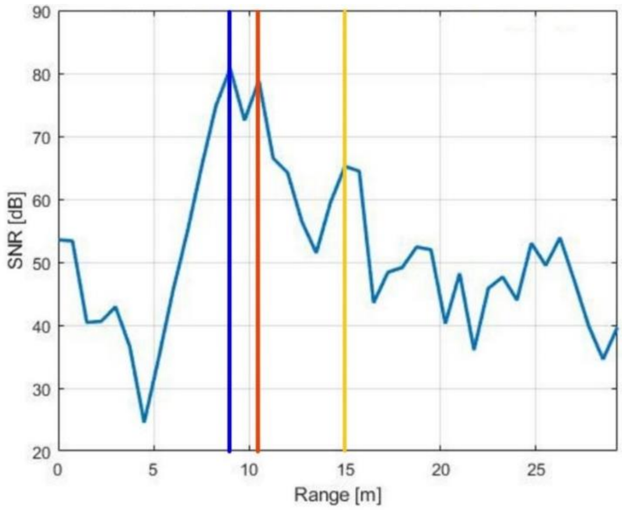

Figure 5. Range vs. Signal Noise Ratio at set up 3

The displacement vs time graphs for two selected tram crossing events are shown in Figure 6 and Figure 7. A maximum displacement of approximately -0.88 mm was observed at this set up, occuring during the inbound crossing event. This was detected in the 15 m line of sight range corresponding to the mid-span of beam B1_4.

The tram loading for the inbound crossing event is closest to the monitored areas. There were smaller observed bridge deflections for the outbound crossing event. An uplift of approximately 0.2 mm is observed after the tram has crossed the span (for the inbound tram) and before the tram has entered the span (for the outbound tram). This is due to the continuous nature of the bridge beams - the tram load on the adjacent span causes uplift in the monitored span.

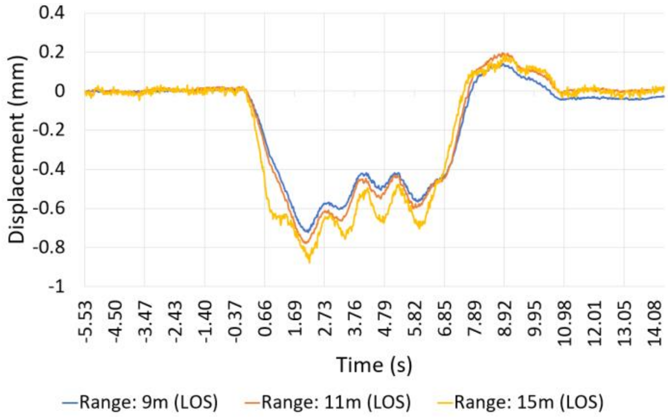

Figure 6. Maximum measured deflection at set up 3 for inbound crossing event No. 6.

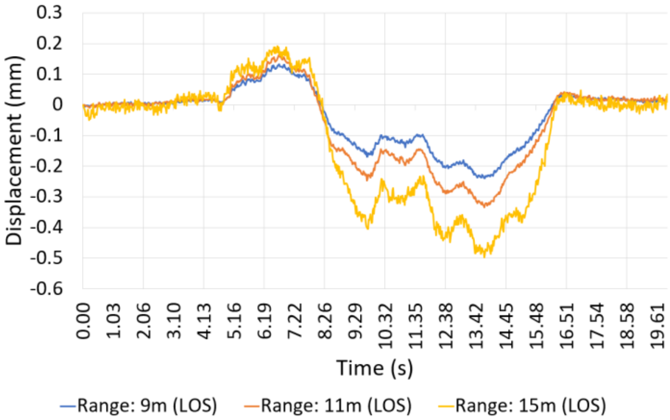

Figure 7. Maximum measured deflection at set up 3 for outbound crossing event No. 5

3.2 Bridge Frequency Observations

The monitored structure did not exhibit any observable ambient vibration due to its relatively short span and high stiffness. A basic frequency analysis of the excited bridge was carried out on the displacement measurement obtained during the measurement campaign. The results are presented in Figure 8.

It can be observed that the frequency decreases as the tram crossing time increases. Therefore, it is likely that the frequencies observed in the signals are a function of the tram crossing speed and therefore cannot be used to determine the natural or excited frequency of the bridge. The dominant frequencies occur in the range between 0.75 – 1.2 Hz.

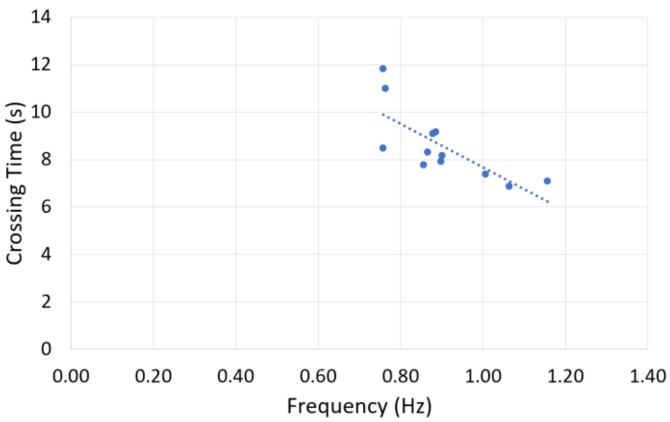

Figure 8. Frequency analysis of all measurements

4 FINITE ELEMENT MODEL

As part of the design of the new Grand Parade Bridge structure, Arup developed a finite element model (FEM) in SOFiSTiK software composed of both the existing Luas bridge structure and the proposed extension. In Figure 9, the former is displayed.

Figure 9. Existing Luas Bridge Finite Element Model

The structure is modelled using shell and beam elements and loaded accordingly extended into three dimensions by the addition of elements to represent the support columns and pile caps.

As this assessed structure is located within the last two stops of the Luas green line, Cherrywood and Brides Glen, the corresponding load of the passage of the carriage is adjusted in order to correctly reproduce the scenario of the relatively emptier vehicle. This is even more relevant taking in account the time of the day at which this monitoring application was conducted, corresponding to off-peak operation of this type of transportation.

As mentioned before, for comparison purposes between the model and the measurement the maximum measured bridge deflection was chosen which was measured at set up 3 as described in Section 3.1.

The maximum observed deflection was of -0.88 mm at mid-span on the loaded span of the structure for the inbound passage of the Luas tram. Similar displacements were picked up when loading the other span at its midspan (maximum observed deflection of 0.84 mm).

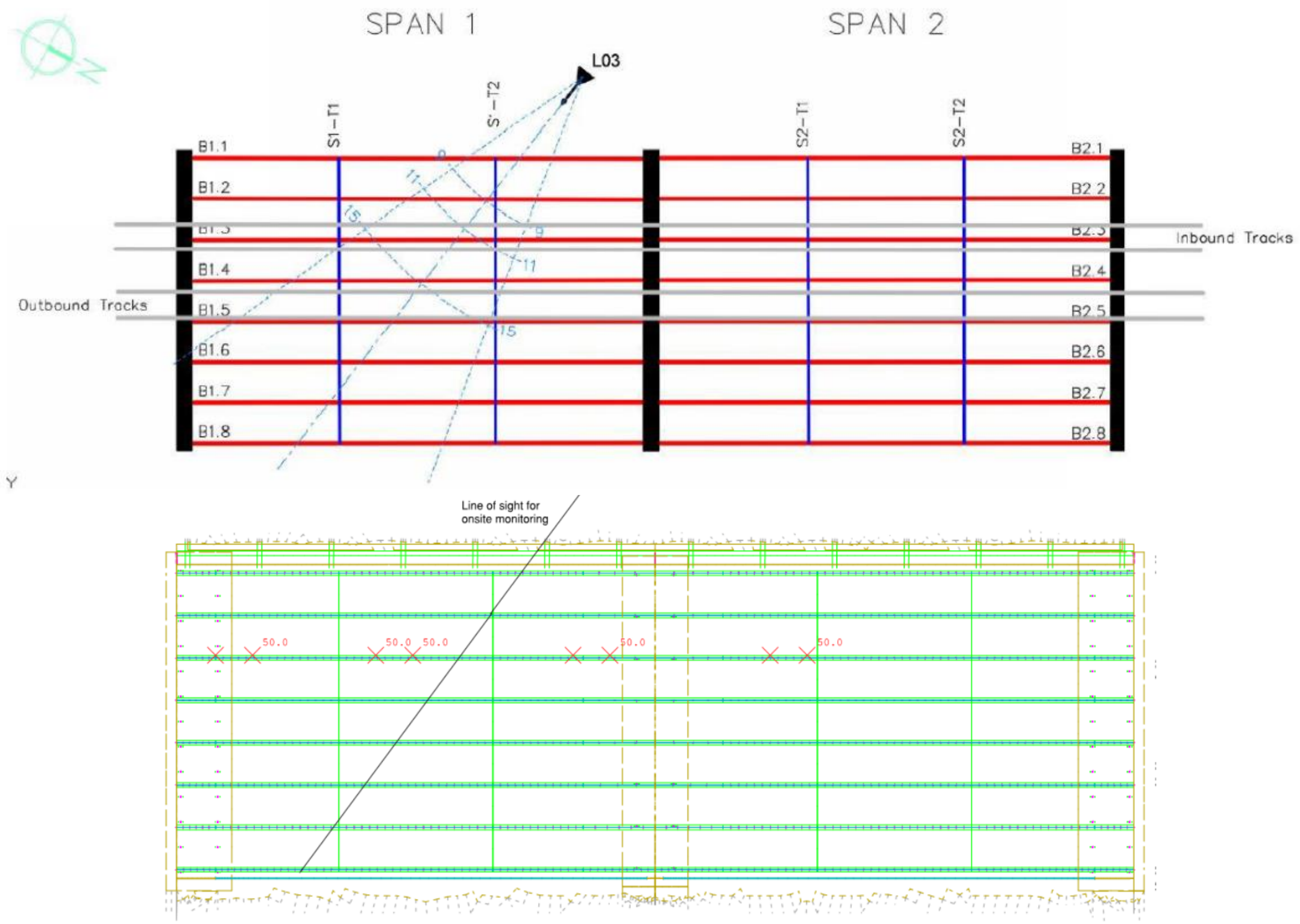

Figure 10. Bridge structural member naming convention, instrument set up location, radar line of sight and range bins for set up (above) and superimposed in the FEM model (below)

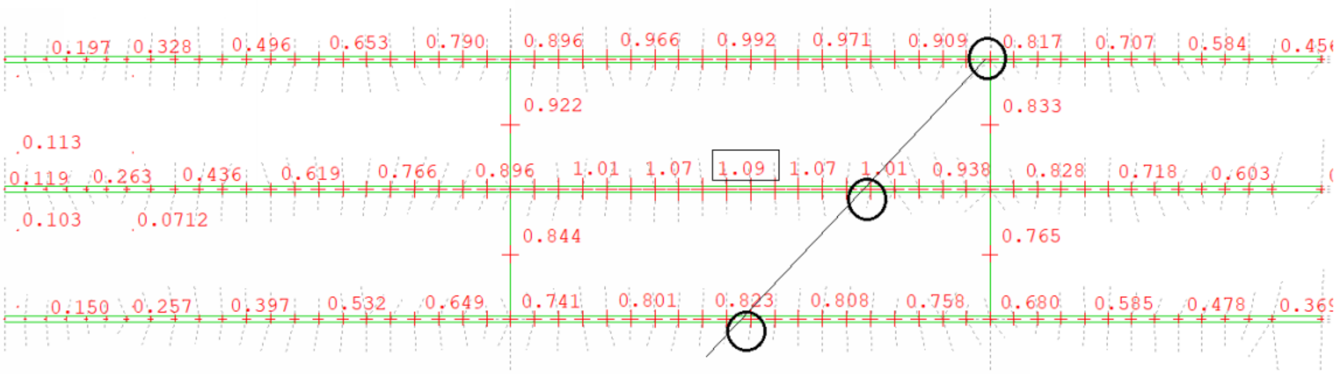

Figure 11. FEM obtained displacements with adjusted axle load

The adjustment of the axle load for the considered Luas tram is made in order to replicate the conditions verified on site during the dynamic monitoring as mentioned before. The monitored deflections have been compared with displacements derived from unfactored load movement along 2 No tracks defined in the FEM structural model and depicted in Figure 10.

In this way, it is observed how the values measured on site through the interferometric radar are well in agreement with those obtained from the developed finite element model for the existing structure as seen in Figure 11. Here the point locations measured by the radar sensor are highlighted for an easier comparison.

From comparing the nodal deflections in the model (range 0.82-1.01 mm) to the onsite observed deflections (range 0.7-0.88 mm), the difference is within the range of 0.13 mm.

Considering the submillimetre nature of the observed displacement, the sensor accuracy (0.01-0.1 mm), its spatial resolution (0.75 m) and finally the resolution of the axle load location iterations in the FEM model, these results are considered to be well within agreement.

Hence, through the conduction of this monitoring application with the use of the interferometric radar, the designers had the confidence going forward that these results showed that the developed finite element model was a fair representation of what had been constructed and was a strong basis for the design of the extension of this structure and its interaction with the to be built Grand Parade Bridge.

5 CONCLUSION

The use of accurate geospatial measurement to validate structural design models is a worthwhile step in the design process, especially where extensions or integrations into existing structures are planned. In the case of the Grand Parade Bridge extension, the strucutre being extended is a critical piece of transport infrancture with unique loading condtions.

The application of dyanmic structural monitoring at this bridge gave the designers confidence in their finite element model of the existing structure and its behavior under the load of the Luas tram. This was due to the good agreement between the derived deflections of the model when compared with the obtained measurements by the interferometric radar. The adjustment of the tram load in order to better characterisation of the idle traffic situation and specific location of this structure within the green Luas line route also provided further assurance on the correct representation achieved by the FEM and its accuracy for the future design of its integration into the to be built Grand Parade Bridge extension.

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