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Finite element modelling of the Loopline Bridge and model validation using ground-based radar interferometry

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ABSTRACT: This research investigates the procedure of using ground-based radar interferometry to develop and validate a finite element model of the Loopline Bridge in Dublin, Ireland. A description of the bridge is outlined and a three-dimensional finite element model was developed using RFEM, a commercial software package. The modelling approach was first validated against known theoretical solutions. The bridge model was then verified with section property calculations, experimental studies in the literature and deflection tests. The dynamic deflection at midspan of the Loopline Bridge was measured for two train crossing events using ground-based radar interferometry. A single train crossing event showed the deflection of the loaded side of the span with respect to the unloaded side. Additionally, a dual train crossing event demonstrated the twist in the deck from the train loads travelling in opposite directions on separate sides of the bridge. The same loading conditions were simulated in the finite element model and the resulting deflections were extracted. A comparison between both sets of deflection data was carried out and their correlation validated that the model accurately captures the behaviour of the real Loopline Bridge structure for both train loading scenarios.

KEY WORDS: Bridge; Finite Element Model; Model Validation; Radar Interferometry; Deflection;

1 INTRODUCTION

Bridges are among the most complex and important structures in modern transportation systems and crucially require maintenance and monitoring for both safety and economic reasons. Finite element (FE) models are regularly used in modern engineering for the structural analysis of bridges. FE models cannot solely predict the actual behaviour of such structures. The accuracy of FE modelling strongly depends on the experimental validation of the numerical results [1]. Therefore, a validation process is required which introduces the actual condition of the structure under observation, to synchronise the FE model and increase its accuracy [2]. This research aims to investigate the procedure of using ground-based radar interferometry to develop and validate a finite element (FE) model of the Loopline Bridge in Dublin.

Ground-based radar interferometry is a newly established, non-destructive, powerful remote sensing technique that can precisely detect live dynamic deflections in bridges. This method of measurement has several advantages compared to conventional sensors; including its high accuracy, being remote and non-intrusive, and its ability to be carried out from a great distance over a short period of time [3],[4]. For this technique, the radar instrument generates and transmits electromagnetic waves from its antennas with a high frequency. The system then measures the radial displacement of specific target objects by comparing the phase differences between the emitted and reflected electromagnetic signals from an object, at different moments in time [5]. The vertical displacement is then computed using simple trigonometry, typically processed by the built-in software of the device on site.

The Loopline Bridge, originally constructed between 1889 and 1891, is a wrought iron lattice truss girder bridge in the centre of Dublin City. The five span viaduct structure carries two curved ballasted tracks of the active Dublin loop line over the River Liffey in addition to several roads and streets. Restoration works were carried out to the structure between 1958 and 1960 which comprised the replacement of the trough deck with welded steel stringer beams to a flat deck plate, and the replacement or reconditioning of several cross girders. The 36 m single-span section of the bridge over the River Liffey will be considered and focused on for the purpose of this paper, shown in Figure 1. Construction and refurbishment detailed drawings for the bridge and specific railway vehicle information was provided and utilised for this research courtesy of Iarnród Éireann Irish Rail.

Figure 1. The Loopline Bridge span over the River Liffey.

The dynamic deflections of the Loopline Bridge under operational conditions were measured using a ground-based radar interferometer, carried out by Murphy Geospatial. Two train loading events of interest were analysed – a single and dual train crossing event.

An FE model was developed and the modelling approach was analysed with comparisons to known theoretical solutions for a simply supported beam with various loads applied. A two-dimensional model is first formed and verified before the development of the three-dimensional model. The FE model is verified with cross-sectional property calculation checks, simple deflection loading tests and experimental truss deflection tests from the literature. Lastly, the final model is validated with the real deflection measurements of the bridge obtained using the ground-based radar interferometry device.

It was found that the developed FE model accurately imitates the behaviour of the Loopline Bridge for both train crossing events. The deflections of the FE model are shown to correlate with those measured on the real bridge using the ground-based radar interferometric device. The limitations of the research include the secondary sourced experimental data and the assumptions made in the FE modelling due to the unknowns associated with the bridge structure and train loading.

2 DEFLECTION MEASUREMENTS USING RADAR INTERFEROMETRY

2.1 Experimental setting

The dynamic deflections of the Loopline Bridge under operational conditions were measured by Murphy Geospatial on 30th January 2018, using a commercial IBIS-FS interferometric radar, photographed in Figure 2. The device was set up on the adjacent bridge which provided the best line of sight for the radar to measure the midspan deflection of the structure at both sides. Other impactful characteristics such as weather conditions, proximity and visibility of the structure were favourable.

Figure 2. Interferometric radar set up at the Loopline Bridge.

2.2 Experimental crossing events and loading

The dynamic bridge responses of two train crossing events are focused on for the purpose of this paper. It should be noted that the deflection measurements obtained by the interferometer are with reference to the unloaded, static deflection of the bridge due to its self-weight.

Crossing event No. 1 lasts for approximately 30 seconds and consists of a southbound Diesel Multiple Unite (DMU) arriving first onto the east side of the span before a northbound EMU (Electrical Multiple Unit) DART (Dublin Area Rapid Transit) arrives shortly after, travelling in the opposite direction on the west side of the bridge. The DMU exits the bridge span first, before the EMU, causing both sides of the span to be individually and simultaneously loaded at different stages of the crossing event.

Crossing Event No. 2 lasts for approximately 60 seconds and features a northbound EMU arriving onto the west side of the span for the full duration of the event leaving the west side of the span left unloaded. Both crossing events are summarised in Table 1.

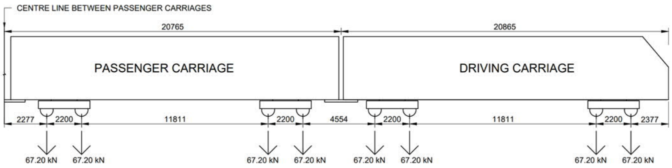
Table 1. Train crossing event details.

Crossing Event	Train	Direction (Span Side)	Time (s)
1	DMU	Southbound (East)	31.0
	EMU	Northbound (West)	
2	DMU	Northbound (West)	60.0

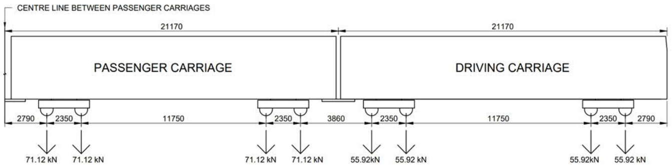
The railway vehicles that crossed the bridge during the crossing events, detailed above, were identified through observation. The specific vehicle classes, selected accordingly due to their median wheel loads, were considered to be a four-axle 29000 class DMU and a four-axle 8200 class EMU. The axle and wheel loads of each carriage are summarised in Table 2, with the axle spacing and wheel loads illustrated in Figure 3.

Table 2. Typical weights of Iarnród Éireann railway vehicles.

Train	Carriage	Axle Load (kN)	Wheel Load (kN)
DMU	Driver & Passenger	134.30	67.20
EMU	Driver	111.83	55.92
	Passenger	142.25	71.12



a) 29000 Class DMU (all dimensions in mm).



b) 8200 Class EMU (all dimensions in mm).

Figure 3. Typical axle spacing and loading of Iarnród Éireann railway vehicles.

2.3 Ground-Based Radar Interferometry Measurements

The midspan vertical deflections of both edges of the bridge were captured and analysed. The dual train crossing event demonstrated the twist in the deck from the train loads travelling at different times, in opposite directions and on separate sides of the bridge. The single train crossing event showed the deflection of the loaded side of the span with respect to the unloaded side. The displacements over time graphs for the two train crossing events are shown in Figure 4 and Figure 5. The timing for each crossing event is considered to have started when the first train enters onto the bridge.

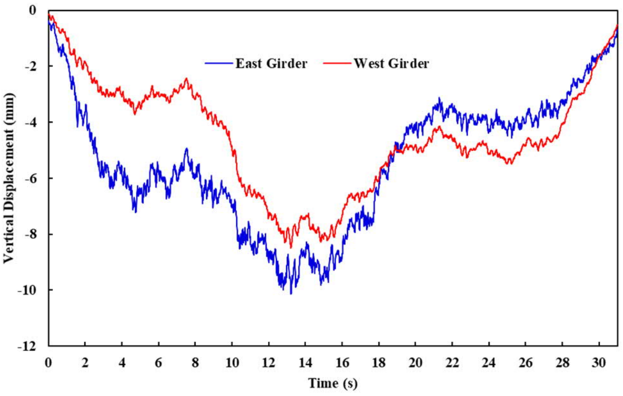


Figure 4. Measured midspan deflection for Crossing Event No.1.

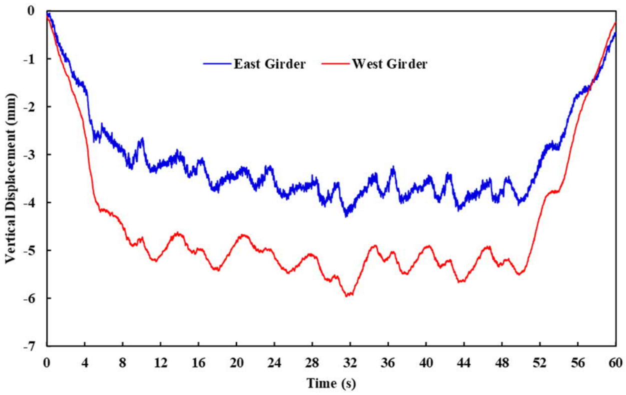


Figure 5. Measured midspan deflection for Crossing Event No.2.

3 FINITE ELEMENT MODEL

3.1 Modelling method

An FE model of the Loopline Bridge was developed using RFEM, a commercial software package. Typically, it is advised to simplify FE models down to one or two-dimensional structure models, however a three-dimensional model is chosen for the purpose of this study with the objective of successfully modelling the twisting of the deck caused by the two, oppositely moving loads from train crossing event No. 1.

The FE model has been developed using nodes and lines in a three-dimensional plane. Relevant member cross sections were created and assigned to the model lines using beam elements, with each element's corresponding structural characteristics associated. The FE modelling approach was first validated against known theoretical solutions. A simply supported beam was modelled and analysed with various load cases applied, with the expected deflections calculated theoretically for comparison. The FE beam model gave identical results to the theoretical solutions, hence validating the modelling approach.

3.2 Loopline Bridge model

For all associated models; structure arrangement, section properties and both local and global support conditions were input to reflect that of the as-built structure.

Material properties for the model elements were adopted from known steel characteristics in the 1960s period, from when the structure underwent reconditioning, and the wrought iron was inevitably replaced by steel [6]. Therefore, steel S355 was considered for all structural materials within the model. No element self-weights were active in the model to allow for the deflection results to be only due to the loading and therefore comparable with those measured by the radar interferometer.

A simplified two-dimensional FE model of the bridge consisting of one truss girder was first created to ensure the model behaved as expected. The model was created using a 'wireframe' comprised of nodes and lines to which element members were assigned, see Figure 6. Loading of a single typical railway vehicle was idealized and applied to the bottom chord member elements of the model. Satisfactory midspan deflection results were observed in the model when compared to the measured deflection data from Crossing Event no. 2, with the 2D model simulating half of the loading on half of the structure.

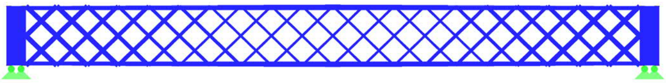


Figure 6. Two-dimensional truss girder FE model.

After the 2D model gave satisfactory modelled deflections, a three-dimensional wireframe FE model was developed in the same manner, presented in Figure 7. All supports were fixed except for Support 3 and 4 which allowed longitudinal translation, in line with the details of the real-life structure.

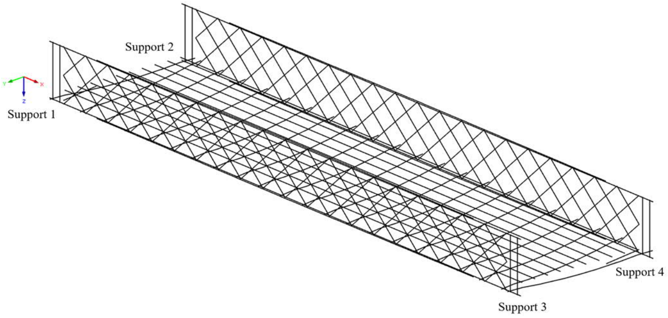


Figure 7. 3D Loopline Bridge wireframe model.

The 3D model accurately represented the articulation of the superstructure; two truss girders supporting several transverse cross girders from the bottom chords. Longitudinal steel stringer beams were modelled, supported by the cross girders, to allow for the application of moving loads to the FE model. Furthermore, these elements assisted with the longitudinal distribution of loads, helping to prevent localized deflections, and partially providing the structural role of the bridge deck which was unknown and out of the modeling scope.

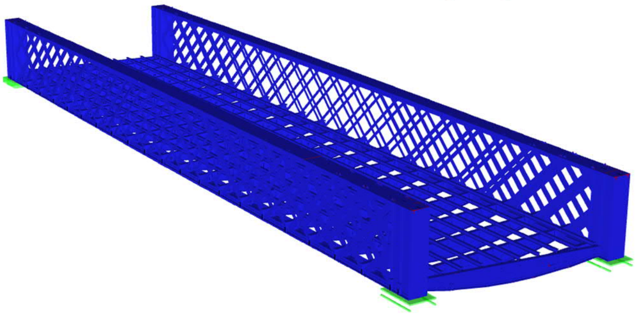


Figure 8. 3D Loopline Bridge FE model.

3.3 Model verification

FE modelling is only an approximation and is not completely robust. A model verification process is an important step in identifying small errors in the modelling process that could have significant impacts on the results. The 3D FE model was first verified in terms of the modelled cross-sectional properties. The automatically calculated section properties from RFEM were comparable to those obtained using several standard equations, derived from First Principles. Secondly, simple deflection tests were carried out on the model to assure it deflected appropriately and expectantly. Point loads were applied to the midspan of the central and quarter span cross girder and separately, to the truss girders at midspan and quarter span. Deflections were extracted from the truss girders at quarter and midspan, in addition to midspan of the supported cross girders at them location on the structure. The deflection results from a 50kN point load applied to the central two cross girder at midspan are shown in Figure 9.

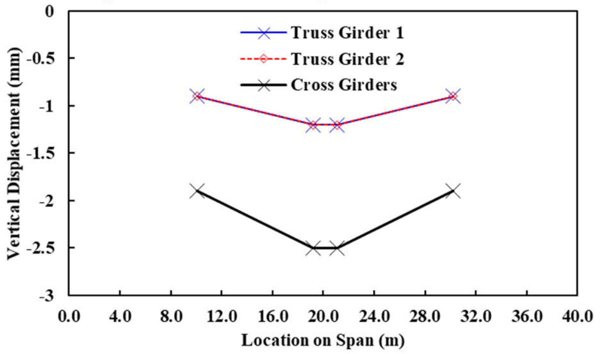


Figure 9. Model deflections due to loads on cross girders.

Lastly, deflections observed by the model were validated against three experimental and field truss structure deflections obtained from the literature. One of these studies considered a 4 kN/m^2 load applied to the middle third of a 48.8 m steel truss pedestrian footbridge [7]. Representative loads were applied along the FE model's cross girders to replicate uniform loading on a deck. The resulting deflection curve comparison in Figure 10.

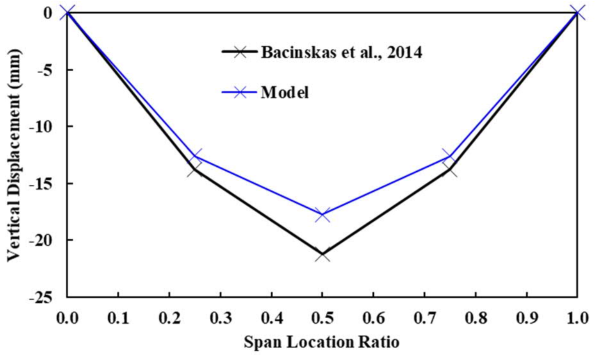


Figure 10. Deflection curve comparison with literature field test.

3.4 Model Validation with Interferometry Measurements

As previously discussed, every FE model should be verified based on experimental data or a mathematical approach to conform to reality. Simplification is inevitable in computer-aided modelling approaches which may cause some disparity between the real case scenario and the modelled case. The ground-based radar interferometric measurements are used to calibrate the model behaviour.

Identical loading conditions to those outlined in Table 2 were introduced into the RFEM model. These loads are treated as static loads with a moving step of 1.5 m. Specific loading details were not precisely recorded during the experimental crossing events which resulted in several additional unknown factors. Firstly, the exact times for each train entering the span for crossing event No.1 were unknown. Estimates of these critical times were made through analysing the deflection measurements of the ground-based radar interferometry device (Figure 4) which are shown in Table 3. The timing for the second crossing event only consisted of one crossing vehicle and is therefore known.

Table 3. Train crossing event No.1 timing estimations.

Approx.Time (s)	Action	Travel Direction
0.0	DMU enters span	Southbound
7.5	EMU enters span	Northbound
17.5	DMU exits span	Southbound
31.0	EMU exits span	Northbound

While the number of carriages present for crossing event No. 2 were identified from available video footage, the number of carriages and therefore axle loads to be applied for each train was unknown for crossing event No. 1. To estimate the number of carriages, an iterative approach was employed to align the modelled loading and resulting deflections with the measured deflections of the radar interferometer. Static deflections were measured in the model with point loads, representing the axle weights of the vehicles, moving along the structure in steps of 1.5 m. This step count was used consistently for all the modelled loading with only the number of carriages being adjusted. Table 4 displays the resulting determined and identified number of carriages for each railway vehicle during both crossing events. These values are within the standard Iarnród Éireann fleet carriage ranges and therefore conform to reality and to the likely loading.

Table 4. Number of modelled railway vehicle carriages.

Crossing Event	Vehicle	No. of Carriages
1	DMU	6
1 & 2	EMU	8

To compare the model deflections with those measured, the number of static load cases required to have the loads move over the bridge was translated into to the time taken for the actual crossing events to occur. After this process, the final loading conditions applied across the model gave the following vehicle velocities (Table 5) which conform to possible actual velocities due to the speed restrictions on this section of the line.

Table 5. Modelled railway vehicle velocities.

Crossing Event	Vehicle	Velocity (km/h)
1	DMU	32.7
	EMU	32.7
2	EMU	31.4

4 RESULTS & DISCUSSION

Deflections were extracted from the model at the midspan of both truss girders for both modelled loading cases. These points of interest are at the same locations on the bridge which were measured by the ground-based radar interferometer and so can be compared accordingly. An example of the deformed three-dimensional FE model for a typical load case during the moving simulation of the first crossing event is portrayed in Figure 11. Each wheel load is assumed to distribute equally to two longitudinal steel stringers, therefore each axle is represented by four point loads applied each to a steel stringer.

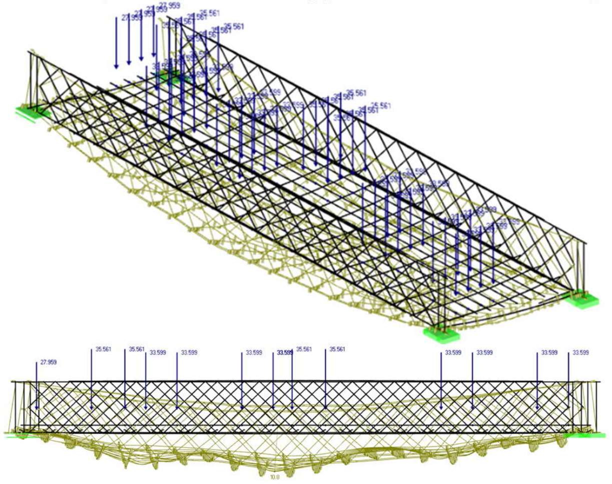


Figure 11. Final 3D FE bridge model deflection results: 3D projection (above) and elevation (below) (300 scale factor).

The deflection results extracted from the model for the simulation of both crossing events are presented in Figure 12 and Figure 13 respectively.

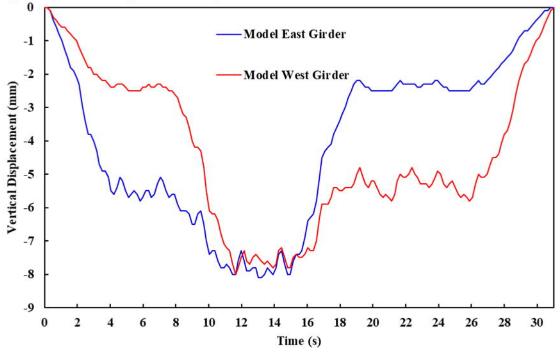


Figure 12. 3D FE bridge model deflection results for crossing event No.1

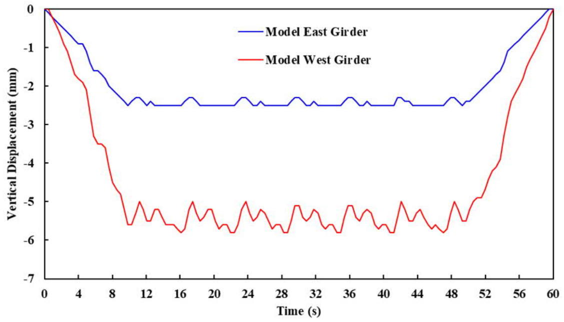


Figure 13. 3D FE brid model deflection results for crossing event No.2

4.1 Verification of model

The objective of this research was to develop a three-dimensional FE model of the Loopline Bridge and validate it with the measured midspan deflections obtained using ground-based radar interferometry. The deflection experienced by both sides of the span for two chosen railway vehicle crossing events have been analysed with the results from the developed FE model for both crossing events demonstrating a correlation between the performance of the model and the real deflections experienced by the bridge.

The model verification process, most noticeably checking the cross-sectional properties against theoretical calculated values, was deemed effective after this verification check identified several issues, while the model was showing extremely localized deflections at that stage. Additionally, the global deflections of the model were verified with simple loading tests and were comparable to truss deflections obtained from the literature. For the latter; the quantity and locations of applied loading, including the self-weight being active, and the point at which deflections were measured, were all mirrored in the FE model so that it could be compared accordingly to that of the literature.

4.2 Modelled and measured deflections

The measured dynamic deflections from the ground-based radar interferometer and the FE modelled static deflections for both crossing events were analysed. The two sets of data for both sides of the bridge are portrayed in Figure 14.

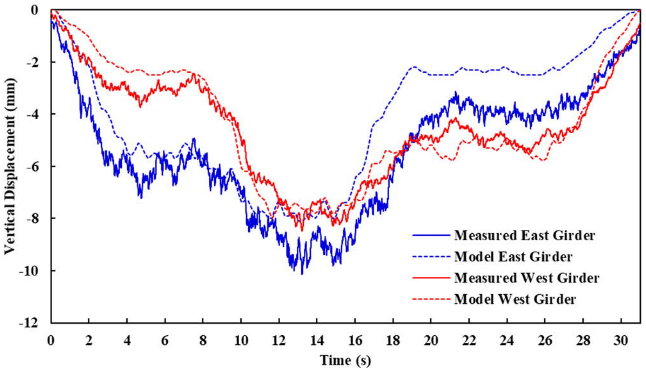


Figure 14. Deflection comparison for crossing event No.1.

As the DMU railway vehicle first loads the east side of the span, the measured deflections for both girders are marginally greater than the deflection observed in the model, lasting 7.5 seconds until they equate as the EMU enters onto the other end of the span. The deflections of both sides are then equal for a short amount of time until a magnitude difference to the east girder of 1.0 – 1.5 mm occurs from 12 seconds onwards. A strong correlation in the timing of changes in deflections is seen for both girders. The results show the model effectively simulates the torsion or ‘twisting’ of the bridge deck caused by different sides of the span being loaded at different stages during the event. This can be seen with the change in maximum deflected side of the span, alternating from the east to the west girder.

Additionally, at the start of the event, the deflection of the loaded (east) side is twice as large in magnitude as the unloaded (west) side in both the model and the bridge indicating an accurate representation in the model of the degree in twist of the deck. The model shows this same degree of twist again at the end of the event with the west side loaded, however this does not align with the measured deflections of the structure.

Likewise, for the second crossing event, Figure 15 compares the deflection of the loaded side of the span, the west side, during the single EMU railway vehicle crossing event.

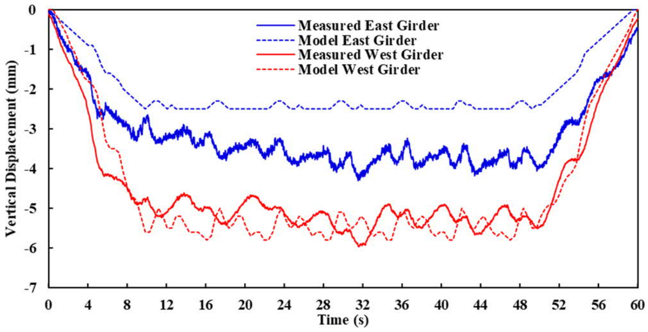


Figure 15. Deflection comparison for crossing event No.2.

The deflection of the model for the loaded west side correlates accurately with the measured deflection. The deflections experienced by the unloaded west girder show a constant difference in deflection, of approximately 1 mm. As the EMU is fully loading the span from 10 seconds onwards, the measured and modelled deflections of the west girder are seen to have a constant fluctuating 1mm rate of change, with the modelled deflections typically fluctuating at a marginally greater level. The deflection of the unloaded side is less comparable to the measured deflections. However, the deflections for both girders are shown to fluctuate within a similar range and at equal occurrences, with the east girder fluctuating in opposite directions.

In the results from both crossing events, the deflection results from the model show strong similarity with the measured deflections. There is a clear discrepancy between the modelled and measured deflections specifically identified for the deflection of the unloaded east girder while the west side is being loaded. It makes theoretical sense for the model to behave relatively equally but mirrored when either side of the span is individually loaded because of the approximately similar loads exerted by the EMU and DMU. Furthermore, despite the marginal skew of the deck, there is an identical approach in the geometry of the bridge for both vehicle directions on each side of the span. It is likely that the inconsistent deflections for when the west side is independently loaded, in comparison to that of the east side, is due to unsymmetrical structural behaviour of the bridge because of factors that were not accounted for in the modelling process such as bearing issues, defects or construction errors in the bridge.

Several limitations have influenced the accuracy of these results both in the reliability of the experimental data and some unknown variables in the development of the FE model. Firstly, the measured bridge deflections are a secondary source of data, carried out prior to this research. Additionally, dynamic displacement measurements are compared to static deflections of the model, creating a source of error due the influence from the dynamic amplification phenomenon. Applying dynamic loads to the model was out of the scope of this research. Furthermore, the rail vehicle model types and specific crossing event timings required estimations, and inevitably present additional loading due to passengers or luggage was unknown and therefore not accounted for. Lastly, the properties of the steel deck and track ballast were unknown, and modelling these elements was not within the scope of this research, resulting in less accurate load distribution.

5 CONCLUSION

This paper focused on the procedure of using ground-based radar interferometry to develop and validate an FE model of the Loopline Bridge in Dublin, Ireland. Ground-based radar interferometry is a newly researched, powerful remote sensing technique that accurately measures the deflection of structures due to loading. By analysing the measured dynamic deflections of the Loopline Bridge and showing a correlation with the deflection of the FE model, this study validates the accuracy of the developed model in relation to the ground-based radar interferometry measurements. Several assumptions made in the modelling process were defined with reference to their limitations on the outcome of the research. The final validated FE model was found to effectively represent the behaviour of the real Loopline Bridge structure which was confirmed through a comparison of the real and modelled deflection magnitudes.

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