NUMERICAL AND EXPERIMENTAL ASSESSMENT OF DYNAMIC EFFECTS OF ROAD TRAFFIC IN A CABLE-STAYED BRIDGE

R. Calçada, A. Cunha and R. Delgado

Faculty of Engineering of the University of Porto
Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
E-mail: acunha@fe.up.pt

ABSTRACT

This paper describes the development, updating and validation of the numerical modelling of the bridge-vehicles system of a new cable-stayed bridge (Salgueiro Maia Bridge, in Portugal), presenting several comparisons between calculated and experimental results, associated to the modal analysis, static and dynamic tests of the bridge under controlled heavy roadway traffic.

1 INTRODUCTION

The authors have recently developed an experimental study of the dynamic behaviour of a new cable-stayed bridge (Salgueiro Maia Bridge, in Portugal) under controlled heavy roadway traffic, circulating at different speeds and along several lanes. This experimental approach involved the use of a new strain measurement system with remote control from the lab, based on strain gages embedded in the bridge deck and load cells in stay-cables, and the main results achieved were published at the last IMAC conference [1].

The present paper complements the previous reference, being especially focused on the development and validation of the numerical modelling of the bridge-vehicles system, presenting several comparisons between calculated and experimental results associated to the modal analysis, static and dynamic tests of the bridge.

2 BRIEF DESCRIPTION OF THE BRIDGE

Salgueiro Maia Bridge is the new Tagus crossing about 50km upstream Vasco da Gama Bridge, comprehending a single-plane cable-stayed bridge with a central span of 246m and lateral spans of 78m and 42m (Figure 1). Due to the high seismic risk of the area, the deck and towers were completely isolated, interposing appropriate isolation devices between that main part of the bridge structure and the corresponding supporting piers. The deck is 28.2m wide, being formed by a concrete box girder of 10x2.5m, complemented by lateral slabs supported by pre-cast concrete struts connected to the bottom of the box-girder. The towers, with a total length of about 50m above the deck, are a mixed steel / concrete structure, especially conceived to facilitate the execution phase.

3 EXPERIMENTAL ANALYSIS OF THE BRIDGE RESPONSE UNDER ROAD TRAFFIC

3.1 Experimental approach

The experimental assessment of the bridge behaviour was conducted according to the following steps: (i) experimental identification of modal parameters for calibration of the numerical modelling, on the basis of ambient vibration tests; (ii) installation of a strain measurement system for dynamic measurements under traffic loads; (iii) application of this system in the static tests at the final stage of construction of the bridge; (iv) experimental evaluation of dynamic amplification factors associated to the passage of heavy trucks at different speeds along several lanes; (vi) experimental characterisation of the pavement roughness on the basis of a laser scanning system.

3.2 Measurement system

A set of embedded strain gages was installed near the mid-span, according to Figure 2. The choice of the points of instrumentation was dictated by the interest of evaluating not only global dynamic effects on the deck, but also local effects on concrete slabs [2]. Moreover, sixteen load cells were still manufactured and installed by Freyssinet in the inferior anchorages of the stay cables, according to the distribution shown in Figure 1. Ten of the stay cables were equipped with a load cell, while three others (cables AT2, AT1 and AT18) were equipped with two load cells. All the signals captured by these sensors are being acquired, digitised and analysed using 16 bit HBM Spider8 units in connection with a PC as data acquisition and conditioning system. This computer in the bridge is remotely controlled by another PC located at the University of Porto. Additional instrumentation installed by LNEC [3] was still temporarily used, namely a set of accelerometers (Figure 1, U1-U5) placed at 5 different deck cross sections, during the dynamic tests, and displacement measurement systems (optical and hydraulic systems), during the static tests.
3.3 Static and dynamic tests

The static load tests of the bridge were performed according to the load configurations schematically represented in Figure 1. For that purpose, 20 trucks of the tractor-semitrailer type were used, with a gross weight of 38-40t each. The configurations 1 to 7 correspond to the loading of the bridge in the whole width of the carriageway, two trucks beside downstream and other two beside upstream. Eccentric loading, with trucks occupying only the downstream (1D, 3D, 4D, 5D and 7D) or the upstream sides (1U, 3U, 4U, 5U and 7U) of the carriageway, were still applied.

The dynamic tests consisted of the passage on the bridge of trucks of the same type used in the static load tests, circulating always from South to North, at speeds of 15, 30, 45, 60, 75 and 90km/h, in the following conditions: (i) passage of one truck along the slow lane of the 2x3 lanes scenario, corresponding to the future enlargement of the carriageway (1st series); (ii) passage of one truck in the slow lane of the 2x2 lanes scenario, corresponding to the present situation (2nd series); (iii) passage of six trucks circulating by side in three groups of two trucks (3rd series); (iv) passage of isolated trucks in the slow lane of the 2x3 lanes scenario (4th series), over a wood plank 4cm height, located at the midspan. The real speed of the trucks in each passage was accurately measured using a police radar.

3.4 Measurement of the pavement roughness

The pavement roughness, which is a determinant factor of the dynamic structural response, was measured with the help of a laser profilograph, which allows to obtain the longitudinal profile along two lines, one in each wheeltrack, of a lane of the carriageway. Figure 3(a) shows, for example, the longitudinal profile obtained for the right wheeltrack of the slow lane in the 2x3 lanes scenario. The length of acquisition was about 2000m, sampled at 0.10m intervals. The quality of the pavement was evaluated on the basis of the calculation of the International Roughness Index (IRI) [4] and using the classification established by ISO Standard ISO-TC-108 [5]. The IRI is calculated from a measured longitudinal profile, previously smoothed with a moving average whose baselength is 0.25m, by accumulating the absolute value of the relative body-axle displacement of a standard quarter-car model moving at a speed of 80km/h, and dividing this total value by the profile length, which leads to a summary roughness index with units of slope (m/km).

3.5 Numerical modelling of the vehicle

The numerical modelling of the vehicle took into account the characteristics of the heavy lorries really used in the static and dynamic tests performed. The vehicle is an articulated lorry constituted by a tractor, having a single front and rear axles, with a trailer having a three axles group, as represented in Figure 5. From the dynamic point of view, the model of the vehicle is formed by the following elements: (i) Two rigid bodies, with mass M1 and rotary inertia I1, concentrated in the center of gravity of each body, linked together at a hinge, allowing rotation, so that only vertical dynamic forces are transmitted between the bodies; (ii) Springs with stiffness k1 and dash-pots with viscous damping c1, simulating the suspension system of the vehicle; (iii) Masses M2 simulating the axles and the wheels; (iv) Springs with stiffness k2 and dash-pots with viscous damping c2, simulating the contact between the wheels and the road surface. Figure 5 presents the values of the parameters of the vehicle model, as well as the corresponding mode shapes and natural frequencies. The first three modes, with frequencies of 1.836, 2.077 and 2.673Hz, involve essentially tractor and trailer bodies motion. The other modes correspond to axle-hop vibrations at frequencies in the interval 10.462-14.054 Hz.

4 NUMERICAL MODELLING OF THE BRIDGE-VEHICLES SYSTEM

4.1 Finite element modelling of the bridge

The numerical analysis of dynamic effects of road traffic in Salgueiro Maia Bridge involved the development of a finite element model, based on the use of 3-D beam elements (Figure 4). For that purpose, the bridge was discretised in 388 elements (190 elements for the deck, 52 for the towers and 72 for the stay cables). Beyond that, 74 beam elements were introduced to simulate the elastic supports used to realise the behaviour of the seismic isolation devices. The constants c1 and c2, used for the construction of a Rayleigh damping matrix (C=C1, M=M1, C2K), were calculated fitting the expression $\zeta=\frac{c_1}{2M_1+\frac{c_2}{K}}$ to the identified modal damping factors of vertical bending and torsional mode shapes, by the least squares method, the following values having been obtained: c1=3.710×10^{-2} s^{-1} and c2=8.114×10^{-4} s^{-1}.

4.2 Numerical modelling of the vehicle

The numerical modelling of the vehicle took into account the characteristics of the heavy lorries really used in the static and dynamic tests performed. The model of the vehicle is formed by the following elements: (i) Two rigid bodies, with mass M1 and rotary inertia I1, concentrated in the center of gravity of each body, linked together at a hinge, allowing rotation, so that only vertical dynamic forces are transmitted between the bodies; (ii) Springs with stiffness k1 and dash-pots with viscous damping c1, simulating the suspension system of the vehicle; (iii) Masses M2 simulating the axles and the wheels; (iv) Springs with stiffness k2 and dash-pots with viscous damping c2, simulating the contact between the wheels and the road surface. Figure 5 presents the values of the parameters of the vehicle model, as well as the corresponding mode shapes and natural frequencies. The first three modes, with frequencies of 1.836, 2.077 and 2.673Hz, involve essentially tractor and trailer bodies motion. The other modes correspond to axle-hop vibrations at frequencies in the interval 10.462-14.054 Hz.

4.3 Analysis of the bridge-vehicle interaction

The numerical analysis of the bridge-vehicles behaviour was developed establishing separated equations of motion for the bridge and the vehicles, and evaluating the dynamic component of the vertical force applied by the vehicles to the bridge, at each time instant, solving that set of differential equations using the Newmark method. At each time instant, an iterative procedure for the compatibilization of the two structural systems was used. This procedure is described in detail in ref. [6]. It’s worth noting that this numerical analysis took into account the eccentric application of the loads with regard to the longitudinal axle of the girder, according to Figure 6, as well as the spatial variability of the pavement roughness.

5 COMPARISON BETWEEN NUMERICAL AND EXPERIMENTAL RESULTS

5.1 Evaluation of modal parameters

The finite element model of the bridge was updated and validated on the basis of ambient vibration tests [3, 7]. These tests served in particular to adjust the lateral stiffness
of the seismic isolation devices interposed between the deck-towers system and the piers, which depend on the corresponding level of distortion. Table 2 shows the rather good correlation achieved between calculated and identified natural frequencies. Identified values of modal damping factors are also summarised in that table.

<table>
<thead>
<tr>
<th>Identified frequency (Hz)</th>
<th>Calculated frequency (Hz)</th>
<th>Identified modal damping (%)</th>
<th>Type of mode of vibration</th>
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<tr>
<td>0.43</td>
<td>0.43</td>
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</tr>
<tr>
<td>0.53</td>
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<td>1st towers bending</td>
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<td>2nd towers bending</td>
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</tr>
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<td>0.709</td>
<td>0.75</td>
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</tr>
<tr>
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<td>1st torsion</td>
</tr>
<tr>
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<tr>
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<td>1.163</td>
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<td>1.63</td>
<td>1.600</td>
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<td>2.72</td>
<td>2.735</td>
<td>0.57</td>
<td>3rd torsion</td>
</tr>
</tbody>
</table>

Table 2: Identified and calculated modal parameters

5.2 Results of the static tests

The comparison between experimental and numerical results of the static tests was done in terms of vertical displacements and rotations of the deck, as well as of axial forces in stay-cables. This comparison shows, in general, a rather close agreement of results, except in the case of the evaluation of axial forces in the shortest stay-cables, which may reveal some limitation of the 3-D beam model to simulate this local behaviour. Considering, for instance, the load configuration 4, the measured vertical displacement at midspan was 219mm, whereas the calculated value was 230mm (+5%). Similar relative differences of deck rotations were also obtained in case of eccentric loading. Figure 7 compares, on the other hand, the numerical and experimental values of the axial force in stay cables SR6 and SR11, obtained for the several configurations of the static load test trucks positions.

5.3 Results of the dynamic tests

The experimental results of the dynamic tests served, in a first instance, to check the main pattern of the calculated dynamic response. Such type of comparison is shown by Figure 8, where the dynamic effect associated to calculated bending moments at the midspan section and to strain values at the strain gage 9X are represented. Subsequently, the comparison of experimental and numerical results was made on the basis of dynamic amplification factors related with the previous control variables (Figures 9, 11) and of axial forces in stay-cables, as well as of peak vertical accelerations at midspan (Figure 10). Inspection of the results obtained showed a satisfactory agreement between measured and calculated values, although some scatter of the estimates has been noticed, as consequence of the random nature of the pavement roughness. Moreover, the numerical model overestimates DAFs of axial forces in the shortest stay-cables.

6 CONCLUSIONS

This paper described the development, updating and experimental validation of the numerical modelling of the structural behaviour of Salgueiro Maia cable-stayed bridge, taking into account the bridge-vehicles dynamic interaction and the real characteristics of the pavement roughness. The comparison between experimental and numerical results was made in terms of: (i) natural frequencies and mode shapes, (ii) vertical displacements and rotations at the midspan cross section of the deck, as well as of axial forces in stay-cables, during the static tests, and (iii) peak vertical accelerations of the deck and dynamic amplification factors (DAFs) of those response control variables, during the dynamic tests under controlled heavy traffic. This comparison could show the existence of a rather good correlation, that evidences the satisfactory reliability of the numerical model. However, some discrepancies could be found, namely in terms of DAFs of some response control variables, which can stem from some scatter of estimates associated to the random characteristics of the pavement roughness, as well as from some limitations of the 3-D beam numerical model to conveniently simulate some local behaviour. An appropriate reduction of the disturbance induced by the former factor should naturally involve the development of averaged DAF estimates, based on a higher number of truck passages over the bridge.

ACKNOWLEDGEMENTS

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REFERENCES

Figure 1: Lateral view of Salgueiro Maia Bridge with indication of the stay cables instrumented with load cells, of the sections instrumentated with accelerometers and of the configurations of the static load test trucks positions.

Figure 2: Midspan cross-section with location of the embedded strain gages.

Figure 3: (a) Longitudinal surface profile measured along the slow lane (2x3 lanes scenario) from Almeirim to Santarém; (b) Evolution of IRI values corresponding to intervals of 100m; (c) Classification according to ISO Standard ISO-TC-108.
### Table: Material Properties

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<th>Deck</th>
<th>Towers</th>
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</table>

### Figure 4: Finite element model of the bridge

*Mode 1 – f = 1.836 Hz*

*Mode 2 – f = 2.077 Hz*

*Mode 3 – f = 2.673 Hz*

*Mode 4 – f = 10.462 Hz*

*Mode 5 – f = 13.276 Hz*

*Mode 6 – f = 14.004 Hz*

### Figure 5: Schematic representation of the vehicle model and of the first eight modes of vibration

*Mode 7 – f = 14.008 Hz*

*Mode 8 – f = 14.054 Hz*
Figure 6: Analysis of the interaction between the vehicle and the bridge

![Diagram of longitudinal axle of the deck](image)

<table>
<thead>
<tr>
<th>Bridge</th>
<th>Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Action</td>
<td>$Q_b(t) = Q_{dia} + Q_{dyn}^{-1}(t)$</td>
</tr>
<tr>
<td></td>
<td>$M_b(t) = (Q_{dia} + Q_{dyn}^{-1}(t)) \times \theta_i$</td>
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<tr>
<td>Result</td>
<td>$u_i, \dot{u}_i, \ddot{u}_i(t)$</td>
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<tr>
<td></td>
<td>$\theta_i, \dot{\theta}_i, \ddot{\theta}_i(t)$</td>
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</table>
| Convergence criterion | $\frac{Q_{dyn}(t) - Q_{dyn}^{-1}(t)}{Q_{dyn}(t)}$ if < tolerance $\rightarrow t + \Delta t$ | $\frac{Q_{dyn}(t) - Q_{dyn}^{-1}(t)}{Q_{dyn}(t)}$ if > tolerance $\rightarrow i + 1$

Figure 7: Comparison between numerical and experimental results of the axial force in stay cables SR6 and SR11 obtained for the configurations of the static load test trucks positions

![Graphs for Stay cable SR6 and SR11](image)

Figure 8: Dynamic effect of the calculated bending moment at the midspan section vs strain at strain gage 9X for the 1st series of tests and a vehicle speed of 90 km/h

![Graphs for calculated bending moment and strain](image)
Figure 9: Comparison between experimental and numerical results of dynamic amplification factors for the 1st and 2nd series of tests, as function of the vehicles speed.

Figure 10: Comparison between experimental and numerical results of maximum midspan vertical accelerations for the 1st and 2nd series of tests, as function of the vehicles speed.

Figure 11: Comparison between experimental and numerical results of dynamic amplifications factors of axial forces in stay cables SR18, SR11, SR6 and ST2, for the 1st series of tests and a vehicle speed of 90km/h.