Global and local dynamic behaviour of the Sesia viaduct, a steel-concrete composite railway bridge on the HS line Turin-Milan

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ABSTRACT: Steel-concrete composite bridges have become an important alternative to concrete structures in the development of new high speed railway lines throughout Europe, due to considerable advantages concerning design, construction time, durability and costs. Nevertheless design process highlighted many still open problems related to the estimation of dynamic and fatigue effects due to the HS train passages lacking reliable numerical models and suitable assessment methodologies.
In the framework of the recently launched research project "DETAILS" (funded by European Commission), that aims at analyzing dynamic interaction phenomena and fatigue behaviour of these types of bridges, the Sesia Viaduct, a steel-concrete composite box girder bridge, has been deeply investigated by means of a wide experimental modal analysis campaign in operational conditions.
In the experimental campaign, three spans of the bridge were instrumented by accelerometers covering 103 sensor locations and by optic fibers, to obtain detailed mode shape information for correlation and updating of Finite Element models. Furthermore the accelerometer locations have been designed in order to identify the global dynamic behaviour and the ones of particular substructure and elements (i.e. the bottom steel plate, the diagonal of the cross girder, the bottom flange stiffener etc.). Fiber optic sensors have been used to measure the strain field at two stations of the bridge in order to analyze the distortions of the cross section under the train passages.
The paper present the acquired vibration data under ambient and train excitation, showing Operational Modal Analysis results and providing a comprehensive description of the dynamic behaviour of the whole structure and relevant structural elements.

1 INTRODUCTION

Steel-concrete composite bridges are widely used in the realization of the European high-speed (HS) railway networks. Even though concrete solutions are still mostly preferred in many countries, composite ones became more and more a valid alternative thanks to the last enhancement of materials and technologies (Millanes 2004, Hoorpah et al. 2004, Schröter and Muller 2004). The presence and the typologies of composite bridges in the European High-Speed railways are quite different, depending on the specific features of the building sector, the prevailing topographical conditions, the maintenance costs and the policy of local steel industries. Among the several typologies, twin girder bridges were widely adopted due to their structural efficiency and simplicity during erection phases (especially if launched), multiple girder decks were used for shorter spans (demonstrating a good structural response due to the position of girders directly beneath the rails) while box girders were typically used for horizontally curved and
longer span bridges due to their higher flexural capacity, torsional rigidity and low corrosion sensitivity thanks to the reduced exposed surface.

Such relatively new design solutions in the period of high expansion of railway networks amplified open problems and uncertainties concerning with dynamic response to high-speed train loading, structural modelling, evaluation of actual fatigue loads and fatigue assessment procedures (Millanes 2004). Lightness and low damping properties expose such bridges to resonance-induced vibrations produced by trains running slower than the maximum design speed of 350 km/h. Moreover, the correct estimation of structural stiffness plays a key role in determining the structural dynamical behaviour and sensitivity to resonance effects: any erroneous estimation of bridge stiffness induces an incorrect evaluation of the eigenfrequencies and the speed at which resonance occurs. The demanding safety and durability requirements of new HS lines makes it necessary to enforce a strict fatigue control of steel and composite bridges.

The research project DETAILS “DEsign for opTimal life cycle costs (LCC) of high-speed rAILway bridges by enhanced monitoring Systems”, funded by the Research Fund of Coal and Steel of the European Commission, aims at the improvement of design, safety and durability of steel-concrete composite solutions for the realization of railway bridges in HS networks (Chellini et al. 2008). The proposed objectives have been achieved by integrating structural modelling with experimental tests and health monitoring in order to obtain necessary information on actual bridge loading, structural modelling, fatigue resistance and damage assessment. Three case studies have been selected as representative examples of three different typologies: the M5 twin parallel girder bridge located on the high-speed railway line Vienna-Salzburg (Austria); the Sesia box girder viaduct located on the Turin-Milan (Italy) High Speed Railway line and the composite filler beam EÜ Erfittalstraße bridge located on the high-speed line Cologne-Aachen (Germany). In the first phase of the research programme, a wide experimental campaign analyzing the dynamic behaviour of such case studies was performed by means of Operational Modal Analysis techniques to accurately identify the bridge modal parameters (eigenfrequencies, damping ratios and mode shapes) and the level of vibration under train passages.

In the paper, the experimental modal analysis campaign performed on the Sesia viaduct will be introduced showing sensor layouts and data acquisition; then the global and local dynamic behaviour of the bridge, obtained by Operational Modal Analysis, will be discussed presenting the achieved results.

2 THE SESIA VIADUCT

The Sesia Viaduct is located on the Turin-Milan Italian HS railway line near Novara on the homonymous river. The viaduct is a box girder steel-concrete composite bridge designed in 2003 and it consists of seven 46 m long spans for a total length of 322 m (Fig. 1). Each simply supported girder span has the same double box cross section (Fig. 2): the bottom steel box is composed by lower flanges and three webs (presenting only few stiffeners in the upper part); the concrete slab has geometrical dimension of 13.6 m width and 0.4 m thickness and it is formed by “predalles” with an integrating cast and stud connections to the steel box. The steel box is formed by three parts, each about 15 m long and joined together by welded connection. The bearings scheme is formed by fix, mono-directional and bi-directional supports, as represented in Fig. 3 in order to avoid internal stress due to thermal actions. The reinforced concrete supporting piers are founded on piles.

3 EXPERIMENTAL MODAL ANALYSIS CAMPAIGN

The location and typology of sensors were designed to evaluate the global and local dynamic behaviour both in vertical and horizontal direction. Because of the large extension of the viaduct, only a subpart of the entire structure was analyzed in the experimental vibration tests: thus only the second span from Turin side was extensively instrumented even though some sensors were placed in both adjacent spans (the first and third one) to evaluate the vibration transmission and the dynamic coupling between spans.
The complete accelerometer layout consisted of 103 sensors positions (12 on the first span, 86 on the second and 5 on the third span). The sensors were placed both in vertical and horizontal directions, allowing the identification of both global vertical and transverse modes. At the supports, longitudinal vibrations were also measured.

The availability of a total amount of 33 accelerometers (10 PCB capacitive and 23 PCB piezoelectric ICP accelerometers) were used, requiring a measurement strategy based on reference sensors. Fig. 4 shows the accelerometer layout and the selected reference positions, whereas Fig. 5 shows the sensors layout in the intermediate and end cross-girder.

Local strains of the girder in the longitudinal direction was measured with fiber optic sensors (SOFO system, SMARTec 2006). These sensors measure the relative displacement between two points, 1 m or 1.2 m apart. A total of 8 sensors were placed at four different levels on two vertical lines in order to measure the local strains in the bottom and upper part of the cross section. These measurements were carried out on two cross sections: one next to the pier and another at a quarter of the span (Fig. 6).

The unmeasured excitation sources were wind, traffic on the near highway and test crew members walking inside the bridge box (ambient vibrations) and the actions due to ETR 500 train passages, choosing a sampling frequency of 800 Hz and 1024 Hz respectively. These measurements were be used to estimate the modal parameters (i.e. eigenfrequencies, damping ratios, mode shapes) of the bridge.
The acquisition system consisted of an LMS SCADAS 305 front-end controlled by LMS TestLab Spectral Testing software (LMS Instruments 2007). The power was supplied by a generator, with a double back up provided by a UPS system and the internal batteries of the laptop and the SCADAS 305 front-end.

Figure 4: Accelerometer layout in the three selected spans of the viaduct.

Figure 5: Examples of sensor placement in the intermediate cross-sections and the end cross-girder.

Figure 6: Fiber optics sensor layout.
4 MODAL IDENTIFICATION

In Fig. 7 typical accelerations measured on the Sesia viaduct are shown, representing the signals of vertical reference sensors 2a06, 2c04 and 2c12 (respectively at mid-span and at quarters of the second span), while in Fig. 8 are illustrated auto Power Spectral Density functions estimated on the basis of the measured accelerations.

The modal identification was performed by means of two different techniques, namely the Stochastic Subspace Identification (Hermans and Van der Auwerer 1999, Peeters 2000) and the Operational PolyMAX method (Peeters et al. 2004, Peeters et al. 2007) both implemented into the software package LMS Test.Lab (LMS Intenational 2007). These two method belong the class of so-called Operational Modal Analysis techniques that rely on the assumption of white noise input.

4.1 Global modes

The first identified global modes are shown in Fig. 9, where it’s easy to notice that some mode shapes look very similar, limiting the observation only at the second span of the bridge on which the majority of the sensors where placed. Looking at the modal deformations of the adjacent spans, it’s possible to separate the similar modes: in fact it clearly emerged that those similar modes differ for the modal displacements of neighbouring spans, dividing such mode families into symmetrical and anti-symmetrical ones, as schematized in Fig. 10. According to the mode shapes of adjacent spans, the identified modes of the bridge in Fig. 9 can be divided into symmetrical and anti-symmetrical ones.

The eigenfrequencies and damping ratios obtained from both PolyMAX and Stochastic Subspace Identification are listed in Table 1 and compared by the MAC values shown in Fig. 11.

The experimentally identified mode shapes revealed that a dynamic interaction exists between spans. Although each span is statically decoupled, it seems that the asphalt layer underneath the ballast, the ballast layer and the rails are realizing a connection between the spans that is clearly reflected in the dynamic properties of the bridge (Chellini et al. 2008).

From the modal analysis of the free vibration measurement, immediately after the train leaves the second span, three modes were identified which correspond to the symmetrical modes identified from the ambient vibration tests: thus it can be concluded that the symmetrical modes are predominately excited when the train passes the bridge.

4.2 Local modes

Cross Girder

Analyzing the accelerations measured by sensors located on the Cross Girder (section 2-06), it was possible to distinguish some peaks of the cross PSD not present in the other sensor spectra (Fig. 12). Thus the modal extraction process was performed by PolyMAX, identifying two local modes shown in Fig. 13 and Table 2. Such modes described the local distortion of local cross girder characterized by a local bending deflection of the box web flanges while the r.c. slab behaves like a rigid body.

Figure 7: Typical acceleration signal recorded during ambient vibration tests (reference sensors 2a06, 2c04 and 2c12).

Figure 8: Examples of evaluated auto-PSD of ambient vibration tests (reference sensors 2a06, 2b06, 2c06, 2c04, 2c08, 2c12).
Symmetrical scheme
Mode 1

Anti-symmetrical scheme
Mode 2

Mode 3

Mode 4

Mode 5

Mode 6

Figure 9: Global mode shapes identified by SSI and PolyMAX methods. Some modes look very similar as they differ only in the interaction with the adjacent spans.

Symmetrical scheme

Anti-Symmetrical scheme

Figure 10: Symmetrical and Anti-Symmetrical scheme for the identified mode shapes.

<table>
<thead>
<tr>
<th>Mode Shape</th>
<th>Eigenfrequency Hz</th>
<th>Damping ratio %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PolyMAX</td>
<td>SSI</td>
</tr>
<tr>
<td>1st vertical bending mode</td>
<td>3.63</td>
<td>3.64</td>
</tr>
<tr>
<td>1st torsional mode</td>
<td>4.13</td>
<td>4.11</td>
</tr>
<tr>
<td>2nd vertical bending mode</td>
<td>8.37</td>
<td>8.36</td>
</tr>
<tr>
<td>2nd torsional mode</td>
<td>8.94</td>
<td>8.98</td>
</tr>
<tr>
<td>2nd vertical bending mode</td>
<td>9.93</td>
<td>10.00</td>
</tr>
<tr>
<td>2nd torsional mode</td>
<td>10.57</td>
<td>10.55</td>
</tr>
<tr>
<td>2nd vertical bending mode</td>
<td>11.22</td>
<td>11.06</td>
</tr>
<tr>
<td>2nd torsional mode</td>
<td>14.36</td>
<td>14.33</td>
</tr>
</tbody>
</table>
Figure 11: Global modes MAC matrix between PolyMAX and SSI.

Figure 12: Cross-PSD of Local Cross Girder layout sensors (amplitude).

Table 2: Local Cross Girder identified mode shapes.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Eigenfrequency</th>
<th>Damping ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19.19</td>
<td>0.33</td>
</tr>
<tr>
<td>2</td>
<td>20.20</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Local Cross Girder: Mode 1

Local Cross Girder: Mode 2

Figure 13: Identified modes by Local Cross Girder layout measurements.

**Bottom stiffener**

The analysis of local Bottom Stiffener acceleration records and cross spectra (Fig. 14) revealed the presence of some local modes identified by Operational PolyMAX (Fig. 15 and Table 3), modes in which the bottom stiffener behaved like a simply supported beam.
Bracing Diagonal Element

Observing the cross spectra of Bracing Diagonal Element sensors in Fig. 16, it was possible to identify some local modes of vibration of the diagonal element (Table 4 and Fig. 17). The extracted modes were those typical of a simply supported beam but they appeared in couples: this fact can be explained having in mind that the sensors were placed in the same vertical plane of the diagonal element, while the bending principal axes of the double L cross section resulted to be inclined.
5 SOME CONCLUSIVE REMARKS

The analysis of vibration properties of a railway bridges is of primary importance because it can provide essential information for the assessment of resonance and fatigue phenomena during the passages of high speed trains.

The experimental dynamic campaign, performed on the Sesia viaduct by means of Operational Modal Analysis techniques, allowed to recognize the dynamic behaviour of the bridge in terms of global vertical and horizontal modes. Furthermore the possibility to recognize the presence of local vibration modes enhanced the knowledge of the real dynamic behaviour of the structure and its subparts and it can improve structural modelling for train-bridge interaction analysis and fatigue assessment.

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