NON-DESTRUCTIVE VIBRATION-BASED INVESTIGATION OF AN EXISTING PRESTRESSED R.C. BRIDGE

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ABSTRACT

A non-destructive dynamic study was developed on a precast r.c. bridge over the motorway junction between A4 and A23, located near the town of Palmanova, in the province of Udine, Italy. The bridge was built in the early 1960’s and is situated at the top level of a three-roads intersection. In order to investigate the conditions of the structure and to analyze its actual global behavior, a non-destructive vibration test campaign was carried out, together with a comprehensive test campaign on materials and constructive details. The experimental results were then compared with the numerical ones obtained by a Finite Element model, previously calibrated with the actual materials’ characteristics, in order to identify the real behavior of the bridge. The use of dynamic tests allows clearly identifying and localizing the most damaged parts of the structure, with sensible stiffness losses. Furthermore, it was noticed that some non-structural elements (i.e. the bituminous mix layer) had an important role on the definition of the dynamic behavior of the whole bridge. Finally, the concrete piers did not show significant variation of stiffness confirming the materials’ test results. The use of dynamic tests gave a strong contribution to the assessment of the health condition of the structure, since they allow identifying and locating the damaged part of the structure, giving a quantitative evaluation of the residual mechanical characteristics. In conclusion, the work allowed giving a comprehensive and complete vision of the health conditions of the structure.

Keywords: P.R.C. Bridge, Structural Identification, Dynamic tests
1. INTRODUCTION

The structure object of the present paper is a viaduct of the highway A4 in the North-East Italy, near the city of Palmanova (UD). The function of the bridge is strategic, since it is part of the junction between the A4 highway and A23 highway.

The deck corresponds to the higher level of a 3-level junction, and it is composed by 3 spans of 11 precast pre-stressed concrete beams, of 12, 25 and 12 meters length respectively. The central span presents a „Gerber” type joint (Figure 1).

The viaduct shows several signs of durability issues, due to atmospheric agents and vehicular traffic. In particular the following damage could be observed (Figure 2 and Figure 3):

- Local damage of the lower flange of 2 beams, due to the impact of a truck, that caused the cut of some strands and the following loss of pretension;
- Water infiltration in correspondence to the „Gerber” joint that caused the damage of the reinforced concrete elements of the joint; the south side beam shows also corroded strands;
- The deck slab show damage on the lower part, with cracking of the precast concrete formworks;
- The piers and pier-beams show limited concrete cover, with following steel corrosion.

![Figure 1. Lateral view of the viaduct](image)

![Figure 2. (a) Corroded strands on side beam; (b) Water infiltration through „Gerber” joint.](image)
Figure 3. (a) Exposed reinforcement on pier-beam and deck; (b) Cracking of deck slab.

2. TESTS ON MATERIALS AND DYNAMIC TESTS

Given the health conditions of the structure, a test campaign was carried out, with the purpose of assessing the geometrical and mechanical characteristics of the viaduct, the constructive details and its conservation state, together with the global behavior of the structure.

In Figure 4 some examples of the tests on materials are showed. Together with them, a static load test was carried out, with the purpose of assess the deformation behavior of the bridge and its response to heavy loads.

Figure 4. (a) Test on concrete; (b) Corrosion test; (c) Static load test; (d) Video-endoscopy.
The dynamic test was developed through the following phases (Figure 5):

- Acquisition of the design information of the structure, and definition of the test modalities;
- Acquisition of the structural vibrations;
- Modal extraction;
- FEM model of the structure;
- Structural identification through model updating;
- Critical analysis of the results.

The tests were carried out through the use of 12 sensors (accelerometers) and with the following excitations:

- Vertical actions generated by a truck (SHT);
- Both vertical and horizontal actions generated by a harmonic exciter (HVT).

Figure 5. (a) Accelerometer; (b) Test campaign; (c) Harmonic Exciter; (d) Acquisition device; (e) sensor position.
3. TEST RESULTS AND MODEL IDENTIFICATION

In Figure 6 are showed the main results obtained in terms of frequency and mode shape identification. After the identification of the modal frequency and modal shapes, the results were compared with the numerical solution (Figure 7). The comparison between the numerical results and the real data gave important information about the global behavior of the structure:

- The Young moduli of the materials were mostly consistent with the expected real values, confirmed by material tests, with some localized exceptions: the dynamic behavior of the deck beams highlighted elements of non-linearity and of non-homogeneous dynamic behavior, symptom of portions of elements affected by loss of stiffness and hysteretic dissipative phenomena. In particular the FEM model updating indicated the need of introduce some localized losses of stiffness, in some cases over 90% with respect to the flexural stiffness of beams without damage. These losses were located in correspondence to the parts where damage was already identified with a visual inspection, confirming the effect of localized damage on global behavior. The localized loss of mechanical stiffness, not identified through tests on material, was instead found in the dynamic investigation, highlighting non-linear behaviors typical of cracked and deteriorated elements;

- The same phenomena were found on the deck slab, with a correspondence between the distribution of stiffness of the calibrated model and the observed crack pattern. The reduction of stiffness was about the 20% with respect to the undamaged slab;

- It was observed that the bridge asphalt pavement, usually not considered in the bridge models, has in this case a strong influence in the dynamic behavior of the whole structure, since it gives a contribution not only in terms of mass but also in terms of stiffness;

- The stiffness of the transversal beams was found to be very low (1/3 of the classical concrete stiffness), confirming the tests on materials;

- The bearing elements, made in neoprene, seems to have an higher stiffness with respect to the literature values; this can be due to the fact that, although from a visual inspection the bearing elements appear in good state, their mechanical properties could be deteriorated in time, with a consequent stiffening of the material and a higher restraint effect to the horizontal deformation.

In Table 1 the comparison between the experimental results and the final FEM model were showed. The results show a good adaptation of the model with respect to the real data.

![Figure 6](image1.jpg)

Figure 6. (a) Identification of the first 4 vertical modes; (b) Identification of the first 3 transversal modes.
Another dynamic parameter was then investigated in order to identify and locate structural damage: the structural damping.

The relationship between damage and damping was object of several scientific papers [1][2][3]. The hypothesis confirmed by several experimental measures consists in quantify the deviation from the linear (viscous) model, usually used on the construction practice, of the real damping measured on site. Several tests on real structures show that the presence of non-linear damping is usually related to the presence of structural damage (like cracks).

In the specific case the measurements made with the excitation of the truck were considered (SHT). This excitation caused a free decay vibration, with an associated free vibration damping. Three channels were investigated; only the most significant one is reported in this paper, i.e. channel 2.

A band pass filter was applied, in order to isolate the most significant frequency. The free decay curve that was obtained was interpolated in order to assess the damping shape that gives the best fit to the decay. Several damping models were investigated:

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**Table 1. Comparison between experimental and numerical results.**

<table>
<thead>
<tr>
<th>Mode</th>
<th>1° Trans.</th>
<th>1° Vert.</th>
<th>2° Trans.</th>
<th>3° Vert.</th>
<th>4° Trans.</th>
<th>2° Vert.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. Frequency</td>
<td>4.67</td>
<td>5.73</td>
<td>6.20</td>
<td>11.61</td>
<td>13.95</td>
<td></td>
</tr>
<tr>
<td>FEM Frequency</td>
<td>4.74</td>
<td>5.66</td>
<td>6.08</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Participating mass</td>
<td>87.7 %</td>
<td>25.2 %</td>
<td>5.4 %</td>
<td>(Trans.)</td>
<td>(Vert.)</td>
<td>(Vert.)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>freq.</th>
<th>Ch. 4</th>
<th>Ch. 7</th>
<th>Ch. 9</th>
<th>Ch. 10</th>
<th>Ch. 11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>1° Trans.</td>
<td>0.881</td>
<td>1.00</td>
<td>0.426</td>
<td>0.870</td>
</tr>
<tr>
<td>FEM</td>
<td>0.989</td>
<td>1.000</td>
<td>0.496</td>
<td>0.784</td>
<td>0.800</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>freq.</th>
<th>Ch. 1</th>
<th>Ch. 2</th>
<th>Ch. 4</th>
<th>Ch. 5</th>
<th>Ch. 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>1° Vert.</td>
<td>0.018</td>
<td>0.511</td>
<td>0.538</td>
<td>0.021</td>
</tr>
<tr>
<td>FEM</td>
<td>-0.018</td>
<td>0.737</td>
<td>0.186</td>
<td>-0.038</td>
<td>1.000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>freq.</th>
<th>Ch. 1</th>
<th>Ch. 2</th>
<th>Ch. 4</th>
<th>Ch. 5</th>
<th>Ch. 8</th>
<th>Ch. 10</th>
<th>Ch. 11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>2° Trans.</td>
<td>0.019</td>
<td>0.769</td>
<td>0.810</td>
<td>0.028</td>
<td>1.000</td>
<td>0.119</td>
</tr>
<tr>
<td>FEM</td>
<td>0.045</td>
<td>0.423</td>
<td>0.570</td>
<td>-0.014</td>
<td>1.000</td>
<td>0.026</td>
<td>0.009</td>
</tr>
</tbody>
</table>
- Linear damping (viscous);
- Non-linear damping (quadratic);
- Non-linear damping (friction).

The best fit was assessed through the RMSE (Root Mean Square Error) method. The results are showed in Figure 8.

The results show that the non-linear model has a RMSE smaller than the classical linear model. Moreover, the accelerometers closer to damaged elements showed a higher effectiveness of the non-linear model; instead, accelerometers located far from damaged parts showed that the viscous model gave the best fit to the decay.

The use of the technique of non-linear damping assessment allowed therefore identifying and locating damage independently from the previous visual inspection, confirming the appearance of non-linear damping is a useful method in order to identify and locate damage independently from the presence of a baseline dynamic measurement.

![Figure 8. Free decay of channel 2. Viscous model vs. Combined (non-linear) model.](image)

4. CONCLUSIONS

A non-destructive dynamic study was developed on a precast r.c. bridge over the motorway junction between A4 and A23, located near the town of Palmanova, in the province of Udine, Italy.

Both the piers and the deck showed signs of damages that could significantly decrease the level of safety of the bridge and could lead to a danger for the road users.

For this reason, in order to investigate the conditions of the structure and to analyse the actual global behaviour of the structure, a non-destructive vibration test campaign was carried out, together with a comprehensive test campaign on materials and constructive details.

The experimental results were then compared with the numerical ones obtained by a Finite Element model, previously calibrated with the actual materials' characteristics, in order to identify the real behaviour of the bridge.
The results showed signs of non-linear dynamic behaviour of some parts of the structure, due to non-linear hysteretic dissipative phenomena. An optimization of the numerical model through the procedure of model updating was carried out. The use of dynamic tests allows clearly identifying and localizing the most damaged parts of the structure, with sensible stiffness losses. Furthermore, it was noticed that some non-structural elements (i.e. the bituminous mix layer) had an important role on the definition of the dynamic behaviour of the whole bridge. Finally, the concrete piers did not show significant variation of stiffness confirming the materials’ test results.

The tests and analysis carried out on the above described structure showed that the results obtained from dynamic tests are consistent with the theoretical assumption and with the results obtained from tests on materials. Moreover, the use of dynamic tests gave a strong contribution to the assessment of the health condition of the structure, since they allows to identify and locate the damaged part of the structure, giving a quantitative evaluation of the residual mechanical characteristics.

The use of the technique of non-linear damping assessment allowed therefore identifying and locating damage independently from the previous visual inspection, confirming the appearance of non-linear damping is a useful method in order to identify and locate damage independently from the presence of a baseline dynamic measurement.

In conclusion, the work allowed giving a comprehensive and complete vision of the health conditions of the structure.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the availability and kindness of all the “Spa Autovie Venete” team, which made this research possible and give a strong contribution to the accomplishment of the work.

REFERENCES

