Diagnostics and preservation strategies applied to historic iron infrastructures: the Paderno arch bridge (1889)

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1 Introduction
The railway bridges, built between the second half of 19th century and the beginning of 20th century, have historic significance embodying the distinctive characteristics of the construction methods of the time, mainly related to masonry and iron structures and often represent a distinguishable but harmonized entity in landscapes. The railway bridges are, at the same time, architectonic heritage and frequently innovative structures, solving problems of environmental impact with bold engineering solutions related to the requirements of the railways loads, so that the structural dimensions of piers and spans stem from the optimization of the planned railway routes. In addition, these structures were the top of the technology, engineering and architecture of the time, showing a deep knowledge of materials and technological solutions no more in use; due to the high quality of design, these bridges have often shown a remarkable life-time and are, in many cases, still in service. This heritage could be at risk if not correctly interpreted in its structural features and material properties; further critical issues are the continuing increasing requirement, in terms of either number of daily passages or increase of weight and speed of the trains, and the lack of addressed investigation and analytical procedure aimed at the control of such important structures. The evaluation seems especially complex for historic iron bridges, in absence of systematic research on the technological and mechanical properties of the material and on its durability. Further uncertainties concern the behavior of the assemblages and jointing, which often drive the crisis of the system. The diagnosis should result from experimental investigation, both on-site and in laboratory, and from the structural analysis, based on appropriate mathematical models. The experimental phase is aimed to define the material properties, construction details, internal composition, general characteristics of the structure itself and localize eventual defects. The investigation on iron member is generally addressed to the local material evaluation and corrosion inspection, collecting parameters not easily linkable to the whole structure behavior. The analytical model of a historic structure, even when based on the original drawings, accurate field survey and mechanic characterization of the materials, always involves simplifying assumptions and several uncertainties in the material and geometric properties and boundary conditions; hence, the model possibly needs to be validated by full-scale tests. Within this context, operational modal analysis could have a key-role, involving the global behavior of the structure and providing meaningful parameters for the model calibration. A further advantage, in case of strategic infrastructures like railway bridges, is the possibility to keep in use the structure during the investigation campaigns. The availability of an effective model, representative of the real structure in its present state of preservation is the starting point any assessment evaluation. For this reason,
a wide experimental campaign should mandatory precede the analytic phase of the structural assessment of such historic infrastructures. Furthermore, the international debate concerning the assessment of historic structures and the possible following interventions, define a series of requirements or criteria oriented to ascertain the efficiency of the solution together with its compliance with recognized conservation principles. Between the several requirements, it is worth to mention the priority of the structure monitoring, even long-term, in order to check the stability in time of the building behavior. The paper summarizes the dynamics-based assessment of the historic San Michele bridge at Paderno d’Adda (Italy). The San Michele bridge over the Adda river at Paderno, built between 1887 and 1889, is one of the masterpieces of XIX century iron architecture and a symbol of Italian industrial archaeology heritage [SNOS, 1889], [Nascè, 1984]. In order to address a Structural Health Monitoring (SHM) program of the bridge that is still used as a combined road and railway bridge, a series of dynamic tests was performed in operational conditions between June 2009 and June 2011 which drove to the installation of a permanent dynamic monitoring system [Gentile, 2011]. The whole investigation includes dynamic testing and long term monitoring, visual inspection and development of a baseline FE model of the historic bridge.

2 Description of the historic bridge
The S. Michele bridge (Fig.1), better known as Paderno bridge, was designed in 1886 by the head of the SNOS technical division, the Swiss engineer Julius Röthlisberger (1851–1911) [SNOS, 1889], [Nascè, 1984]. The bridge consists of a single span parabolic arch, supporting an upper trussed box girder by a series of piers (Fig. 1). Three piers are erected from masonry bases while the others are supported by the parabolic arch; all the piers are battered in both directions according to the European practice of the late XIX century. The basement of the piers and the abutments are built in stone-block masonry and protected by granite coatings. According to the international classification of Philadelphia (1876), the material used in the bridge construction can be classified as wrought iron. Tests carried out on few samples of the bridge members between 1955 and 1972 [Nascè, 1984], revealed rather poor metallurgical, chemical and mechanical characteristics. As it has to be expected for a wrought iron, the material is characterized by a stratified structure along the rolling plane and frequent non-metallic inclusions. Preliminary visual in-
spectors allowed to point out the state of preservation of the bridge rather poor due to the lack of maintenance, with diffuse damages induced by the corrosion observed on a wide number of structural members.

3 Ambient Vibration Tests
Several ambient vibration tests (AVTs) were carried out on the Paderno bridge between June 2009 and June 2011, in order to characterize the dynamic behavior of the structure and for addressing a SHM program [Gentile, 2011]. Three AVTs were firstly carried out between June and October 2009 on the roadway deck of the bridge. It is worth underlining that those tests represented the first experimental survey carried out on the global characteristics of the bridge since the original static proof tests (1889-1892) [SNOS, 1889], [Nascè, 1984]. The first test (June 2009) was aimed at investigating the vertical dynamic behavior of the bridge; the subsequent two tests were performed to check the possible variation over time of the previously identified resonant frequencies (September 2009) and to investigate the transverse dynamic behavior (October 2009), respectively. The above experimental survey [Gentile, 2011] clearly highlighted that:

a) the vertical bending modes exhibit non-symmetric modal deflections on the upstream and downstream sides of the deck. Since drawings and documents available, concerning both the original design and the refurbishments, do not show any significant lack of symmetry between the two sides of the bridge, the observed non-symmetric mode shapes, revealing a different stiffness of the downstream and upstream sides, are conceivably related with the different state of preservation of the structural elements on the two sides. The observation of the typical corrosion damages, unevenly distributed on structural elements of the deck and the arch, strengthens and corroborates this conclusion;

b) under service loads (road traffic), the natural frequencies of vertical bending modes exhibited slight variations, possibly depending on the excitation/response level.

In order to design a monitoring system prior knowledge of the modal parameters of the structure (natural frequencies and mode shapes) is generally required [Magalhães, 2008]. Although the tests performed in 2009 provided valuable information on natural frequencies and mode shapes of the roadway deck, no information on modal deflections of the railway deck were available. On the other side, the railway deck turned out to be more suitable for installing the monitoring system since mounting, wiring and even inspecting the sensors and all other devices is relatively easy with the support of RFI technical staff. Hence, further dynamic tests [Gentile 2011b] were performed between March 2010 and June 2011. The test performed on March 2010 involved a large number of instrumented points on both roadway and railway deck and was mainly aimed at: (a) better understanding the dynamic characteristics of the bridge and (b) checking the number of points to be permanently instrumented on the railway deck. During the test, again slight variation of the natural frequencies was observed and variation of few mode shapes between the two tests of June 2009 and March 2010 was also detected. It is further noticed that the sensor set-up mounted on the railway deck allowed the identification of
almost all the normal modes previously detected. In the subsequent tests, performed on 25-26 November 2010 and 13-14 June 2011, the response was continuously recorded at the points scheduled for permanent monitoring for 15 and 24 hours, respectively. During these tests the temperature was not measured since the main objectives were (a) defining a baseline list of modes for monitoring (i.e. those modes that generally exhibited a significant occurrence over several hours of continuous recording) and (b) testing the robustness and reliability of the tools developed for data acquisition, storage, signal processing and automated modal identification.

For example, typical results, in terms of identified natural frequencies, obtained by applying the developed automatic modal identification procedure to the data collected on 14/06/2011, 07:00-08:00 are shown in Figs.2 (transversal modes) and 3 (vertical modes). All the modes in Figs.2 and 3 exhibited a high occurrence during the tests of continuous acquisition and hence were included in the baseline list of the modes to be monitored. It has to be observed that the vertical modes VB1-VB4 (Fig.3a-d) and the transversal bending modes TB1-TB15 (Fig.2a-o) were identified in the previous tests, as well. On the contrary, the vertical bending modes VB5-VB7 (Fig. 3e-g) were not detected in the previous tests of June 2009 and March 2010.

![Fig.2 - Transversal modes generally identified from ambient vibration data (14/06/2011, 07:00–08:00)](image-url)
4. The monitoring system
The dynamic monitoring system was installed on the San Michele bridge during the month of November 2011 and is fully active since November 28, 2011. The system is completely wired and consists of 21 MEMS accelerometers, 7 data acquisition (DAQ) units, 2 thermocouples, 2 Ethernet switch devices and 1 industrial PC. The global arrangement of sensors and hardware components along the bridge is schematically illustrated in Fig.4. The MEMS accelerometers are placed on the railway deck, along seven cross-sections corresponding to the bearings of the truss-box girder between the abutments (Fig.4), according to the sensor layout adopted since the AVT of March 2010. Each instrumented cross-section is equipped with 3 sensors, in order to measure the vertical accelerations, on the downstream and upstream sides, and the lateral acceleration. The two thermocouples are placed on the second and the fifth cross sections only, one per side in order to measure the air temperature nearby the structure on the upstream and the downstream sides, respectively. A dedicated processing software was developed in LabVIEW, including preliminary pre-processing, extraction of the time series associated to the railway traffic only and used for statistical analysis of data and automated modal identification. Details on the signal processing tools are given in [Busatta, 2011].
5. Results from continuous monitoring
The aim of the monitoring on the bridge, as well as in similar case studies [Magalhães, 2008], is the check of the structural state of preservation through the control of the time evolution of the natural frequencies, distinguishing the effects of temperature and loading. This purpose is particular important for the S. Michele Bridge, where in the previous calibration tests slight but clear fluctuation of the frequency were measured [Gentile, 2011], in absence of relevant temperature variation.

5.1 Road traffic monitoring
In order to investigate the road traffic effect on the modal characteristics of the bridge, the root mean square (RMS) values of the acceleration time series are evaluated from the some dataset of 2400 s subsequently used for the OMA. For example, Fig.5 shows typical daily variations of the RMS values of the accelerations recorded in the vertical (red line) and lateral (blue line) channel, that are characterized by the largest RMS values. It should be noticed that two rush hours of road traffic typically occur in working days (Fig.5a) around 07:00 and 17:00; furthermore, the level of road traffic is quite high between the rush hours while the traffic intensity significantly decreases at late evening and during the night. This typical RMS pattern can be used to hourly characterize the intensity of the excitation/response level due to road traffic, which is clearly lower during the weekends or in holydays (Figs.5b and Fig.6a)

Fig.5 - Typical daily variation of the RMS accelerations in: (a) a working day and (b) a holiday

Fig.6 - (a) Typical variation of the RMS values of vertical (red line) and transversal (blue line) accelerations between 28/11/2011 and 18/12/2011 and (b) temperature records for the same period
5.2 Temperature variation

Fig.6b displays the temperature records from the two sensors installed in the upstream (blue line) and downstream side of the bridge during the first weeks of monitoring. It can be observed (Fig.7a) that the temperature series are very similar, except between 13:00 and 16:00: during these hours the sun directly enlightens the downstream side of the bridge so that the temperature on that side is few °C higher (Fig.7b). Mean temperature trends are, of course, necessary to investigate the possible environmental effects on the modal parameters.

5.3 Monitoring of the frequency variation

Automated identification of the modal frequencies from the datasets collected during the period from 28/11/2011 to 12/05/2013 provided the frequency tracking shown in Figs.8a (transversal modes) and 8b (vertical modes). The inspection of Figs.8a-b suggests the following comments:

1. the algorithm for automatic modal identification exhibits good and robust performance, as all the expected modes (including the closely spaced modes) are clearly identified with high occurrence;
2. the natural frequencies exhibit relatively small but clear variations, that are well described by the algorithm for the automatic identification of modal parameters;
3. during the period under analysis, some interruptions of the monitoring occurred due to maintenance operations in the electric cabin providing power to the monitoring system and owned by the municipality of Paderno. The longest interruption occurred between 14/05/2012 and 17/06/2012 and allowed...
to completely solve the related issues;

4. Figs. 8a and 8b show anomalous increase of all modal frequencies in winter time. This phenomenon observed in the first weeks of February 2012 and, more frequently, between December 2012 and February 2013 is related to snowfalls and low temperatures. More specifically, the temporary and anomalous increase of modal frequencies was associated to the presence of ice on the iron bearings of the girder and the consequent locking of the bearing. Furthermore, the presence of ice on the structure conceivably involved an augmented cross-section of many structural elements and, hence, an increase of the local stiffness of iron members. Since the stiffening due to low temperature and ice has to be considered as temporary, the correlation analysis between modal frequencies and environmental/operational conditions was performed excluding the “ice periods” in order to consider the evolution referred only to a “normal” behaviour of the structure (i.e. without the fictitious stiffening due to ice);

Furthermore, the work covered has addressed which environmental/operational conditions drive the changes observed in the identified modal frequencies. The natural frequencies of all modes turned out to decrease with increased (road) traffic intensity and the transversal modes are generally more sensitive to the traffic acceleration than the vertical ones. The temperature affects almost all the natural frequencies as well, but its effect is non-linear for some modal frequencies and not always characterized by a frequency decrease with increased temperature.

Notwithstanding the quite complex mechanisms that define the normal response of the structure under changing temperature and traffic conditions, multivariate regression models turned out to be appropriate to predict the modal frequency changes of the bridge, given the measured environmental/operational conditions, and to address the SHM strategy of the bridge.

5. Conclusions

A multi-channel dynamic monitoring system has been installed in the San Michele bridge, that is a centenary iron arch bridge crossing the Adda river about 50 km far from Milan. The paper firstly summarizes the results of preliminary AVTs carried out since June 2009 to evaluate the dynamic characteristics of the historic bridge and to design the monitoring system. Subsequently, the monitoring system and the software developed in LabVIEW for automated processing of the collected data are described. In particular, an automatic version of the well known FDD method [Brincker, 2001] was developed and its application to the acceleration datasets collected in the period from 28/11/2011 to 12/05/2013 was presented and discussed.

Furthermore, the frequency tracking of all modes reveals that the operational (i.e. the intensity of road traffic) and environmental conditions significantly affect the frequency variation of several modes. Once the normal response of a structural system to changes in its environmental and operational conditions has been explored and can be filtered out to normalize response data, any further changes in dynamic characteristics should rely to structural changes, which could be either a slow degradation (e.g. reduction in member stiffness.
due to corrosion) or some sudden change.

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**References**
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