EVACES2021
9th International Conference on
Experimental Vibration Analysis for Civil Engineering Structures
14-17 September, 2021 ONLINE

SHM campaign on 138 spans of railway viaducts by means of OMA and wireless sensors network

Lorenzo Bernardini[1], Lorenzo Benedetti[1], Claudio Somaschini[2], Gabriele Cazzulani[2], Marco Belloli[3]

[1] Ph.D. Student, Department of Mechanical Engineering, Politecnico di Milano - Milano, Italy.
[2] Postdoctoral researcher, Politecnico di Milano, Milano, Italy.
[3] Full time Professor, Politecnico di Milano, Milano, Italy.

ABSTRACT

Condition-based monitoring applied to railway bridges represents a topic of major importance and interest among developed countries, such as Italy. In fact, bridges and viaducts represent key components of the transportation network, and therefore they increasingly draw infrastructure managers' attention. The present work is the result of a project carried out by Politecnico di Milano, consisting of a large experimental campaign conducted on a series of viaducts of the Italian railway network. The ensemble of structures under investigation is composed by 11 viaducts, for a total amount of spans equal to 138. According to a similarity criterion, the latter were subdivided into 8 groups, featured by different properties. Due to its transient nature, the experimental campaign was conducted by means of wireless accelerometers, and it consisted in the extraction of the main modal parameters of each analyzed viaduct span, as well as the characterization of the trains travelling on the line. Through the adoption of an operation modal analysis (OMA) technique, it was then possible to construct a large database of the dynamic features concerning the studied viaducts. This database may be exploited for future studies as an important baseline reference condition, by which potential outlier values may be captured, as a sign of damage occurrence among the monitored structures.

Keywords: Operational Modal Analysis, railway bridges, wireless sensors network, Structural Health Monitoring, condition-based monitoring.

1. INTRODUCTION

High-speed railway lines play an important role in passengers and goods transportation within Italy. To ensure ride comfort and safety, infrastructure managers are continuously seeking improved condition-based monitoring systems, able to assess in real-time the health status of the structure and its time-trend [1]. As described in [2], the condition-based assessment of high-speed railway line usually focuses on two aspects, namely track irregularity and bridge natural frequencies [3]-[4]. Since damage-sensitive, natural frequencies may be chosen as an index of the actual health status of a monitored structure: indeed, phenomena such as a crack generation/propagation, resistant section corrosion, deterioration and material ageing lead to a decreased bending stiffness of the bridge span and therefore lower natural frequencies [5]. Therefore, the idea of keeping track of the time evolution and trend of the natural frequencies regarding a certain structure (or a set of them) subject to observation can be useful from a monitoring point of view. In fact, a sudden change in terms of natural frequency may indicate the occurrence of a damage along the bridge/viaduct span, thus alarming the infrastructure manager, that can readily act in order to fix it, as soon as possible. In this context, detecting a damage at its earliest stage would mean an important achievement in terms of passenger safety and maintenance costs: it would allow to avoid sudden catastrophic failures and head to huge savings (i.e., optimized maintenance strategy). To do so, it is mandatory to get rid of any other environmental and operational aspects that influence the time evolution of the natural frequencies (i.e., temperature): this implies the use of processing algorithms such as the principal component analysis (PCA), as illustrated by the authors in [6]. Exploiting the natural frequency evolution as a structural health monitoring tool [7] requires the definition of a reference baseline to compare the new data with. An outlier value with respect to the reference condition may highlight the fact that a damage occurred on the structure subject to study [8]. Therefore, in the health monitoring working flow, the first step to accomplish consists of constructing a database that is representative of the (healthy) reference baseline to which new measures will be compared, to capture any sudden changes. As briefly mentioned above, the present work is the outcome of an experimental campaign conducted on 11 viaducts of a stretch of the Italian high-speed railway line; this resulted in a total amount of instrumented spans equal to 138. The purpose of this campaign is not just to build up a reference database for future studies, but also to investigate the possibility to infer the health status of a certain span directly from the statistic population regarding a group of spans that share the same material properties and geometrical dimensions (i.e., width and length).

Due to the transient nature of this campaign and the large number of spans under investigation, to enhance and ease the experimental operations, a set of wireless sensors was adopted, as described in detail in the following section.

The content of this paper is organized as follows: the first section aims at describing the experimental setup, providing a brief insight on the general framework concerning the campaign. Moreover, the set up and the equipment used are described in detail. The second section deals with the description of the signal processing techniques adopted for extracting modal parameters and moving loads properties respectively. Then, in the following part, the main outcomes of the experimental campaign are gathered and discussed. Final conclusions and main remarks, with a focus on possible future outlooks, are drawn in the last section.

2. DESCRIPTION OF THE EXPERIMENTAL CAMPAIGN

2.1. General framework

Each span of the viaducts treated during the experimental campaign was instrumented by means of a couple of sensors placed at midspan (Figure 1, left): moreover, for each viaduct, one single span was instrumented by a larger number of sensors (Figure 1, right), namely ten, in order to capture higher order torsional and bending modes and pier contribution to the span motion. In addition to this, for each day of measurement a set of four sensors was used in order to get the number of train passages on the viaducts and to identify the speeds as well as the loading properties of the rail vehicles. The general framework depicted above was adopted to measure the first torsional and bending mode shapes and their associated frequencies, since these modes are the ones featured by the highest participant modal mass. The total amount of instrumented span, as briefly stated before, is equal to 138 units, that correspond to 11 different viaducts under experimental investigation during the campaign: eleven of them are featured by a simply supported beam section, while just one is featured by a closed deck section. Since the aim of this paper is to draw conclusions on the possibility of grouping spans having analogous dynamic properties, given that they share the same constructing material, same section and length, the single viaduct with a different cross-section typology was then discarded. This results in a final ensemble of spans that can be then divided, through geometrical similarity (span length), into eight groups, according to Table 1.

Table 1 Different span lengths.

Span length [m]	23.6	24.7	31.2	33.6	34.5	34.7	35.6	36.5
Number of spans	4	15	3	14	7	40	8	38

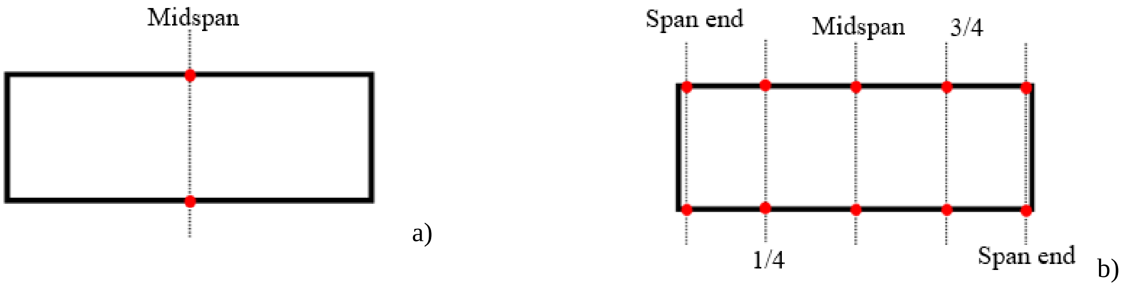

Figure 1 Span top views: red circles represent sensors. a): span instrumented at midspan. b): finer mesh for the span.

2.2. Experimental set up

Due to the large number of spans to be instrumented a wireless sensors network was adopted, to ease and speed up the whole experimental campaign. The adopted sensors consist of MEMS accelerometers, designed and produced by LORD microstrain, with a full scale of 10g if mounted on the bridge side walkway (Figure 2): instead, 40g devices were mounted on the sleepers

(Figure 3) with the aim to classify the rail vehicles travelling on the viaduct. The latter were placed in the following way: each track is featured by a couple of accelerometers, positioned on two sleepers, spaced of a known distance (around 20 m). The sensors mesh was synchronized by means of their base station (Figure 4). During the entire campaign, the sensors were left on the structure for at least 10/15 hours, to acquire the largest number of transits as possible. To couple the sensors with the studied structure, each accelerometer was magnetically attached to a steel plate, which was then directly glued to the viaduct deck or sleeper.

Figure 2 Wireless accelerometers mounted on the side walkway (10g full-scale).

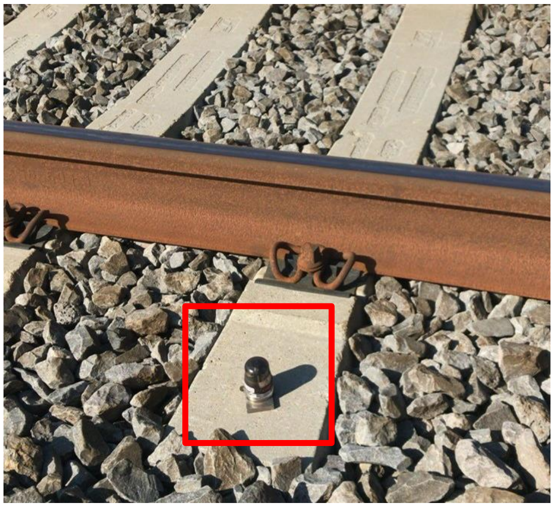

Figure 3 Wireless accelerometers mounted on the sleepers (40g full-scale)

Table 2 collects the acquisition properties of the sensors used during the experimental campaign: for each sensor, the record starts once the threshold value, in terms of acceleration, is exceeded and it stops after at least 40 s, in order to acquire the free decay of the span after the train transits. In fact, for modal properties identification the structure free decay is needed.

Table 2 Sensors acquisition properties.

Sampling frequency of the deck accelerometers [Hz]	256
Sampling frequency of the sleepers accelerometers [Hz]	1024
Distance between consecutive sleepers accelerometers [m]	20

Trigger threshold for deck accelerometers [m/s^2]	0.05
Trigger threshold for sleepers accelerometer [m/s^2]	0.5
Pre-trigger [s]	5
Minimum observation length [s]	40

Figure 4 Base station box and its antenna.

3. SIGNAL PROCESSING

3.1. Time domain analysis

The excited motion of the viaduct span response, measured through the sensors mounted on the sleepers, was exploited in order to determine the following properties of the travelling rail vehicles: the track, the train typology (number of wheelsets and their distance), the speed and the direction of motion. First of all, by computing and comparing the sums of the moving standard deviation of the acceleration signals sensed on the two tracks respectively, it is possible to determine on which track the train has actually travelled. Once the track has been determined, the direction of motion of the rail vehicle must be identified: knowing the sampling frequency and the spatial distance between adjacent sleepers accelerometers (see Table 2), through the cross-correlation algorithm, it is possible to obtain both the direction of motion of the vehicle and its speed (from the RMS of the vertical components of the signals measured on the track). Finally, again from the RMS of the vertical component of the signals measured on the sleepers, it is possible to recognize the vehicle typology travelling on the viaduct: as mentioned before, this identification was done by simply computing the number of travelling wheelsets and their relative distances. Therefore, from the number of axles and their spatial distance it is possible to find out which are the trains that travelled on the structure.

3.2. Modal analysis

The main purpose of this work was the identification of the first natural frequencies of the viaducts under investigation. To do so the excited motion part was neglected in order to keep only the free decay of the response (see Figure 5). Therefore, the first step consists of the removal of the forced motion from the global deck response, by means of a trigger logic. Once this operation is accomplished, it is possible to process the data for extracting the modal properties of the viaduct: this was done by means of the commercial software ARTeMIS, that exploits two different algorithms, namely Frequency Domain Decomposition (FDD) and Stochastic Subspace Identification (SSI-data) algorithms.

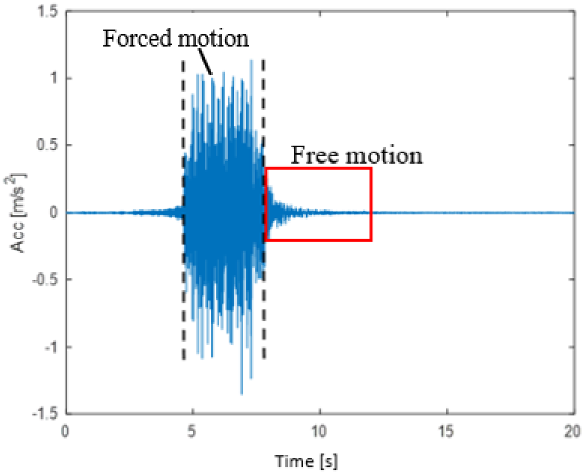

Figure 5 Example of deck midspan response with the distinction of the forced and free motion.

4. RESULTS

It is now recalled that the spans were divided in different groups according to their length (i.e. eight, Table 1). Then, given the purpose of this work the results will be presented as follows: in order to be statistically consistent, only the outcomes (in terms of natural frequencies) concerning the span typologies featured by the highest number of examples are provided to the reader. Therefore, the spans for which results are presented and discussed are the ones featured by one of the following lengths, namely 24.7 m, 33.6 m, 34.7 m and 36.5 m, while the others are neglected. In Figure 6 the box plot of the frequencies associated to the first longitudinal mode shape grouped as a function of span length is shown. The same diagrams have been drawn also for the first bending and torsional mode shapes, again categorized as a function of the span length, as illustrated in Figure 7 and Figure 8 respectively. The longitudinal modes are featured by a larger presence of outlier frequency values than the other two mode typologies, as illustrated in Figure 6 (see red crosses): referring to the span length of 34.7 m, it is worth mentioning that the outlier values are all due to one of the eleven investigated viaducts. This means that the longitudinal mode rather depends on constraints, such as pier height, bridge bearings and number of adjacent spans, than on the span length: that is why we observed such a large dispersion. In other words, given a certain span length, for the longitudinal mode shape associated frequency, we may find out a remarkable number of outliers depending on the bridge and its features (i.e. span boundary conditions).

As expected, in Figure 7, it is possible to observe the progressive decrease of the first flexural natural frequency with the increase of the span length. Moreover, the number of outliers is lower than the one observed and described before: as a consequence, it is clear that spans sharing the same geometrical properties present closer values in terms of bending frequency, whatever is the bridge considered among the ones investigated during the experimental campaign. The same reasoning can be extended also to the first torsional frequency (see Figure 8). In this specific case, it is worth also noticing that the span length seems to have a lower influence on the frequency than the previous case in the sense that if it does not change remarkably the resulting torsional frequency will not significantly differ.

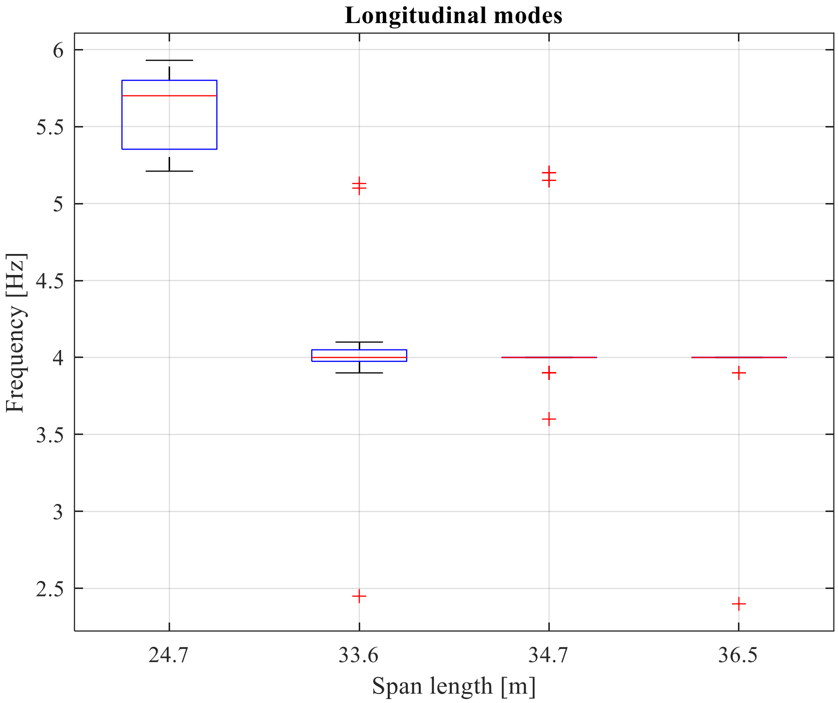

Figure 6 Box plot for the frequencies associated to the 1st longitudinal mode.

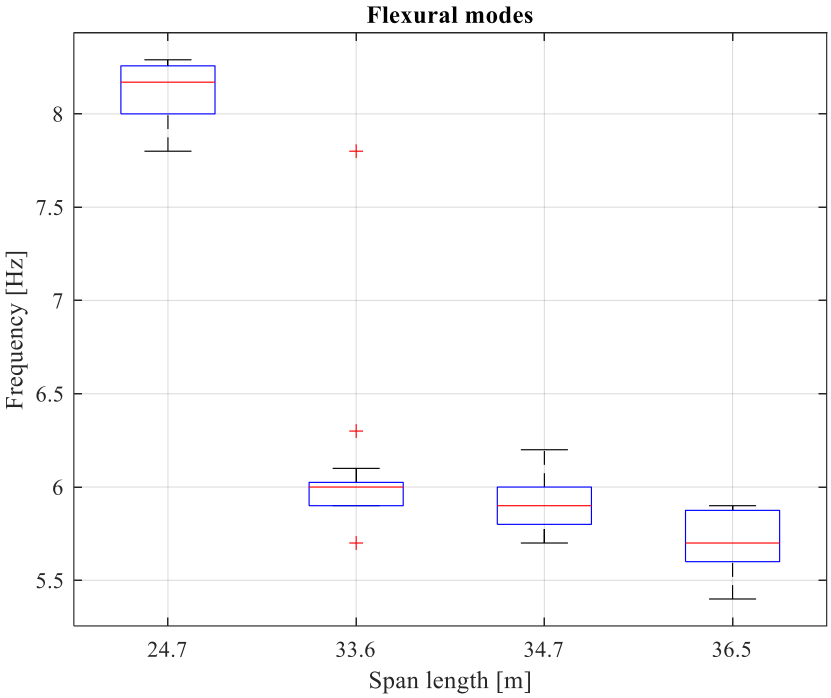

Figure 7 Box plot for the frequencies associated to the 1st flexural mode.

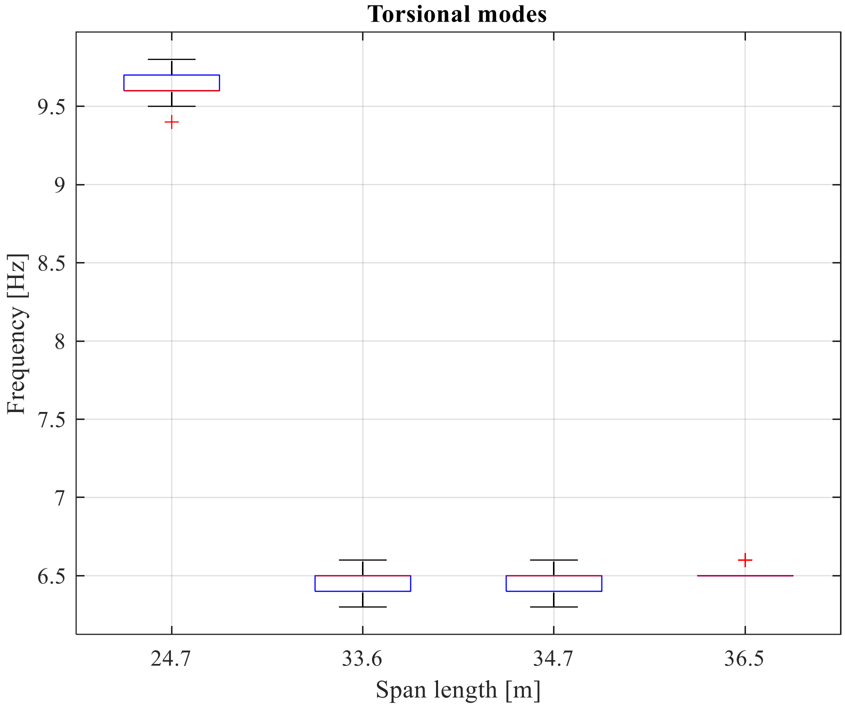

Figure 8 Box plot for the frequencies associated to the 1st torsional mode.

According to authors opinion, the frequency dispersion concept presented above deserves to be further studied and deepened: in fact, the research is still ongoing in order to analyze and understand whether the dispersion at constant span length depends on the deck (i.e., its health status) or on span constraints.

5. CONCLUSIONS

The present paper is the result of an experimental investigation of the modal properties of a set of 11 railway viaducts. One purpose of this campaign was to identify the natural frequencies associated to the first longitudinal, flexural and torsional mode shapes: this was done with the idea to build up a reference baseline data set useful for future studies on the health status of those viaducts. In addition, this investigation represents a chance to evaluate the possibility of grouping, with a reasonable data dispersion, the natural frequencies of spans that share the same material and geometry but belong to different viaducts. In other words, this work aims to examine the impact played by different boundary conditions (f.i., pier height) on the aforementioned frequencies values. The idea was to experimentally assess how remarkable are the frequency changes due to the viaduct under investigation, given that a certain span length is considered: therefore, we may hopefully be able to distinguish damage-associated outliers from the one depending instead on the bridge typology. The results concerning bending and torsional frequencies are promising since featured by a low number of outliers, thus meaning that these modes rather depend on the span geometry than on the considered viaduct (i.e., on boundary conditions). In other words, whatever is the viaduct, all the spans sharing the same length showed similar results in terms of flexural and torsional frequencies, with a small number of outliers. An extension of this result is that, if a span, that was never observed before belongs to a certain group featured by a specific length, and once investigated turns out that its first torsional and bending natural frequencies are far from the statistics of the corresponding population, it may mean that something wrong has occurred (i.e., a damage). As observed in the previous section, this reasonings are not valid for the longitudinal modes frequencies that present indeed a larger number of outliers: in this case it would be much more demanding to identify and associate a certain outlier to an actual damage occurrence. An aspect that deserves to be deepened in the next future studies is to investigate the effect of seasonal changes of temperature (and environmental conditions in general) on the modal properties of the studied spans: as already stated along the paper, environmental conditions changes may hide the damage, or cause false alarms. Therefore, as a first step, the reference data base must be constructed for each season of the year: in this way, frequency changes due to temperature seasonality may be somehow predicted and its influence (confounding effect) on the monitoring process is mitigated.

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