Integrated System for Continuous Dynamic Monitoring: ”Ponte Nuovo Del Popolo” Bridge

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INTEGRATED SYSTEM FOR CONTINUOUS DYNAMIC MONITORING : « PONTE NUOVO DEL POPOLO » BRIDGE

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ABSTRACT

The Italian territory is characterized by a high seismic risk and the presence of several existing structures and infrastructures leads to the definition of accurate procedures and methodologies to evaluate their safety conditions and the life-cycle performance. In this framework Structural Health Monitoring (SHM) is currently more and more considered as a key activity to increase the knowledge on the structural behavior of existing bridges. The paper reports the on-site diagnostic investigations and the installation activities of a SHM system of the "Ponte Nuovo del Popolo" bridge, located in the city center of Verona. The results of the first 1.5 year of monitoring are presented, analysing the operational conditions of the structure subjected to both static and dynamic loads. Specific algorithms and processing software were developed and implemented to perform the continuous real time treatment and analysis of static data and the automated extraction of modal parameters based on the measurement of the bridge's response to ambient vibrations. The bridge is subjected to widespread damaging phenomena, mainly concentrated on the external longitudinal beams. The SHM system is composed by six uniaxial accelerometers and 16 linear displacement transducers and its acquired data are constantly related to the environmental parameters (temperature and relative humidity).

KEYWORDS : *reinforced concrete bridge, civil engineering SHM applications, modal analysis, realtime and automated SHM.*

INTRODUCTION

To contain the inconveniences due to life-cycle damage it is necessary to study in depth the causes of damage of transport infrastructure and in particular of bridges. Old and historical bridges currently represent almost the entire European road and railway bridge stock. The intrinsic weakness of some structural elements, the deterioration occurrences and the updating of structural codes, evidenced that many bridges have inadequate structural performance and a great necessity to be upgraded to the standards of the current seismic codes. The existing stock of bridges in the Italian infrastructure network is composed by numerous typologies of structures that are subject to high levels of damage. The standard methods of investigation and safety evaluation, in some cases are not sufficient and the need of control and monitoring is always increasing. Structural Health Monitoring (SHM) systems are becoming common means of control and safety evaluation of the existing and newly built structures.

Therefore, this work was focused on the observation of the static and dynamic characteristics of existing structures by means of various methods. In particular, a classic method for dynamic identification of a structure lies in modal analysis, which allows extracting the dynamic parameters of the structure, such as its natural frequencies, damping ratios, mode shapes, from experimental measurements.

In contrast to the classical experimental modal analysis, which requires the excitation of the structure by means of particular instruments, another, recently developed, type of analysis has been considered, the operational modal analysis (OMA) [1] [2]. OMA observes the response of the structure subjected to the natural excitations, such as wind, vehicular traffic, seismic micro vibrations and so on. The advantages that this technique have been presented, among which the fact that it is no longer necessary to interrupt the functionality of the structure under examination and this allows the execution of monitoring operations over time and makes possible a variety of applications, such as Structural Health Monitoring. Furthermore, this method is the only one that provides a global dynamic characterization of the real structure: in fact, FE models provide global information of a structure's model, not of the structure itself, and static measurements provide real information but of local nature.

In the context of this work, an application that allows the performance of activities of dynamic identification by means of two methods was developed: Frequency Domain Decomposition and Stochastic Subspace Identification. This application is called Structural Identification and Monitoring / Automatic tool for Operational Modal Analysis (SIM/AtOMA).

1 SIM/ATOMA

SIM/AtOMA (System Identification and Monitoring - Automatic tool for Operational Modal Analysis) is a software tool realized within this work by the research team of the Department of Civil, Environmental and Architectural Engineering of Padua that allows the user to perform structural dynamic identification and monitoring tasks, implementing two Operational Modal Analysis methods: the Enhanced Frequency Domain Decomposition and the Stochastic Subspace Identification.

The identification procedure requires a consistent set of raw acceleration measurements performed on the structure and provides, for both methods, the structure's natural frequencies and damping ratios. It is also possible to configure AtOMA to perform automatically the analysis on new data using template files, in order to allow a continuous monitoring of the dynamic characteristics of the structure. The program disposes of a graphical user interface (GUI), which makes it simple and user friendly (Figure 1).

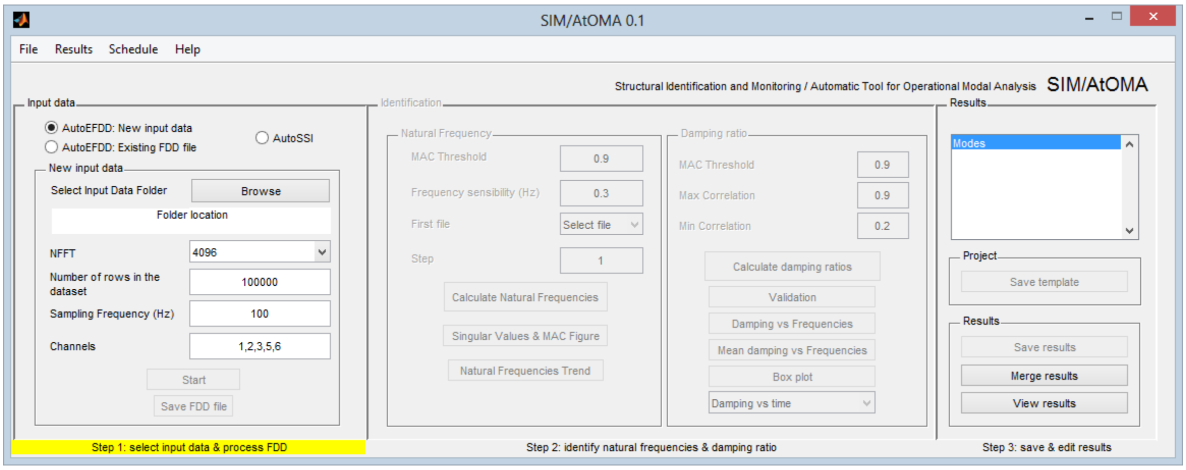

Figure 1: SIM/AtOMA user interface

AutoEFDD is an algorithm based on the Enhanced Frequency Domain Decomposition technique that allows the extraction of the resonance frequency and the damping of a particular mode by computing the auto-correlation function [3]. SDOF auto spectral densities are identified using the modal assurance criterion (MAC) around a peak of resonance, and are taken back to the time domain using the Inverse Discrete Fourier Transform (IDFT). A more accurate estimation of the resonance frequency is obtained by determining the zero crossing times, and the damping ratio is calculated using the logarithmic decrement of the normalized auto-correlation function.

As an Operational Modal Analysis method, it assumes that the input forces are stochastic in nature. The only inputs required by the program are the raw measures sets containing the accelerations of the structure. First input data (the files containing the accelerations measurements) are selected and the corresponding characteristics are specified by the user. The Cross Power Spectral Density function is computed for each file and then the CPSD matrices are decomposed using the Singular Value Decomposition. Subsequently the identification of the modal parameters is performed: after the user has set up the parameters, natural frequencies and damping ratios are calculated automatically. Finally, the user is able to save, merge and view the results of the analysis. The AutoEFDD method is suitable for dynamic monitoring.

Stochastic Subspace Identification is the second method implemented in AtOMA for structural identification purpose. The main reason for which this method was implemented lies in its strength and reliability. The SSI method is, in fact, considered to be one of the most powerful tools for the structural dynamic identification. SSI is however characterized by a high computational burden that does not makes it very suitable for monitoring operations, or analysis of a large number of measurement files. The aim is therefore to provide the results of reference on which to base the analysis with the method AutoEFDD, in the absence, or in addition, to the results provided by an FE model of the structure.

2 Ponte Nuovo del Popolo

2.1 Bridge characteristics

The bridge is located in the city center of Verona, over the Adige River, and is characterized by three spans having a total length of over 90m. The structure holds a four-lane roadway, two for each direction of travel, plus two sidewalks for a total width of 14.32 m (Figure 2). The static schema consists of seven main girders and eleven cross beams in the transverse direction with stiffening function. The 7 girders and the thin slab (18 cm), due to bad maintenance since constructed in 1946, revealed severe damage in the middle of the spans due to water percolation. Girders’ and cross beams’ concrete (Figure 2) is highly deteriorated, moldy and carbonated. Before deciding to retrofit it, the Municipality required to evaluate the life of the bridge. It was subject to investigations, like an ambient modal test to detect the principal modal parameters and in each structural element lots of destructive and non-destructive tests were executed.

Figure 2: Ponte Nuovo del Popolo and its damaged girders.

2.2 Materials characterization tests

Four reinforcing bars, in positions that should not aggravate the structural situation, were extracted to define materials properties, such as steel and concrete; ten circular concrete cores with diameter 100 mm were also taken. Tensile tests on steel samples were executed in the laboratory, whereas cylindrical compression tests were executed for the determination of the secant modulus of elasticity of concrete on the concrete cores. Furthermore, some rebound hammer tests on concrete on site, in beams and stringers was performed.

2.3 Dynamic tests

The vibration acquisition campaigns were carried out in two days, on May 10 and 11, 2011. The flow of vehicles over the bridge was normally allowed [4] in a single direction of travel, in a two-lane carriageway. The owner has required the sensors not to be placed on the stone or marble elements, so the accelerometers has been placed on the roadway where the thickness of the pavement was very small (in spite of that very good results were obtained). Eleven setup measurements were installed with 8 DOFs each (total 88 DOFs) allowing a high resolution areal coverage (Figure 3). Comparing the results obtained, both for the mode shapes that the frequencies associated with them, we can observe a good correspondence between the numerical model and experimental modal parameters obtained with the two methods considered. For FDD and SSI methods, identified modes and damping ratios are listed in Table 1.

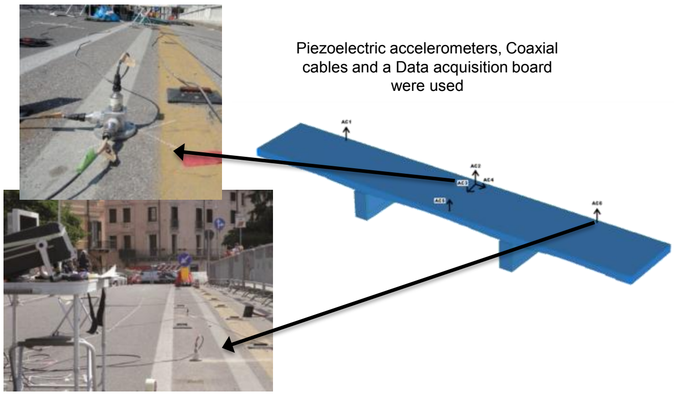

Figure 3: Position of monitoring sensors after preliminary dynamic tests.

Table 1: Comparison between modal techniques and FEM.

Mode	*FDD*	*SSI*	*FEM*
	f [Hz]	*f [Hz]*	*f [Hz]*
1	4.980	4.985	4.958
2	6.250	-	5.654
3	6.738	6.702	5.895
4	7.422	7.337	6.605
5	8.691	8.691	7.510
6	8.960	-	7.510
7	-	10.466	10.89
8	11.600	12.308	12.91
9	15.060	14.384	13.87

In order to study in more details the structural response of the most deteriorated elements some validations have been conducted under the Italian Codes (NTC 2008). In order to simulate the behavior of the degradation, it has been considered a reduced section of concrete. This vulnerability analysis revealed the deficiency of the elements and suggested the installation of a permanent monitoring system.

2.4 Bridge safety SHM system

A monitoring system has been installed in order to evaluate the general behavior of the structure for further damage detection and the local displacement at the damaged elements. Guided by the need to monitor only some essential parameters, a few sensors were installed (Figure 4).

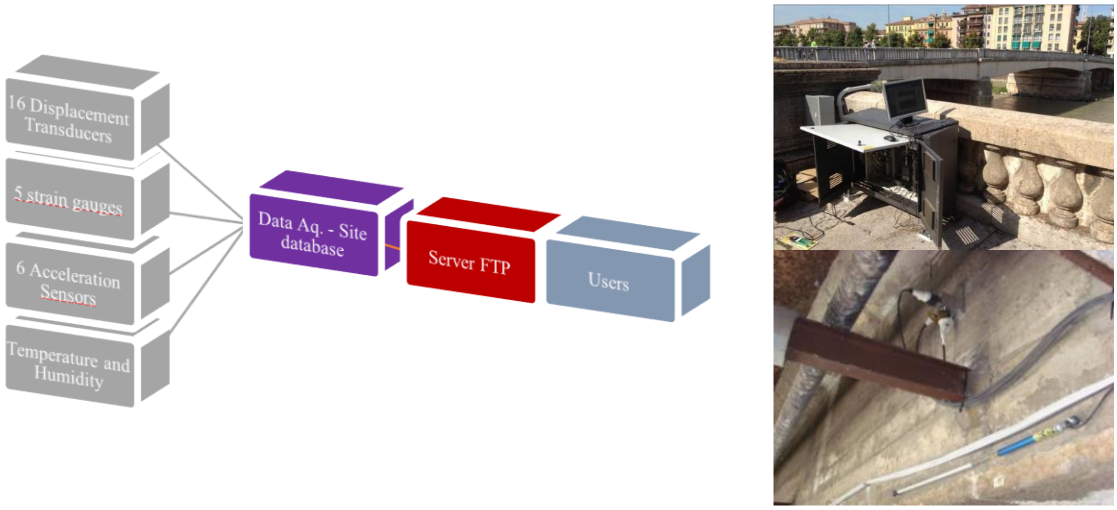

Figure 4: SHM schematic representation.

The installation of the monitoring system was carried out in March 2012. The system is composed by six uniaxial accelerometers (transducers acceleration), by sixteen linear potentiometers (displacement transducers) and seven strain gauges (one of which is to control for the reading of the deformation due to the temperature and humidity). The displacement transducers and sensors strain gauges were placed on all main beams at the center-line of the various spans, which realizes the maximum deformation. The acceleration sensors are installed at the middle of the bridge as a reference and then in the middle of the side spans, in order to grasp the global dynamic behavior of the structure and the change of the natural frequencies during earthquakes or heavy traffic. The installed dynamic monitoring system allows the analysis of a large amount of data taking into account two main aspects: (i) daily extraction of the fundamental modal parameters; (ii) registration and analysis of possible seismic events.

Significant effort is devoted to the analysis of recorded data. In particular the research activities are currently focused on the implementation in MATLAB environment of automatic and semi-automatic procedures for both static and dynamic data processing, applicable to many types of structural systems.

Regarding the static monitoring, it was observed a cyclic trend of displacement and congruent with the environmental parameters. The comparison between the damaged and undamaged beams did not provide significant results because it has not shown any sign of progressive increase of the damage. Therefore, the displacements are mainly due to environmental conditions and not to traffic. Despite the multiple damage present, we can confirm that there are good reserves of strength and that the crack pattern is stable (Figure 5).

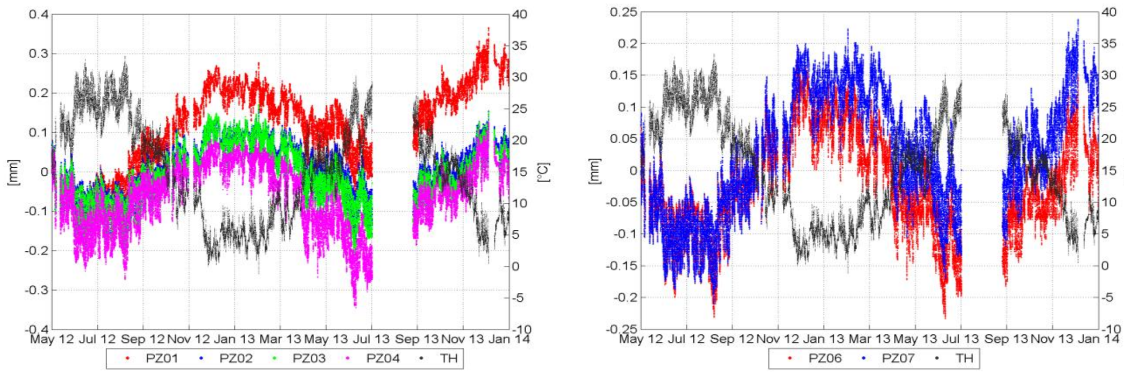

Figure 5: Displacement trend of the monitored beams, comparison between damaged and undamaged beams

The dynamic monitoring results are shown in Table 2 and Table 3 and were achieved from the application of the software SIM/AtOMA implemented in this research work. These results have been obtained by excluding the statistical outliers values (using the box-plot method). Considering the natural frequencies in Table 2, Modes 1, 2, 4, 5, and 6, exhibit a low standard deviation and a high success rate (the number of tests completed in total, excluding the outliers) and this indicates a good reliability for these results. It has been, on the contrary, not always possible to correctly identify mode 3, which shows a lower success rate. This is probably due to accelerometers position.

Table 2: Frequency results of the monitoring using AutoEFDD

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
f_{max} (Hz)	5.029	6.226	6.909	7.788	11.743	12.598
f_{min} (Hz)	4.883	5.786	6.543	7.495	11.572	11.865
f_{mean} (Hz)	4.954	6.090	6.809	7.560	11.700	12.051
f_{std}	0.035	0.126	0.098	0.071	0.054	0.174
success rate	95%	89%	60%	95%	90%	95%

Analogously, for Table 3 all calculated damping ratio parameters for the first 6 modes can be considered as structural, since their value is minor than 10 %. Mode 1, 5 and 6 are the ones that exhibit less dispersed value, having a low standard deviation. Damping ratios calculated for mode 2, 3 and 4 are, on the contrary, more dispersed.

Table 3: Damping results of the monitoring using AutoEFDD

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
ζ_{max}	2.393%	5.974%	4.782%	4.782%	2.519%	2.659%
ζ_{min}	0.577%	0.435%	0.277%	0.349%	0.270%	0.199%
ζ_{mean}	1.532%	2.994%	1.816%	2.367%	1.132%	1.123%
ζ_{std}	0.375	1.252	1.049	0.928	0.470	0.549
success rate	93%	86%	54%	96%	84%	92%

The trend of natural frequencies shows an almost constant behaviour during the months of observation. The lower frequencies show a greater stability while the higher ones are more dispersed (Figure 6).

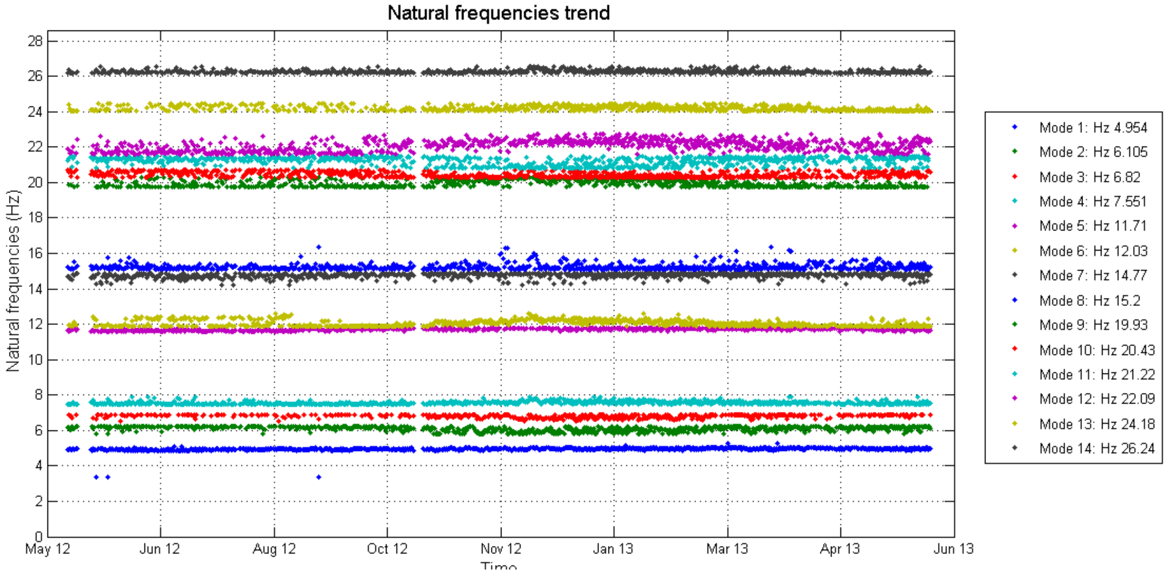

Figure 6: Natural frequencies trend

Figure 7 shows the developing over time of the damping ratio parameter for each structural mode (from mode 1 to mode 6). A seasonal trend variation is visible for all the structural modes. Modes 1, 2, 3, 4, 6 show, on average, the highest damping ratio values in the winter period and then settle again on the previous values, while mode 5 exhibits lower values in the winter period.

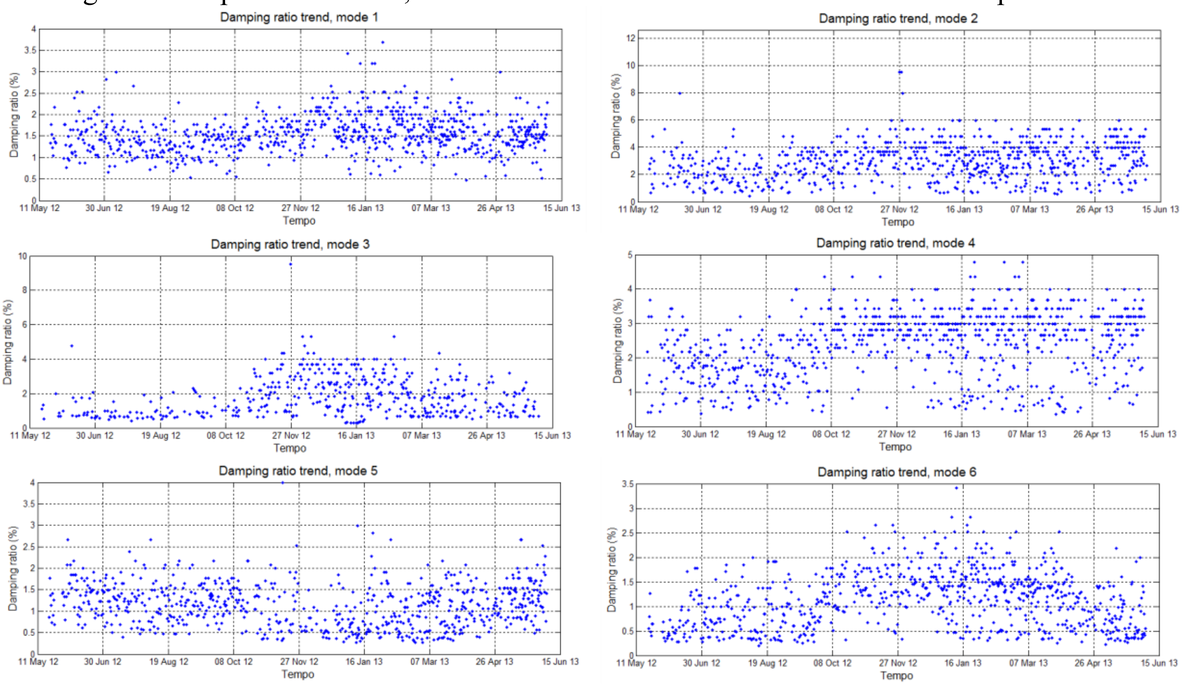

Figure 7: Damping ratio trends for the first six structural modes

In order to validate the results, another method is used to extract the modal parameters of the structure: Stochastic Subspace Identification, through the AtOMA's AutoSSI procedure. Once the results provided by AutoEFDD are available, the extracted structural modes are searched inside the results given by SSI. While high success rates mean that the structural mode is considered to be valid, low success rates do not automatically imply the invalidity of the result, since SSI itself is a method that requires a calibration. Moreover, due to the slowness of the SSI algorithm, it was not possible to carry out the analysis of all the files of monitoring, therefore only a small sample of the total has been considered. The results, for the first six structural modes, given by AutoSSI procedure are displayed and compared with AutoEFDD ones in Table 4.

Table 4: Comparison of the natural frequencies extracted using AutoEFDD and AutoSSI

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
f(EFDD)	4.954 Hz	6.090 Hz	6.809 Hz	7.560 Hz	11.700 Hz	12.051 Hz
Success%(EFDD)	95.3%	89.1%	59.9%	95.1%	89.7%	95.3%
f(SSI)	4.944 Hz	6.062 Hz	6.938 Hz	7.649 Hz	11.660 Hz	12.229 Hz
Success%(SSI)	97.1%	65.7%	82.9%	94.3%	71.4%	97.1%
Error ε	0.2%	0.5%	1.9%	1.2%	0.3%	1.5%

The validity of the natural frequencies extracted using AutoEFDD is clear for most of the structural modes: modes 1, 3, 4, 6 exhibit in fact a high success rate. SSI did not always identify modes 2 and 5, but the validation is overall positive, since they were correctly identified in more than 65% of the monitoring files considered.

The parameters of damping ratio calculated with SSI are of the same order of magnitude as those calculated by the method EFDD. The estimates of the damping ratio for modes 1, 4, 5 are comparable with those obtained using EFDD, while those calculated for modes 2, 3 and 6 present much higher values: these values are probably attributable to the reduced number of files on which the analysis was performed. For each pair of values of the relative error was calculated as the ratio of the absolute error and the mean of the two values.

CONCLUSION

Experimental dynamic analyses and SHM systems, both static and dynamic, were used in this study to assess the actual behavior of an old damaged bridge and to elongate their life-cycle. The structure was subject to several tests with different kinds of sensors like accelerometers and displacement transducers that helped not only to assess slow development of crack openings on the structure but most importantly could get global dynamic information.

SIM/AtOMA has allowed us to confirm the validity of the methods used, as an operation of dynamic identification had been previously carried out by means of a commercial software. This previous analysis had shown the correlation between the structure's actual vibration modes and those exhibited by the FE model. The results given by AutoEFDD and AutoSSI are consistent with the previous analysis and have allowed to observe the development of the modal parameters of the structure for over a year of measurements.

By means of the two applications considered, was therefore demonstrated the ability of AtOMA to provide accurate results of the actual dynamic behavior of a structure.

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