STRUCTURAL MONITORING FOR SEISMIC DAMAGE EVALUATION: A CASE STUDY

STEFANO ANASTASIA, PEDRO POVEDA-MARTÍNEZ,
BENJAMÍN TORRES-GORRIZ & SALVADOR IVORRA-CHORRO
Departamento de Ingeniería Civil, Universidad de Alicante, Spain

ABSTRACT

Seismic events are one of the phenomena with greater influence on the structural condition of bridges and viaducts. For this reason, its design and construction must be carried out under dynamic criteria to guarantee its resistance in a wide range of scenarios. Into the Spanish territory, these requirements are included in the Earthquake-Resistant Construction Standard – NCSE02. However, a large number of structures were built before the appearance of seismic regulations and thus, its indications were not taken into account. In these cases, it is crucial to monitor the behaviour of the structure in order to assess possible damage due to dynamic action. This work presents a case study, focusing on the Santa Ana viaduct, constructed in the Quisi ravine, in Benissa, Alicante (Spain). The rivet structure was built in the early 20th century, being unusual finding similar case studies in the literature. The viaduct, which is in the final stage of its useful life, serves as a bridge for a tram line between neighbouring towns. This work aims at studying the viaduct's structural modal shapes and damping factor to establish its possible interaction with a seism. To this end, the viaduct was monitored with eighteen accelerometers distributed along its length. Through an acquisition system, the vibrations suffered by the structure were automatically registered after the passage of each train. The signals were subsequently processed using different operational modal analysis techniques. This allows not only to obtain the modal parameters associated with the structure, but also its temporary evolution and therefore, predictively determine the possible appearance of structural damage.

Keywords: structural damage, operational modal analysis, preservation, conservation, predictive analysis.

1 INTRODUCTION

During the past decade, the European territory suffered a series of seismic events, including a number of catastrophic ones, which caused, among other things, the collapse of viaducts and bridges leading to the loss of numerous human lives. These events had a strong impact on Civil Engineering by drawing the attention of many experts both technical and scientific. Their efforts are focused on keeping the "health status" of the structures, a discipline known as Structural Health Monitoring (SHM) [1] and for which it is necessary to establish the behaviour of the structure in order to determine its apparent stability.

The current international scenario, where many efforts have been focused in bridges, has led to a deeper understanding of the problem. In this context, SHM normally encompasses all those techniques intended to monitor structures and it results applicable not only in buildings, but also in civil structures, especially in bridges and viaducts [2]. The purpose of monitoring civil structures is to identify sudden or progressive damages by controlling its behaviour in operating conditions or even during particular environmental conditions [3]. It should be stressed that modern constructions may include elements capable of dissipating the energy transmitted by a seism to the system (seismic isolators). In this way, the fundamental frequency of the structural vibration is reduced to a value below the earthquake frequencies. However, previous constructions lack this type of elements and therefore, the damage suffered by the structure can be irreversible and gradually lead to its collapse. For this reason, measuring the damage suffered by the structure after a seismic event is of crucial importance to ensure its integrity.

WIT Transactions on The Built Environment, Vol 202, © 2021 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/ERES210051

The damage identification procedure is usually based on modal analysis, a fundamental tool for SHM [4]. The method requires to register the dynamic responses of the structure, which generally involves the use of acceleration transducers. These measurements allow to evaluate the modal parameters of the structure, which variation highlights the damage suffered by the construction. A clear example is the damping factor, which can be classified as a “damage index” and it is based on the vibration response of the structure. In order to obtain the structural condition, modal parameters should be obtained before and after an excitation event. The results allow to verify if the variation of the modal parameters corresponds to a critical damage level for the structure, which in our case is represented by a bridge [5]. Therefore, since the damage is always accompanied by a reduction in rigidity, the SHM based on output-only modal analysis will consist of identifying changes in modal frequencies. Generally, the SHM using vibration analysis comprises five steps: (i) sensing; (ii) location; (iii) classification; (iv) evaluation; and (v) forecast. Modal analysis involves the determination of natural frequencies, damping ratios and modal shapes of a structure from its dynamic response.

The SHM based on modal analysis is already used by many technicians, and it is especially important in bridges. The damage suffered by the structure in different locations and components actually leads to different frequency changes. However, it remains difficult to determine the location of damages simply by observing changes in modal frequencies, since modal shape is the only parameter related to position. To address this problem, many studies have focused on searching indices that can identify both the damage and its position from modal shapes. Some clear examples are the Modal Curvature Index [6], the Modal Assurance Criterion (MAC) [7] and Coordinate Modal Assurance Criterion (COMAC) [8].

This work aims to illustrate some practical aspects of damage detection methods. The research activity, conducted by the Department of Civil Engineering of the University of Alicante, is part of this complex and articulated panorama. It refers to the structural monitoring of the QUISI railway bridge to control possible damages produced by earthquakes or the deterioration of the structure. To do this, the natural modal frequencies of the structure are automatically obtained with the passage of each train. The data provided by the system, corresponding to the signal acquired by different accelerometers fixed on the bridge, are analysed in time and frequency. Different operational modal analysis techniques are applied: (i) in the non-parametric field, FDD; and (ii) in the parametric field, SSI-Cov. The results of this study will allow to identify any anomaly in the modal shapes and therefore, determine the presence and location of any damage produced in the structure.

2 MODAL PARAMETERS IDENTIFICATION

The data provided by the measurement system was analysed in time and frequency domains. First, the maximum acceleration of each sensor was obtained for all recorded events. Secondly, an Operational Modal Analysis (OMA) was performed by using several techniques. The purpose of this analysis was to determine the modal frequencies of the structure in order to detect significant changes in its behaviour. In addition to this, the damping factor was calculated.

2.1 Spectral analysis

Fig. 1 illustrates the signals obtained after a railway crossing. The peak values recorded by the accelerometers were determined for each event. This value, which gives an idea of the stresses suffered by the structure, was stored together with some temporal information (date, time …) to conform a historical register.

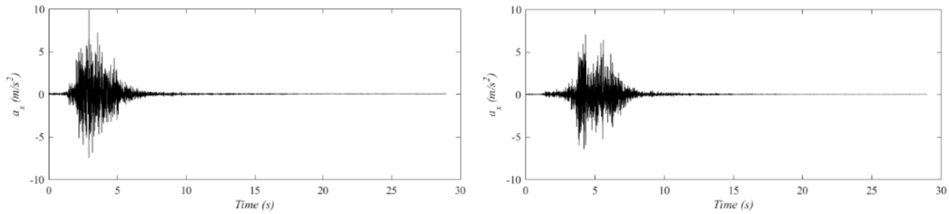

Figure 1: Acceleration recorded when a railway passes at different positions on the viaduct.

A first approximation to determine the modal behaviour of the structure can be obtained by means of a spectral analysis of the signals. However, to avoid frequency components belonging to the excitation source (railway), only the last part of the vibration signal was selected. The time window applied to each register was established from 3 seconds after the peak of maximum amplitude to the end of the signal. The power spectral density (PSD) corresponding to each signal was obtained by using the Welch method (periodogram). To do this, the signals were divided into small segments. Then, thanks to the application of a time window, the Fast Fourier Transform (FFT) was calculated. Finally, all blocks were averaged and PSD was estimated according to the following expression:

$$\varepsilon\{P^{\wedge}{}_{W}(f)\} = \frac{1}{P}\sum_{p=0}^{P-1} \varepsilon\left\{P_{xx}^{(p)}(f)\right\}, \tag{1}$$

where:

$$P_{xx}(f) = \sum_{k=-\infty}^{\infty} r_{xx}(k)e^{-j2\pi fk} = \left|\sum_{n=-\infty}^{\infty} x[n]e^{-j2\pi fn}\right|^2 \tag{2}$$

From the frequency analysis, the structural modes were manually extracted. Since the excitation signal was unknown, the results might contain spurious frequencies that do not belong to the structure. For this reason, it was necessary to implement more advanced methodologies that were able to provide greater accuracy.

2.2 Modal behaviour of the structure

It is extremely useful to identify the natural frequencies of the structure automatically readily. This would allow to establish a continuous monitoring of the structure and thus, an early diagnosis of the damage. In this sense, there are several OMA techniques that efficiently provide modal frequencies and damping factors from the relationship between the vibration corresponding to different points of the structure.

In this study, the Santa Ana viaduct was analysed using two specific OMA-algorithms: the Frequency Domain Decomposition method and the Covariance-driven Stochastic Subspace Identification-Cov [9], [10]. Both methods start with a previous processing where the correlation matrix of the signals is determined:

$$R_j = \frac{1}{n_t}\sum_{k=0}^{n_t-1} y_k y_{k+j}^T. \tag{3}$$

2.2.1 Frequency domain decomposition (FDD) method

The FDD method assumes orthogonal modes. They are estimated through the spectral density of vibration signals. In order to obtain frequencies and modal forms, the matrix of the spectral densities is decomposed through singular value decomposition as:

$$S^{\wedge}{}_{yy}(\omega_j) = U_j S_j U_j^H, \tag{4}$$

where U_j corresponds to an orthogonal matrix with singular vectors $S^{\wedge}{}_{yy}(\omega_j)$, and S_j is a diagonal matrix of singular values. Singular vectors will be related to the modal shapes of the structure.

2.2.2 Covariance-driven stochastic subspace identification, SSI-Cov

The SSI-Cov [11] method is based on the identification of the model through state variables (State Space Model). Modal parameters are identified through the only output system response data. Their covariance function, on which this non-parametric method is based, can be seen as the free dynamic response of the structure. The estimation of the model takes place through the resolution of the Toeplitz matrix (composed of various covariance functions). The matrix is composed and defined according to the following expression:

$$T_{1|j_b} = \left[R_{j_b}\ R_{j_b-1}\ \dots\ R_1\ \ R_{j_b+1}\ R_{j_b}\ \dots\ R_2\ \ \dots\ \dots\ \dots\ \dots\ \ R_{2j_b-1}\ R_{2j_b+2}\ \dots\ R_{j_b}\ \right]. \tag{5}$$

The decomposition of this matrix into singular values (SVD) allows to estimate the modal frequencies of the structure.

2.3 Automated operation modal analysis

The automation of the OMA algorithm aims to obtain a series of snapshots containing the dynamic characteristics of the structure. Therefore, it allows to establish a time evolution of the modal behaviour of the bridge, which is extremely useful to detect possible damages from a deviation. The system involves two basic steps: (i) automatic calculation of modal frequencies (FDD, SSI-Cov) and (ii) the automated tracking of modal properties over time. It must be noted that the FDD parametric identification technique is significant because of its simplicity, and its rigorous physical meaning. Methods used in this work were developed in frequency domain, starting from the estimation of an output spectrum or half spectrum matrices from the measured dynamic responses. The results of this model allowed to produce a series of graphs consisting of a succession of frequency values and damping factors.

3 BRIDGE AND MONITORING SYSTEM

3.1 Structure under analysis

The Santa Ana viaduct, in the Quisi ravine, was built between 1913 and 1915. It has a six-span structure bridged by Pratt-type metal lattices over piles of metal profiles. The viaduct is currently used as a crossing for the tram line 9 between the towns of Benidorm and Denia, in Alicante (Spain) (Fig. 2).

The structure is approximately 170 m long and consists of six spans of various lengths: 21.48 + 21.12 + 42.00 + 42.00 + 21.12 + 21.48 m. The two central spans present a continuous structural scheme, while the four lateral ones are isostatic (Fig. 3).

Figure 2: Front view of the Santa Ana viaduct.

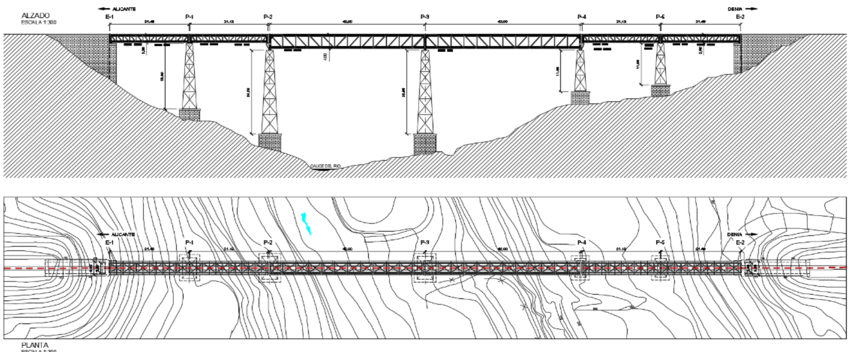

Figure 3: Ground and elevation plan of the Santa Ana viaduct.

3.2 Monitoring system

The monitoring of the structure was carried out through a number of accelerometers located along its length. Moreover, the system included all the necessary equipment for the automatic and continuous acquisition of the signals.

3.2.1 Vibration signals acquisition system

The signals provided by the transducers installed along the structure were acquired by means of a HBK QUANTUMX MX 1601B interrogator (Fig. 4). The system was formed by 16 channels, allowing the supply of accelerometers through constant current or IEPE and a sample frequency of 20 kHz.

Figure 4: Acquisition system QUANTUMX MX1601B.

3.2.2 Acceleration transducers

The monitoring system had a total of 18 accelerometers: 12 uniaxial (B&K 4507-B-006) and 6 triaxial (B&K 4506-B-003); both with a sensitivity of 490 mV/g and a working range between 0.3 and 2000 Hz (Fig. 5). The transducer characteristics guarantee a dynamic range of ±5 g, avoiding the saturation due to the pass of a train. The sensors, stainless steel, were hermetically sealed and their connections were water-resistant. Communication between accelerometers and data acquisition system was carried out through coaxial cable.

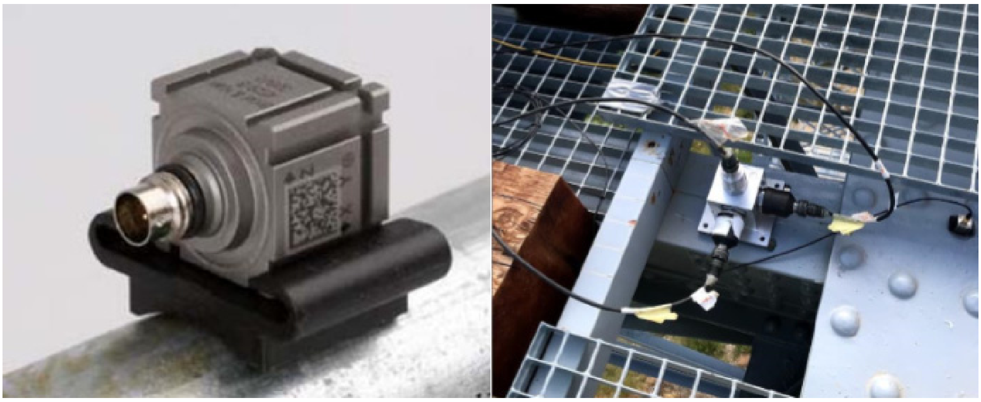

Figure 5: Accelerometers installed in Quisi viaduct.

Accelerometers were distributed along the structure, including two uniaxial sensors and one triaxial sensor in each span as shown in Fig. 6 (symmetrical installation for spans 4, 5 and 6).

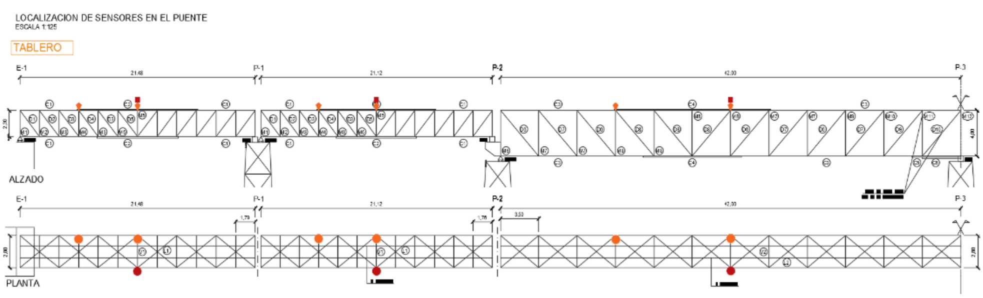

Figure 6: Uniaxial (orange) and triaxial (red) accelerometers location diagram in the first three spans.

3.2.3 Monitoring system configuration

The measurement system was configured to register the vibration of the viaduct with the passage of each railway. To do this, two photoelectric cells were located at both sides of the viaduct. When the passage of a convoy was detected, the acquisition system was activated, recording the signal provided by the accelerometers for a period of 30 seconds. The data was stored on a remotely accessible server, allowing its subsequent processing and analysis. The acquisition corresponding to the X component was carried out using a sample frequency of 200 Hz. In the other cases, the frequency was established to 50 Hz. Table 1 summarises the most relevant characteristics of the signals, including the position and direction of each accelerometer.

Table 1: Measurement position and direction.

Span	Direction	Position*
Span 1/6	X	0.25
	X	0.5
	X	0.5
	Y	0.5
	Z	0.5
Span 2/5	X	0.25
	X	0.5
	X	0.5
	Y	0.5
	Z	0.5
Span 3/4	X	0.4
	X	0.6
	X	0.5
	Y	0.5
	Z	0.5

*Relative position with respect to the span length.

For every train passage, the time signal provided by each accelerometer included into the metal structure was stored in a comma separated value (CSV) file. In addition, a column corresponding to a temperature probe, as well as the necessary data to determine the direction of each train were included. The files generated by the system were automatically stored on a server using Synology Drive technology. The system allows the continuous and simultaneous access of multiple clients remotely for the management of stored information and its subsequent analysis.

From a numerical model of the viaduct, the first modal frequency of each span was obtained (Table 2). These values allowed to verify the proper functioning of the modal analysis algorithms used in this work.

Table 2: Theoretical first modal frequency for each span.

Span	Theoretical first modal frequency (Hz)
1	9.40
2	9.35
3	4.73
4	4.73
5	9.35
6	9.40

4 ANALYSIS AND RESULTS

The PSD analysis clearly showed the most relevant modal frequencies of each span. As shown in Figs 7 and 8, corresponding to the frequency behaviour of span 2 and 3, the experimental results confirmed those obtained theoretically for the structure. In the first case, a frequency of 8.85 Hz was derived from the signals (9.40 Hz by numerical methods, 5% deviation). For span 3, the first mode was located at 4.57 Hz (theoretical results: 4.73 Hz, 3% deviation).

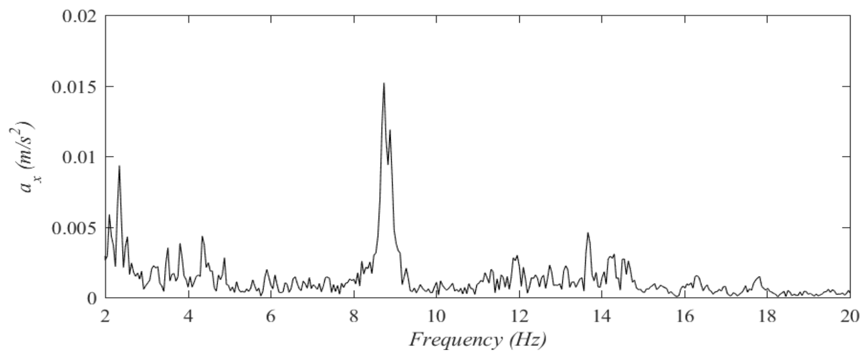

Figure 7: Frequency spectrum corresponding to the central point of spam 2 (X component).

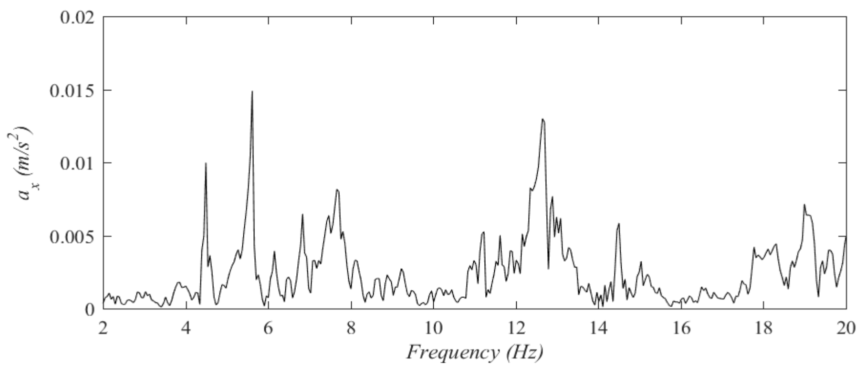

Figure 8: Frequency spectrum corresponding to the central point of spam 3 (X component).

To automatically obtain the modal frequencies of the structure, two different OMA algorithms were used: SSI-Cov and FDD. In the first case, the results provided by the model allowed to produce a series of graphs (Fig. 9) consisting of a succession of poles or peaks, which can be identified along the vertical alignments in the diagram. By means of these figures, it was possible to observe the stability of the poles which had been obtained for the different natural frequencies of the state space model.

Using the OMA methods above, it was possible to measure the modal frequencies of the structure for each event. This information allowed to visualise its evolution over time and therefore, to detect important deviations due to structural damages. Figs 10–12 show the evolution of the vibration modes over a period of nearly 10 days.

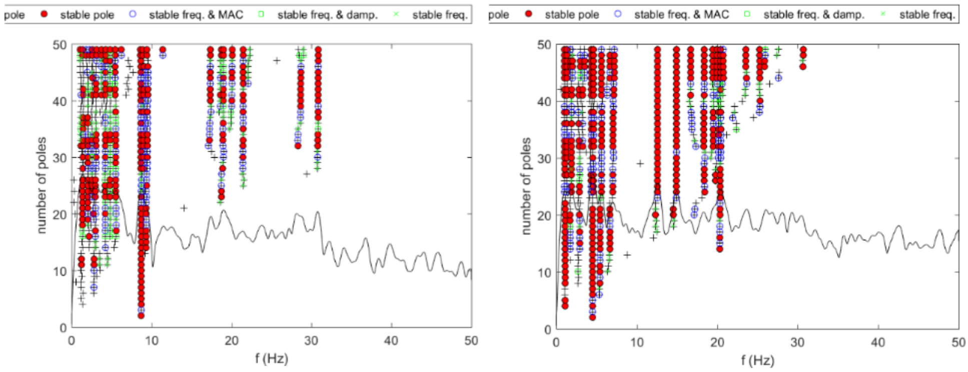

Figure 9: Modal frequencies obtained by means of SSI-Cov method.

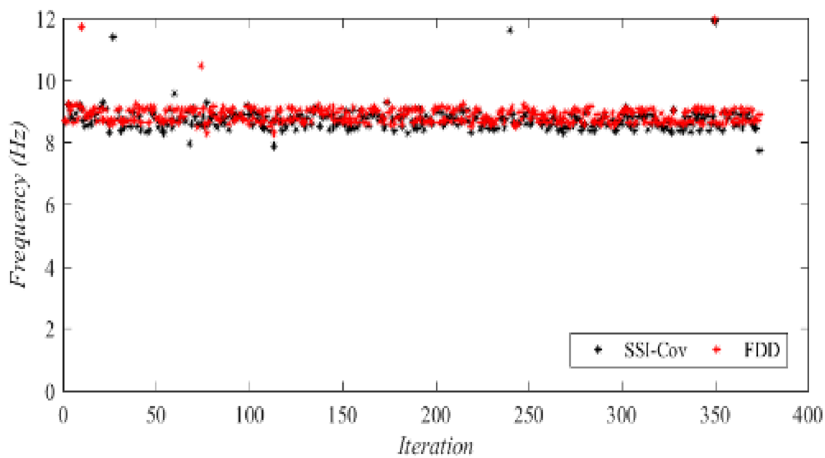

Figure 10: Evolution of the first modal frequency for span 2.

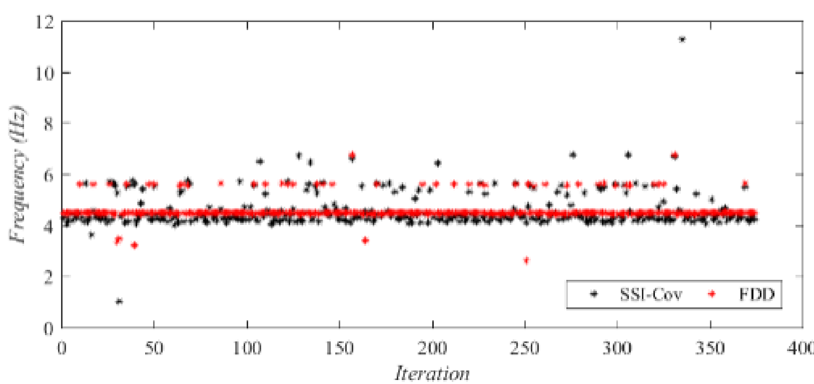

Figure 11: Evolution of the first modal frequency for span 4.

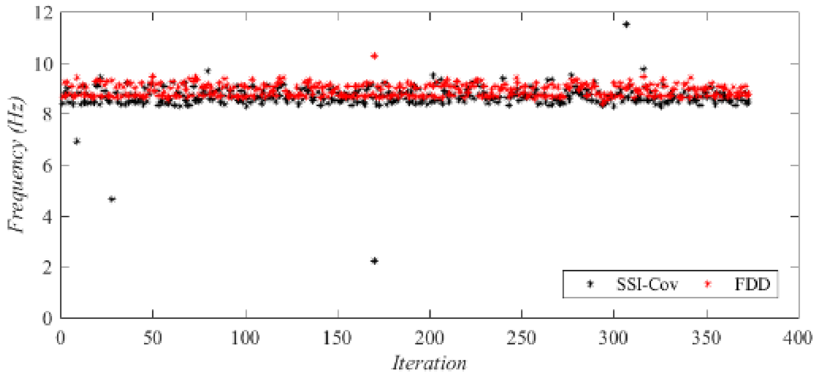

Figure 12: Evolution of the first modal frequency for span 6.

The modal properties derived from SSI-Cov were consistent with those obtained by the FDD method in terms of frequency, damping and shape modal.

5 CONCLUSIONS

The illustrated procedure for automated identification and modal tracking was based on parametric SSI-Cov and non-parametric FDD methods. The procedure was tested and verified with the data recorded on the historic Quisi railway bridge. For this purpose, a permanent monitoring system consisting of accelerometer sensors was designed. The results included in this work correspond to a preliminary study and show a first approximation to the structural monitoring and damage detection. It is extremely important for the application of SHM to gather accurate information of the results in order to obtain a faithful interpretation of the dynamic behaviour of the structure. The preliminary results showed a great correlation between the algorithms used in the analysis and the theoretical behaviour of the structure. However, a better optimisation of the algorithms should be carried out in order to avoid outliers.

To summarize, the proposed methodology is promising for the interpretation of the data provided by a continuous dynamic monitoring system. The developed procedure should take into account some factors that affect the modal identification, such as environmental conditions and background noise.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the Research Fund for Coal and Steel under grant agreement No. 800687 (DESDEMONA EU project). Authors are particularly grateful to ECISA for its major support.

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