Operational Modal Analysis as a Tool for Bridge Model Updating. Application to an Unconventional Case Study

Simone Celati[1](✉), Matteo Castellani[2], Nicola Cavalagli[2], Isabella Mazzatura[1], Andrea Meoni[2], Vincenzo Messina[3], Agnese Natali[1], Filippo Ubertini[2], and Walter Salvatore[1]

[1] Department of Civil and Industrial Engineering, School of Engineering, University of Pisa, Pisa, Italy
`simone.celati@phd.unipi.it`
[2] Department of Civil and Environmental Engineering, University of Perugia, Perugia, Italy
[3] FABRE: Consorzio di Ricerca per la Valutazione e Il Monitoraggio di Ponti, , Viadotti e Altre Strutture, Pisa, Italy

Abstract. When approaching the evaluation of an existing structure, the proper definition of its numerical model can be a difficult task. When designing new structures geometry, restrain conditions and all specific details are chosen by the designer, while in the assessment of an existing structure all these parameters are characterized by uncertainties. Therefore, visual inspections, on-site tests, and geometric surveys are of primary importance for the characterization of the actual structural behaviour and to reduce uncertainties to obtain reliable structural models. In this regard, a technique to assess the representativity of the numerical model is the Operational Modal Analysis (OMA). This technique was applied to characterize the dynamic behaviour and obtain a representative model of a bridge subjected to progressive damage due to external sources that have altered the constraint conditions, so its structural response to external actions. The area where the bridge is located is subjected to the landslide of a mountainside which causes differential movements in the foundations. Ambient vibration tests were performed to characterize the dynamic response of the structure in operational conditions and carry out OMA analysis through up-to-date methods, such as SSI covariance. The results from surveys and OMA highlighted modifications in the supports of the bridge with respect to the initial design. These outcomes were implemented into the numerical model of the bridge to closely match the experimentally obtained modal properties, therefore achieving an updated model which is suited to properly replicate the actual structural performance of the bridge.

Keywords: Prestressed concrete bridge with post-tensioned cables · Visual inspections · On-site surveys · Dynamic behaviour · Operational Modal Analysis · Model updating

M. P. Limongelli et al. (Eds.): EVACES 2023, LNCE 432, pp. 1–10, 2023.
https://doi.org/10.1007/978-3-031-39109-5_1

1 Introduction

The safety evaluation of existing bridges and the assessment of their conservation state is an urgent issue in the majority of European countries. The problem is even more significant considering the number of existing bridges in Europe, which was estimated approximately one million in the final report of COST Action 345 [1]. Existing bridges and viaducts should be assessed on the basis of available information about the actual structural configuration, materials' strength, loading conditions, and potential structural diseases due to natural hazards such as earthquakes and landslides [2, 3]. These pieces of information must be integrated into the numerical models commonly used to assess their structural performance in order to reduce the uncertainties of numerical analyses. In this regard, the execution of geometric surveys [4], visual inspections [5, 6], and other Non-Destructive Evaluation (NDE) tests [7] are of primary importance for the characterization of the actual structural behaviour of bridges and viaducts, and, therefore, for the reduction of uncertainties in numerical models. Among others, Operational Modal Analysis (OMA) methods are also widely adopted in common practice. This method aims at characterizing the dynamic response of bridges and viaducts under ambient vibrations through the determination of their modal features, namely the natural frequencies, mode shapes, and damping ratios [8–10]. The obtained experimental outcomes are then compared with the modal features extracted from the numerical models. Potential discrepancies may be refined by tuning the mechanical parameters defined in the structural models as well as their restraint/constraint conditions.

In this paper, OMA methods were applied to characterize the dynamic behaviour of a bridge subjected to progressive damage due to mountain landslides. Visual inspections and geometrical surveys through Laser Scanner and UAV Photogrammetry were carried out to define the actual geometry and configuration of the structural components in the numerical model. Then, the structural model was tuned by considering the outcomes from the dynamic identification.

2 The Case Study Structure

The case study bridge is a very peculiar structure located in a mountainous zone and bypassing a river. The three-span deck is constituted of a continuous pre-stressed reinforced concrete slab with post-tensioned cables, laying on two pendular pillars and two side abutments. Besides, the planar development of the deck is circular (Fig. 1). The location of the bridge has been interested by severe hydraulic and landslide phenomena, which mutually influenced and induced progressive damage in the structure. Looking at the bridge from the upstream, the active landslide is occurring close to the structure, on the right side. This phenomenon caused and is still making the bridge's right abutment and pillar's foundation move to the left. This movement is fairly visible from the current changing position of the composing elements: both the pendulum pillars rotated in and out of plane, with slight partial detachment of the deck and of the base of the pillar (Fig. 2 highlights this for pillar 1); the deck is progressively detaching from the right abutment (Fig. 3a) and moving toward the left one, locking into it (Fig. 3b). Besides, the progress of the landslide is fed by the river, which contributes to the erosion of the riverbed. The different configuration of the main components of the bridge causes both local damage in the elements and may change the structural response of the bridge to external natural and man-induced actions (such as traffic load), hence the necessity of assessing the current safety level of the structure. For the structural assessment, it is fundamental to build a numerical model the most representative of the current configuration of the structure. To this purpose, the knowledge process to the evaluation of the safety level has been structured as in the following: a) research of original documentation about the structure, including technical drawings, structural details, material certifications, possible previous surveys; b) on-site inspections for the evaluation of the conservation status and of current damage of the components; c) geometric survey for the assessment of the actual spatial configuration of the structural elements and preliminary assembly and definition of the numerical model; d) characterization of the dynamic response of the bridge trough Operational Modal Analysis; e) numerical model updating. In this paper, a focus is made into highlighting the main elements which affect the changing the structural response of the bridge, with respect to the original concept, and on the techniques and instruments adopted for the construction and the calibration of the numerical model: the damage detection, the geometrical surveys for the real configuration of the structural elements, and the OMA to obtain a well-calibrated and representative structural response.

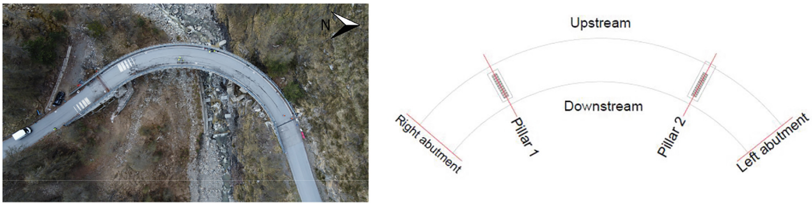

Fig. 1. Plan view of the case study structure (left), with a schematic view of the main structural elements (right).

Fig. 2. View of the current configuration of pillar 1.

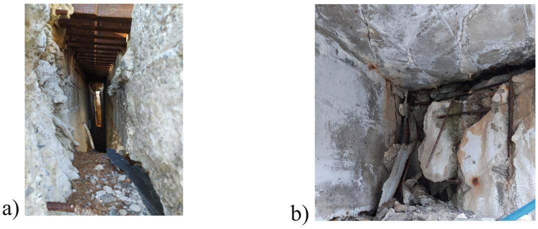

Fig. 3. a) Partial detachment of the deck from the right abutment; b) Progressive movement and locking of the deck toward the left abutment.

2.1 Damage Detection and Geometric Survey Through Laser Scanner e UAV Photogrammetry

On-site inspections were carried out to assess the actual conservation status, local damage of elements and their change of spatial configuration. The evaluation of the conservation status and damage was fundamental to highlight the effects of the landslide-induced movement on the structural components, resulting globally in a change of external and mutual constraints and local change of internal stress distribution in the structural elements. In particular, the movement of the deck to the left side resulted in the following:

- the right end of the deck is lifted from the supports, while the back vertical face is partially detached from the abutment and partially in contact. This turned the original simply-supported configuration into a peculiar constraint, which behaviour is affected by the actual length of the portion of the deck in contact with the abutment and by the friction between the surfaces (Fig. 2 and Fig. 3a).
- The left end of the deck is totally locked in the left abutment, turning the simply-supported constraint into an almost fixed one (Fig. 2 and Fig. 3b).
- The pendular pillars rotated in and out of plane, with a partial detachment of the pillars' base from their basement and partial lift of the deck from the upper side of the pillar. This resulted in a different stress distribution along the height of the pillar for vertical loads, also highlighted by some horizontal cracks on the unloaded side (Fig. 2).

The change of configuration of these elements and the change of external/mutual constraints surely affect the global response of the structure and are among the main parameters to be calibrated in the numerical model. An important role for knowledge of a structure is entrusted to geometric surveys, and in this case gets fundamental to individuate the actual spatial geometrical configuration of the components: two different relief campaign was conducted to obtain different points clouds using Laser Scanner and UAV Photogrammetry [11]. The benefits of this approach allow obtaining a very high degree of precision in a relatively limited time, in both the on-site measurements and post-processing stage. In particular, 40 laser scanner acquisitions were made to fully catch the bridge and its surrounding (Fig. 4a). Then, through 9 manual flight missions using a DJI Mini 2, 167 single photos were taken and a dense cloud of 26˙215˙731 points was obtained through a structure from motion commercial software (Fig. 4b).

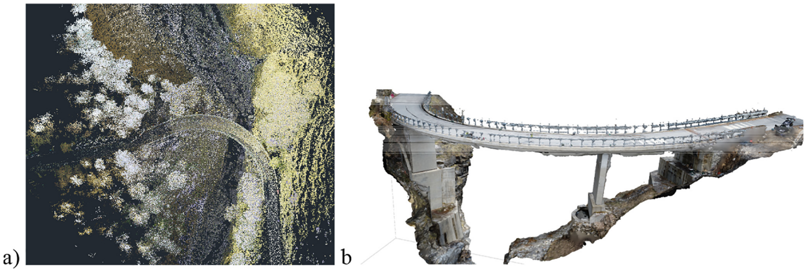

Fig. 4. a) TLS resultant points cloud; b) UAV photogrammetry resultant points cloud.

3 Preliminary Finite Element Model

A preliminary FE model has been developed thanks to the original documentation and of the geometric on-site surveys. This model was also necessary to properly design the OMA, given the relevant uncertainties in the structural response due to the relevant change of configuration of the structure. Based on the laser-scanner and UAV photogrammetry resultant point cloud, the modified geometry was reconstructed initially in the CAD ambient (Fig. 5a). The principal elements (piers, slab, and side wings) have a plane extension, therefore the mid-plane of each one was identified and the particular geometry was reconstructed. Then, the geometry was imported into the finite element software SAP2000 and the elements were modeled using shells (Fig. 5b). The side wings' mid-plan is 42.5 cm higher than the slab's, thus the continuity was modeled by rigid links. The external constraints, slab-abutments and piers-ground, were modeled as perfectly simply supported. Given the detected damage and current state, their actual behaviour and functionality will be studied by analyzing the dynamic identification results and they will be the main parameters to be updated in the finalization and calibration of the final numerical model. To represent the rotation and the consequent loss of the support of half of the piers, the external constraints were applied only to half of the basis nodes (Fig. 5b).

The only loads modeled are the self-weight and the permanent loads, which are the only ones acting during the dynamic test. The only permanent load acting is the asphalt weight, assumed evenly distributed on the deck area with a value of 2 kN/m^2. The prestressing was not modeled in this preliminary model, since it does not affect the mass or the stiffness of the structure, hence it does not affect the dynamic response.

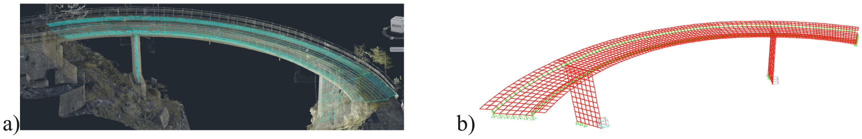

Fig. 5. a) CAD ambient geometry; b) Preliminary finite element model

4 The Operational Modal Analysis

4.1 Ambient Vibration Tests

AVTs were carried out to evaluate the dynamic behaviour of the case study bridge on April 27th, 2022. High-sensitivity (10 V/g) uniaxial seismic accelerometers, model PCB393B12, were mounted on stabilization steel supports, hence positioned on the concrete curbs of the bridge deck as schematized in Fig. 6 to measure vertical, tangential and radial accelerations. Despite the temperature has been extensively proven to influence the fundamental frequencies of structures [12], in this study no temperature measures were acquired. Indeed, the research focuses on the structural response changing due to landslide-caused damage, thus it is assumed that the influence of temperature is comparatively less relevant. For this reason, the preliminary FE model does not account for the temperature effect. It is also worth noting that, when the AVTs were performed, the air temperature was within the range of typical annual values (around 10 °C). Given the limited number of sensors available, two different measurement configurations were performed to comprehensively investigate and represent the mode shapes of the structure. Acceleration measurements were acquired by using a data acquisition system (DAQ), model NI cDAQ-9188, embedding four NI 9234 modules and three NI 9230 modules, with a sampling frequency of 1706 Hz. The duration of each measurement record was equal to thirty minutes, a time window quite larger than 2000 times the fundamental period of the bridge, which usually ensures an accurate estimation of the modal parameters [13]. The modal identification of the bridge was performed by using the software MOVA [14]. Signals acquired for each measurement configuration were first detrended and resampled at 40 Hz, then the Covariance-driven Stochastic Subspace Identification (COV-SSI) method was employed to identify the modal features of the structure. The mode shapes extracted from the measurement configurations were merged through a least squares approach [15].

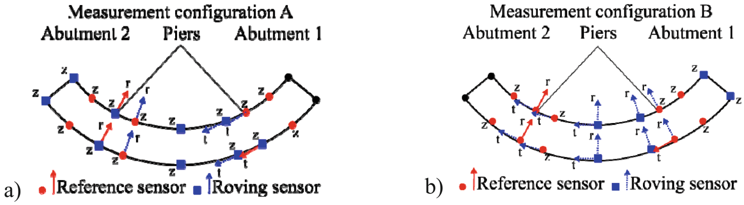

Fig. 6. Measurement configurations adopted to perform AVTs on the case study bridge: a) measurement configuration A; b) measurement configuration B.

4.2 Data Post-process and Identification of the Modes

Figure 7 reports the first eight identified natural frequencies and mode shapes of the case study bridge. A careful examination of the resulting mode shapes reveals unexpected torsional movements at the abutments and pillars of the structure; these motions can be attributed to the occurrence of modifications in the bearing supports of the bridge with respect to the initial design, due to the differential foundation settlements induced by the landslide of the mountainside.

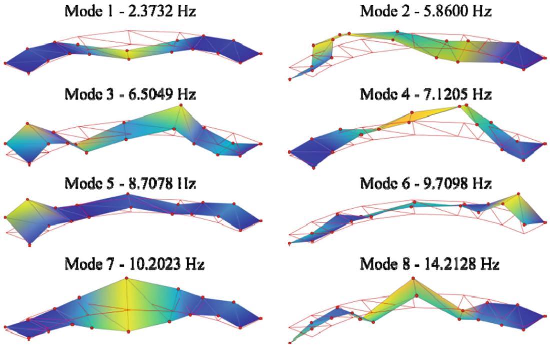

Fig. 7. First eight experimentally identified natural frequencies and mode shapes.

5 Model Updating

Differences between numerical and identified modes are notable (Fig. 8), thus the FE model needs to be updated to better represent the actual state of the bridge. The main damage phenomena are the changes of the external restraints from the design ones due to the settlements caused by the landslide. Therefore, the parameters of interest for the update of the model are the stiffness of the restraints and their reciprocal ratio. To simulate the loss of support and to permit the torsional mode at the south abutment only a small central part of the slab has been restrained with vertical springs (Fig. 9a). At the south pier, the slab shows a torsional motion and diagonal cracks consistent with a lack of torsional restrain, thus the inner connection pier-slab has been modeled only for half of the pier's width (Fig. 9b). Furthermore, the pier's base is restrained only for half of its width, as in the preliminary model (Fig. 9c). Because the slab is forced into the north abutment by the landslide, the radial restrain at the north abutment is considered fixed, whereas, in the vertical and tangential direction, it is modeled as springs (Fig. 9d).

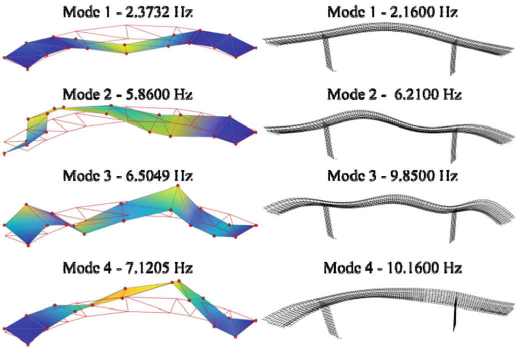

Fig. 8. Comparison between the first four experimentally identified natural frequencies and mode shapes and the preliminary model's numerical ones.

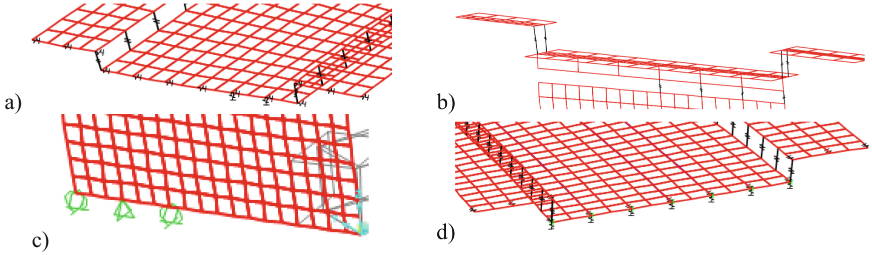

Fig. 9. Modeled restrain at: a) south abutment, b) top south pier, c) bottom south pier, d) north abutment.

The updated model provides frequency and mode shapes consistent with the experimentally identified ones. They are depicted in Fig. 10.

Modes till the eighth, except for the fourth which is not present, are well represented by the model. The greatest differences are due to the impossibility of modeling the one-sided behaviour of the actual bearings through a linear model. Indeed, the contact between the slab and the abutment can only transmit compression, not tension.

The stiffness of the springs and their ratio to each other were defined by minimizing the percent error:

$$\varepsilon_{\%} = (f_{FEM} - f_{sm})/f_{FEM} \tag{1}$$

With f_{FEM} frequency estimated by the updated numerical model and f_{sm} frequency experimentally identified. Table 1 shows the percent error for each identified mode.

The percent errors are below 5% for each mode, with the exception of the fifth. Anyway, the fifth mode is associated with a low participant mass, therefore the model can be considered acceptable, and it can be considered representative of the actual structural behavior. At present, only frequencies and visual validation of the mode shape were exploited to calibrate the model. Besides them, mode shape data could be analytically analyzed (e.g. employing MAC analysis for a quantitative FE-AVT comparison) to improve the model accuracy. This is going to be considered in further studies.

Table 1. Experimentally identified and numerically evaluated frequency and percentage error.

Mode	Preliminary model frequency [Hz]	Experimental frequency [Hz]	Updated model frequency [Hz]	Percentage error [%]
1	2.1600	2.3732	2.2378	−6.05
2	6.2100	5.8600	5.9492	1.50
3	-	6.5049	6.3247	−2.85
4	-	7.1205	-	-
5	9.8500	8.7078	7.7195	−12.80
6	-	9.7098	9.3922	−3.38
7	10.1600	10.2023	10.165	−0.37
8	-	14.2128	14.9821	5.13

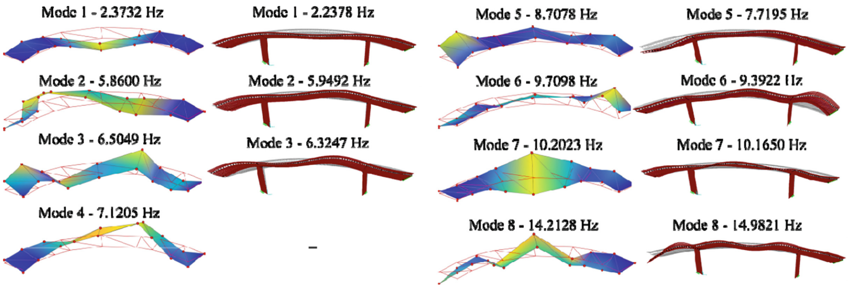

Fig. 10. Comparison between experimentally identified frequency and mode shapes and the updated model's numerical ones, first to fourth on the left, fifth to eighth on the right.

6 Conclusions

This paper presents the application of Operational Modal Analysis for the update and calibration of a numerical model representative of an existing bridge. This structure is a peculiar case study located in an area with ongoing landslide phenomena, which are interfering with the structure. The current spatial configuration and conservation status of the structural elements highlight the changes withstood by the structural elements due to the landslide with respect to the original design, and suggest the necessity of assessing the actual resulting safety level. With this purpose, the numerical model of the structure has been built. A wide on-site survey campaign, comprehensive of: visual inspections for damage detection; geometric surveys through Laser Scanner e UAV Photogrammetry, has been fundamental to define the actual of the structural elements. OMA has been executed for the characterization of the dynamic behaviour and the proper calibration of the external/mutual constraints of the elements of the numerical model. The model updating procedure allowed to fit the dynamic behaviour obtained from the post-process of the dynamic acquisitions, with a percentage error below 5% for each mode, with the exception of the fifth one which is not considered such relevant due to the low participant mass associated. The methodology adopted for this case study allowed to obtain a reliable numerical model, proven to be representative of the current structural response of the bridge and reducing to the minimum the geometrical uncertainties.

Acknowledgements. The support from the Provincial of Imperia under the research agreement with the FABRE Consortium is gratefully acknowledged.

References

1. COST 345. Procedures Required for the Assessment of Highway Structures. Final Report, Reports of Working Groups, pp. 1–6 (2004)
2. Steenbergen, R.D.J.M.: Safety philosophy for existing structures and partial factors for traffic loads on bridges. Heron **55**(2) (2010)
3. Sýkora, M.: Verification of existing reinforced concrete bridges using the semi-probabilistic approach. Eng. Struct. **56**, 1419–1426 (2013)
4. Stavroulaki, M.E., Riveiro, B., Drosopoulos, G.A., Solla, M., Koutsianitis, P., Stavroulakis, G.E.: Modelling and strength evaluation of masonry bridges using terrestrial photogrammetry and finite elements. Adv. Eng. Softw. **101**, 136–148 (2016)
5. Moore, M., Phares, B.M., Graybeal, B., Rolander, D., Washer, G., Wiss, J.: Reliability of visual inspection for highway bridges, volume I (No. FHWA-RD-01-105). Turner-Fairbank Highway Research Center (2001)
6. Hallermann, N., Morgenthal, G.: Visual inspection strategies for large bridges using Unmanned Aerial Vehicles (UAV). In: Proceedings of 7th IABMAS, International Conference on Bridge Maintenance, Safety and Management, pp. 661–667 (2014)
7. Hesse, A.A., Atadero, R.A., Ozbek, M.E.: Uncertainty in common NDE techniques for use in risk-based bridge inspection planning: existing data. J. Bridg. Eng. **20**(11), 04015004 (2015)
8. Gentile, C., Bernardini, G.:Application of radar technology to deflection measurements and OMA of bridges. In: Proceedings of the 3rd International Operational Modal Analysis, pp. 245–254. Brescia (2009)
9. Rainieri, C., Notarangelo, M.A., Fabbrocino, G.: Experiences of dynamic identification and monitoring of bridges in serviceability conditions and after hazardous events. Infrastructures **5**(10), 86 (2020)
10. Siti, S.S., et al.: Operational modal analysis and finite element model updating of ultra-high-performance concrete bridge based on ambient vibration test. Case Stud. Constr. Mater. **16** (2022)
11. Cavalagli, N., Gioffrè, M., Grassi, S., Gusella, V., Pepi, C., Volpi, G.: On the accuracy of UAV photogrammetric survey for the evaluation of historic masonry structural damages. Procedia Struct. Integr. **29**, 165–174 (2020)
12. Sohn, H., Dzwonczyk, M., Straser, E.G., Kiremidjian, A.S., Law, K.H., Meng, T.: An experimental study of temperature effect on modal parameters of the Alamosa Canyon Bridge. Earthq. Eng. Struct. Dyn. **28**(8), 879–897 (1999)
13. Rainieri, C., Fabbrocino, G.: Operational Modal Analysis of Civil Engineering Structures: An Introduction and Guide for Applications. Springer, New York, 2014. https://doi.org/10.1007/978-1-4939-0767-0
14. García-Macías, E., Ubertini, F.: MOVA/MOSS: two integrated software solutions for comprehensive structural health monitoring of structures. Mech. Syst. Signal Process. **143**, 106830 (2020)
15. Au, S.K.: Assembling mode shapes by least squares. Mech. Syst. Signal Process **25**,163–179 (2011)