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In-situ test and model updating of an RC tied-arch bridge

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Abstract

The Italian bridge asset is dated, and the functionality of many bridges is jeopardised by degradation due to ageing and environmental effects, as well as by increasing traffic loads. An adequate operational monitoring and maintenance program is essential for ensuring the safety condition of these critical structures. Administrations in charge and policymakers must clearly understand the actual condition of the infrastructure asset in order to optimise maintenance and retrofit planning. For this purpose, visual inspections might fail to reflect the current condition accurately; thus, additional experimental investigation campaigns are desirable. In the knowledge process for existing bridges, valuable information can be obtained through appropriate experimental tests, such as material testing and dynamic identification. Moreover, the potential of on-site test results in updating structural modelling has been demonstrated, successfully improving the performance assessment of bridges. However, sensitivity-based Finite Element model updating requires a deep knowledge of the examined structure to determine which parameters mainly affect the dynamic response.

In this framework, the contribution of this paper consists of a typological analysis and model updating of an existing RC tied-arch bridge dating back to the 1930s. The structural condition was assessed by an on-site investigation campaign, including a geometric survey, material testing, and ambient vibration test (AVT). For the latter, three algorithms for operational modal analysis were performed to extract the bridge's modal parameters and then compare outcomes. Lastly, results from experimental tests were used to update a 3D finite element model.

Keywords: Ambient vibration test; Experimental test; Model updating; RC tied-arch bridge

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1. Introduction

The Finite Element (FE) method is a powerful tool for solving structural problems. The method is widely used to perform reliable safety margin assessments of existing bridges. Although, on the one hand, the use of the finite element method increases the accuracy of the structural safety assessment, on the other hand, there are many uncertainties and assumptions during the implementation of the numerical model. Therefore, the numerical results should be validated by experimental measurements. Dynamic identification, in particular the ambient vibration test (AVT), can provide detailed information on the structural response in terms of natural frequencies and mode shapes (Ceravolo et al., 2019; Türker and Bayraktar, 2014; Zonno and Gentile, 2021). Therefore, specific procedures have been implemented to minimize the differences between experimental and numerical dynamic characteristics. These techniques use uncertain parameters such as material properties, geometric characteristics, boundary conditions, Etc. for updating the FE model. Two approaches could be used to update the FE model: manual and automatic (global and local) model updating. Manual model updating, performed by trial and error, consists of manual modifications of uncertain modelling parameters defined by engineering judgment. The automated model updating usually performed with specific software consists of performing a series of updating loops based on optimization procedures. These methods have become popular in the last decade, and the literature includes many papers about FE model updating of engineering structures such as bridges (Chen et al., 2014; Petersen and Øiseth, 2017), dams (Türker et al., 2014), buildings and towers (Altunişik et al., 2018a; Kodikara et al., 2016) and historical buildings (Altunişik et al., 2018b; Li and Atamturktur, 2014).

In this contribution, a finite element model updating of an existing RC tied-arch bridge is presented. The paper is organized as follows: in chapter 2, the description of the case study is presented, including the modal parameters for the model updating, and the preliminary finite element (FE) model. In chapter 3, the results of AVT and the manual and automated (global and local) model updating are discussed.

2. Material and Methods

An in-situ test campaign was conducted by carrying out destructive and moderately destructive tests to evaluate the material's proprieties (in particular, concrete compressive strength f_c). Subsequently, an AVT was performed to extract the structure's dynamic characteristics. In this work, the experimental parameters were extracted with MACEC 3.3 toolbox (Reynders et al., 2014), using three extraction techniques: the Frequency Domain Decomposition (FDD) (Brincker et al., 2000), the poly-reference Least Square Complex Frequency domain (p-LSCF) (Peeters et al., 2004; Peeters and van der Auweraer, 2005; Verboven et al., 2003) and Stochastic Subspace Identification (Van Overschee and De Moor, 1996). Finally, Finite-Element Model Updating was performed using a manual and automated approach; the manual approach aims to minimize the error through an iterative process, whereas the automated method is based on a sensitivity formulation defined as (FEMtools, 2012):

$$\{R_e\} = \{R_a\} + [S]\left(\{P_u\} - \{P_0\}\right) \quad \text{or} \quad \{\Delta R\} = [S]\{\Delta P\} \tag{1}$$

where $\{R_e\}$ is the vector of the reference system responses; $\{R_a\}$ is the vector of the predicted system responses for a given state $\{P_0\}$ of the parameters values; $\{P_u\}$ is the vector of the updated parameters' values, and $[S]$ is the sensitivity matrix. Eq. (1) is usually underdetermined, so the Bayes Parameter Estimation (BPE) technique was performed to solve it.

Besides, the automated model updating procedure can be global or local according to the parameter level. A global parameter strategy considers a single value for each selected uncertainty parameter in overall models. Instead, a local parameter strategy considers that the selected uncertain parameters for each element in the finite element mesh have different values.

2.1 Description of the case study

The case-study bridge, built in the 1930s, is located in Padua, northeast Italy. The main structure is a reinforced concrete tied arch with 13 vertical hangers per side and 3 horizontal braces between the two arches. The deck consists of longitudinal and cross beams with a reinforced concrete flat slab. On one abutment, there are sliding supports, called pendulums, while on the other, there are fixed supports. During the restoration works in 1994, the flat slab was restored, and two cantilevered cycle-pedestrian walkways were constructed on the sides of the bridge. The general configuration of the bridge is illustrated in Fig. 1 and Fig. 2. The dimensions of the elements measured on site are the same as reported in the original project documents. However, the thickness of the restored flat slab and road pavement is unknown. For further information on the bridge, see (Pernechele et al., 2021). The concrete compressive strength was estimated through 4 compression tests of cylinder concrete and 13 SonReb tests on the arches, ties, hangers, crossbeams, and abutment. The SonReb compressive strength is estimated according to the method proposed by (Faella et al., 2011). According to (NTC, 2018), the structure's knowledge level was defined as extended (KL2), and a confidence factor CF=1.20 was assumed. In detail, material tests results are resumed in Table 1:

Fig. 1. Case study - RC tied-arch bridge.

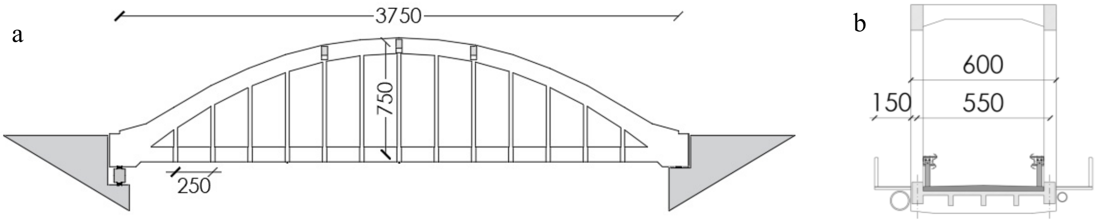
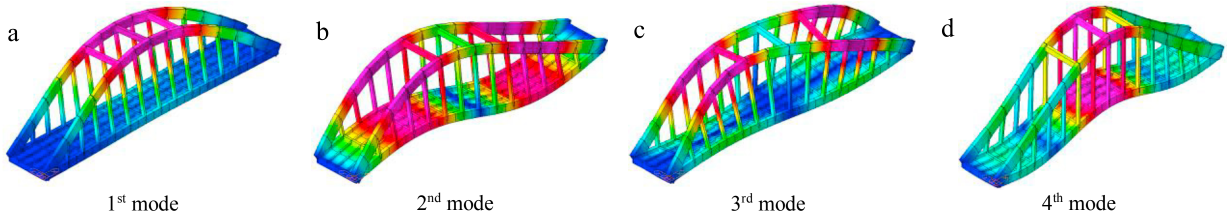


Fig. 2. (a) longitudinal view; and (b) transverse view of the bridge

Table 1. Compressive strength results.

	Arch	Tie	Hangers	Crossbeam	Abutment
N° cylinder compression tests	2	-	-	-	2
N° SonReb tests	2	4	4	1	2
Average compression strength f_c [MPa]	74.55	41.70	34.63	53.00	35.25
f_c/CF [MPa]	62.13	34.75	28.85	44.12	29.38

A 3D FE model was implemented using Midas Civil software (midas Civil, 2022). All the bridge members were modelled through beam elements, except for the slab modelled as a plate. The concrete compression strength was defined as the average value of the superstructure elements reported in Table 1 ($f_c = 40$ [MPa]). The thickness of the flat slab was assumed to be 18 [cm], as in the original project. The weight of the road pavement, barriers and cycle-pedestrian walkways was applied as non-structural masses. An eigenvalue analysis was carried out, and the first four mode shapes are shown in Fig. 3. An ambient vibration test (AVT) was carried out in March 2021, using 23 monoaxial accelerometers divided into two setups (north and south). (Fig. 4)



1st mode 2nd mode 3rd mode 4th mode

Fig. 3. Frist four modal shapes of the case study bridge.

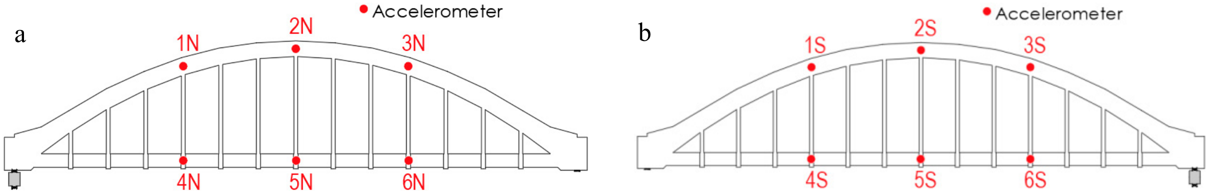


Fig. 4. (a) North Setup; (b) South Setup.

3. Results

3.1 *Summary of AVT results*

Modal parameters were estimated using FDD, p-LSCF and SSI methods. The results in Fig. 5 report the MAC indexes (Allemang and Brown, 1982) between the numerical model and the experimental outcomes. The lower correspondence is highlighted between FEM and FDD (Fig. 5c). As reported in Table 2, the correlation between the numerical and experimental frequencies is low, with a maximum difference of 24.40%.

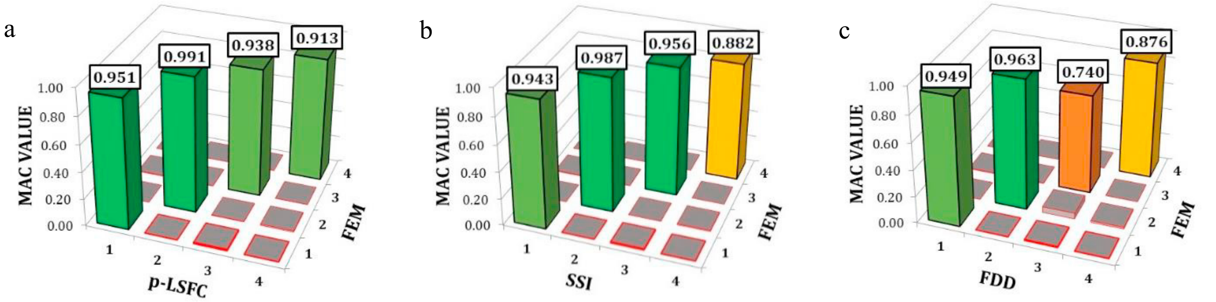


Fig. 5. MAC index (a) p-LSFC-FEM; (b) SSI-FEM; (c) FDD-FEM.

Table 2. Resultant eigenfrequency.

n° mode	Mode type	Initial FEM [Hz]	p-LSCF [Hz]	SSI [Hz]	FDD [Hz]
1	I° Trans	2.768	3.069	2.954	3.027
2	I° Vert	3.094	4.026	4.018	4.004
3	I° Tors	3.633	4.799	4.805	4.785
4	II° Vert	5.986	7.245	7.323	7.080
		Δ_{max}	24.30 %	24.40 %	24.08 %

3.2 Model Updating

The main goal of model updating is to minimize the difference between the natural frequencies of the numerical model and the experimental results. Manual and automated model updating methods were used. In the manual model updating, Young's modulus and density of concrete elements were selected as uncertain parameters. In particular, the structural elements were divided into two groups: the first group (arches, ties and hangers), usually built with more performing concrete and the second group (beams, crossbeams, braces and slab). (Albenga, 1953). In addition, the weight of non-structural masses was also selected as an uncertain parameter. The five uncertain parameters are shown in Table 3, including lower and upper limits defined according to (Ferrari et al., 2019). Fig. 6a shows the normalized sensitivity matrix for manual updating. It can be noticed that first group proprieties (Parameter 1 and 3) are the most sensitive. Table 4 resumes the values of the parameters before and after the model updating.

Table 3. Uncertain Parameters and Limit Values for Model Updating.

Parameter	Structural element	Structural characteristic	Lower limit	Upper limit	Initial value
1	Frist group	E	24000 [MPa]	44580 [MPa]	34290 [MPa]
2	Second group	E	24000 [MPa]	44580 [MPa]	34290 [MPa]
3	Frist group	D	16.8 [kN/m³]	31.2 [kN/m³]	24 [kN/m³]
4	Second group	D	16.8 [kN/m³]	31.2 [kN/m³]	24 [kN/m³]
5	Non-struct. mass	NSM	770 [kg]	1430 [kg]	1100 [kg]

Table 4. Changes parameters for Manual Model Updating.

Parameter	Structural element	Structural characteristic	Initial value	Difference [%]	Update value
1	Frist group	E	34290 [MPa]	+30%	44580 [MPa]
2	Second group	E	34290 [MPa]	-30%	24000 [MPa]
3	Frist group	D	24 [kN/m³]	-23%	18,5 [kN/m³]
4	Second group	D	24 [kN/m³]	-23%	18,5 [kN/m³]
5	Non-struct. mass	NSM	1100 [kg]	-30%	770 [kg]

In automated model updating, more parameters were considered. Global and Local Automated model updating were carried out using FEMtools, and the experimental results were obtained through p-LSCF extraction. Firstly, the global automated updating was performed. It is assumed that each structural component (i.e., arches, ties, hangers, Etc.) has different material proprieties. Young's modulus, material density and the weight of the non-structural masses were selected as uncertain characteristics with lower and upper limits defined as the manual procedure. Hence, fifteen uncertain parameters are considered for the sensitivity analysis. Fig. 6b shows the normalized sensitivity matrix. The characteristics of the arches (Parameter 6 and 12) have the highest sensitivity value. Finally, the local automated model updating procedure was performed. Each FE mesh element was assumed to have a different material property among the defined limit values, defining 819 parameters for the sensitivity analysis. Fig. 6c shows the local normalized sensitivity matrix. In the same way as global model updating, the characteristics of the arches (Parameters from 252 to 283 and from 648 to 679) have the highest sensitivity value. Table 5 presents the comparison between experimental and numerical updated frequencies, while the difference between the MAC indices is shown in Table 6. The maximum difference between the frequencies drops from the initial 24.30% to less than 9% after the updating procedures. The results obtained from the manual model update and global model update are consistent. The local model updating technique achieves frequencies almost equal to the experimental results.

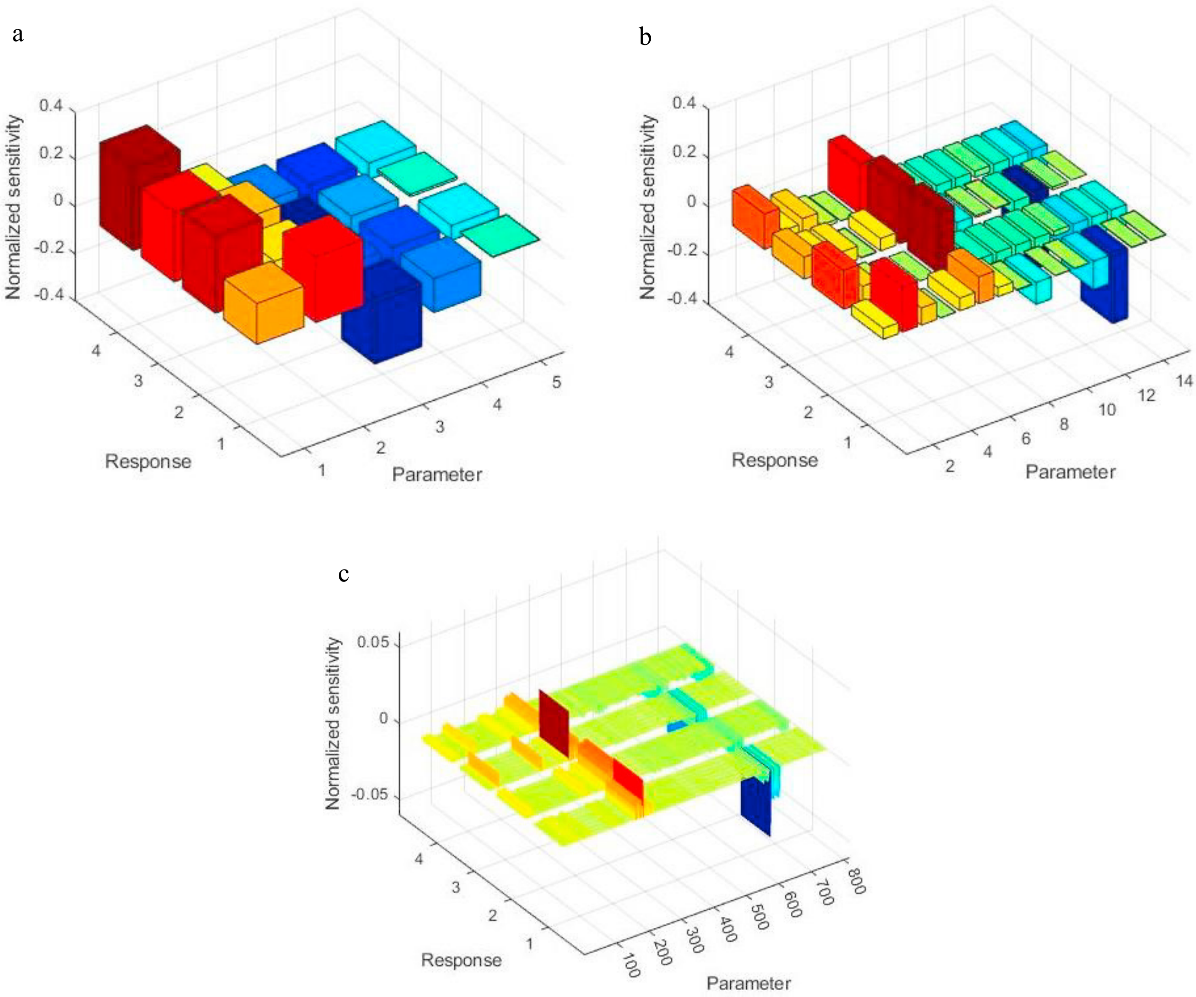


Fig. 6. Sensitivity matrix of selected parameters. (a) Manual, (b) Global automated, (c) Local automated

Table 5. Comparison of Experimental and Updated natural frequencies.

n° mode	AVT [Hz]	Initial FEM [Hz]	Manual updated [Hz]	Global updated [Hz]	Local updated [Hz]
1	3.063	2.768	3.023	3.028	3.067
2	4.026	3.094	3.786	3.851	4.015
3	4.799	3.633	4.368	4.445	4.772
4	7.245	5.986	7.457	7.253	7.239
	Δ_{max}	24.30 %	8.98 %	7.96 %	0.56 %

Table 6. Comparison of Experimental and Updated MAC index.

n° mode	Initial FEM	Manual updated	Global updated	Local updated
1	0.951	0.959	0.939	0.947
2	0.991	0.974	0.991	0.991
3	0.938	0.963	0.937	0.938
4	0.913	0.931	0.932	0.941
Δ_{max}	8.70 %	6.90 %	6.80 %	6.20 %

4. Conclusion

This paper presents the results obtained from the FE analyses, experimental tests, sensitivity analysis, and manual and automatic model update of an RC tied-arch bridge. The characteristics of the materials and the dynamic properties were determined with in situ tests. First, the initial FE model was implemented, and the dynamic characteristics were calculated. Then, manual and automated model updating procedures were carried out to minimize errors between numerical and experimental features. According to the study following conclusions can be drawn:

- The modal parameters were extracted from the AVT using the FDD, SSI, and p-LSFC methods. The lowest MAC index is 0.740 between FDD and FE model for the third mode. Moreover, a maximum frequency gap of more than 24% is reported for the three methods.
- To reduce the differences between the experimental and numerical frequencies, manual and automatic (global and local) model updating procedures were carried out. The manual model updating was performed with an iteration procedure. The automatic model updating was conducted by sensitivity-based analysis using FEMtools software. The possible uncertain parameters used in the manual and automatic updating (global and local) were Young's modulus, the material's density, and the non-structural masses. The elastic modulus and density of arches and ties influence the frequency values significantly. After the model updating, the Δ_{max} drops from 24.30% to 8.98% with the manual updating, 7.96% with the global automated updating, and 0.56% with the local automated updating. In terms of MAC indexes, the Δ_{max}drops from 8.70% to 6.90% with the manual, 6.80% with the global automated updating, and 6.20% with the local automated updating.

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