FE Model Updating of Cable-Stayed Bridges Based on the Experimental Estimate of Cable Forces and Modal Parameters

Marco Martino Rosso[1](✉), Angelo Aloisio[2], Dag Pasquale Pasca[3], Giuseppe C. Marano[1], and Bruno Briseghella[4]

[1] DISEG, Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Corso Duca Degli Abruzzi, 24, Turin 10128, Italy
marco.rosso@polito.it
[2] Civil Environmental and Architectural Engineering Department, Università degli Studi dell'Aquila, via Giovanni Gronchi n.18, L'Aquila 67100, Italy
[3] Norsk Treteknisk Institutt, Børrestuveien 3, 0373 Oslo, Norway
[4] College of Civil Engineering, Fuzhou University, Fuzhou, Fujian 350108, China

Abstract. The paper presents an example of model updating of both the mass and stiffness parameters of a curved cable-stayed bridge in Venice (Italy). Conventional optimization problems of mass and stiffness using ambient vibration data are prone to ill-posedness and ill-conditioning, and generally, the scholar must assume one of the two to achieve a reliable estimate. However, it is possible to assess the mass and stiffness from ambient vibration tests in cable-stayed bridges following a two-step procedure. In the first step, the scholar can assess the mass matrix from the cable forces estimated from the natural frequencies of the cables. Then, the unscaled mode shapes and natural frequencies are used to tune the stiffness matrix in a second step. The authors proved this updating approach with two variance-based sensitivity analyses. The former is the sensitivity of the cable forces to the specific mass and bearing deformability. The latter is the sensitivity of the natural frequencies to Young's moduli. Two global optimization algorithms for mutual validation, differential evolution (DE) and particle swarm optimization (PSO), are then implemented for the model calibration.

Keywords: Cable-stayed Bridge · Operational Modal Analysis · Finite Element Modelling · Sensitivity-based Model Updating · Structural Health Monitoring

1 Introduction

Since operational modal analysis (OMA) provides mass-unscaled mode shapes, the optimization of stiffness and mass matrix simultaneously consequently turns into an ill-posed problem [15,17,19]. Thus, current traditional vibration-based

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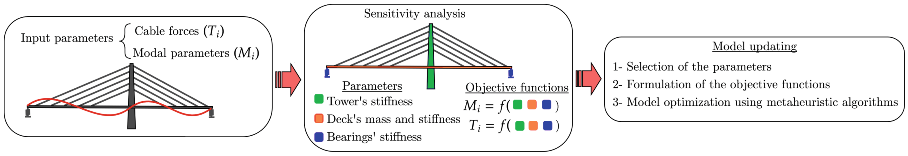

Fig. 1. Illustration of the followed procedure.

finite element (FE) model updating (MU) procedures fail on large-scale structures [7,23]. Nevertheless, in cable-stayed bridges it is possible to experimental determine both deck's modal parameters and cables' natural frequencies [28], which may also provide an indirect estimate of cable forces [12,29]. In this bridge typology, a well-posed FE-MU may be obtained by estimating both mass mode shape scaling factors and cable forces. Regarding the above-mentioned aspects, in the existing literature on cable-stayed bridges, few efforts have been done hitherto [4,6,10,11]. In the current document, the authors attempted to provide an almost complete FE-MU from ambient vibration of the iconic curved cable-stayed case study bridge located in Venice (Italy) at the Marghera harbor [3,9]. A comprehensive description of the case study may be found in [2,5]. The deck curvature provides functional and aesthetic features, as well as additional complications, e.g. construction issues. Moreover, in order to reduce cable eccentricities, the current bridge presents an inclined tower. These peculiarities affect the experimental OMA, which thus becomes a determinant aspect for assessing the reliability of the structural model. Moreover, each cable-stayed bridge is stand-alone due to specific peculiarities, and it is not simple to generalize a unique FE-MU procedure. However, bridges belonging to the above-mentioned category are commonly characterized by three main parts: the deck, the bearings, and the tower. Therefore, the stiffness of the deck, bearings, and tower, jointly with the deck's mass may influence both cable forces and modal parameters. In the current study, the authors followed a step-wise FE updating procedure, as depicted in Fig. 1. In the first step, the mass matrix is determined from the cable forces, in turn, estimated from the natural frequencies of the cables. Then, the unscaled mode shapes and natural frequencies are used to tune the stiffness matrix in a second step. The authors proved the validity of uncoupling the updating procedure by two variance-based sensitivity analyses (SA) [21]. The former is the sensitivity of the cable forces to the specific mass and bearing deformability. The latter is the sensitivity of the natural frequencies to Young's moduli.

2 Finite Element Model Problem Statement

A variance-based SA has been implemented to select which parameters affect at the most the two unknowns, i.e. the cable forces and the modal parameters. It is worth mentioning that since these parameters may be different for various cable-stayed bridges, the optimization formulation cannot be generalized.

DECK

Mode	f [Hz]
1	0.635
2	0.996
3	1.143
4	1.387
5	1.523
6	1.602
7	1.963
8	2.646
9	4.072
10	4.951
11	5.625

STAY CABLES

Cable num.	f [Hz] Mestre side	f [Hz] Venice Side
1	1.230	1.406
2	1.211	1.289
3	1.621	1.641
4	1.543	1.563
5	1.387	1.406
6	1.289	1.328
7	1.250	1.230
8	1.094	1.113
9	0.977	0.938

Fig. 2. Marghera bridge overview and dynamic identification results from [26].

The optimization problem can be formulated as follows in which the objective function (OF) considers both the outputs of the OMA and the SA [7]:

$$\min_{\boldsymbol{x}\in\Omega}\{\boldsymbol{g}(\boldsymbol{x})\}$$

$$\boldsymbol{g}(\boldsymbol{x}) = \begin{cases} \sum_{i=1}^{n_c}\left(\frac{T_i^m - T_i^c}{T_i^m}\right)^2, & \text{Cable forces} \\ \sum_{i=2}^{n_m}\left(\frac{\omega_i^m - \omega_i^c}{\omega_i^m}\right)^2 + \sum_{i=2}^{n_m}\left(1 - \mathrm{diag}(\mathrm{MAC}(\Phi_i^m, \Phi_i^c))\right), & \text{Modal parameters} \end{cases} \tag{1}$$

in which $\boldsymbol{x}$ refers to all the involved bridge parameters defined in an input space Ω. The superscript m is referred to measured parameters, whereas c to the calculated ones. T are the cables forces, ω the angular frequencies, Φ denote the mode shapes, and γ are weighting factors.

3 Deck and Cables Dynamic Identification

In [3,26,27], the dynamic characterization of the Marghera bridge was conducted finding out about 11 modes in the 0-6 Hz frequency band and evidencing both bridge and cable stays modal parameters, as shown in Fig. 2. The authors selected the 11 experimental modes detected in 2011 [26] for the SA and the subsequent optimization. On the other hand, the 18 cable stays' frequencies were determined from measurements collected by sensors placed on every single cable at about 9 m away from the road surface [3]. The cables are progressively numbered from 1 to 9 starting from the tower symmetrically both toward the two opposite directions, i.e. Mestre and Venice, as depicted in Fig. 2. The authors analyzed the interpolating line between the mode order n each natural frequency f_n, concluding that the simplified mechanical model of a fixed-fixed vibrating string can be used to derive the cable forces, which states:

$$f_n = \frac{1}{2L}\left(\frac{T}{\rho}\right)^{0.5} \Longrightarrow T = \rho\left[2L\left(\frac{\partial f_n}{\partial n}\right)\right]^2 \tag{2}$$

Each cable force T is related to the n-th natural frequency f_n of the cable, its length L, and its density ρ. Therefore, the cable force may be obtained by the

Table 1. Cable forces identified from vibration data in the tests of 2011 [26].

	Mestre side									Venice side								
Cable	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
T[kN]	458	757	2359	3715	3842	4199	4828	5289	4771	614	860	2381	3704	3961	4352	4698	5310	4655

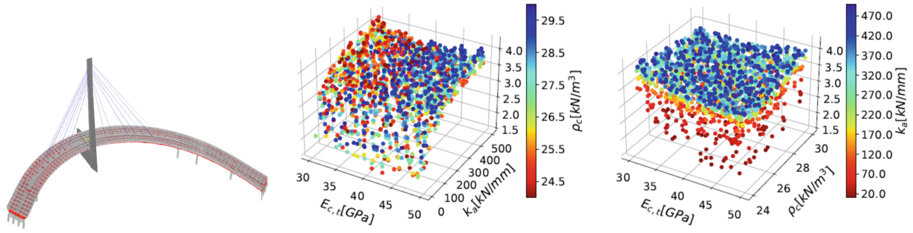

Fig. 3. Marghera bridge SAP2000 FE model and SA results graphs by Eq. (2).

derivative of the interpolating law n-f_n [12]. The cables force estimates retrieved from [26] with the simplified approach are reported in Table 1. It is worth noting that factors like sag extensibility, cable bending stiffness, and intermediate springs do not play a significant role in affecting the cable forces [3,8,16]. However, remarkable discrepancy of the cable forces between the two tower sides have been evidenced.

4 Sensitivity Analysis

A linear FE model shown in Fig. 3 was developed in SAP2000 without considering any geometrical or mechanical non-linearity [1,3,24]. Initial values have been assumed for concrete Poisson's ratio (0.2) and Young's modulus (25.0 kN/m^3), and for the steel's specific weight (78.5 kN/m^3) and Young's modulus (205 GPa). Before MU, a consistent gap exists between model simulated dynamic response and experimental modal parameters, preventing any accurate cable forces estimation. A SA was performed in order to catch the relative influences of the modeling parameters affecting the modal properties and the OF (1). An error function g_1 was set as the first part of (1), accounting for the 18 force values discrepancy between the estimated T_i^m and the numerical T_i^c values:

$$g_1 = \sum_{i=1}^{n_c} \left(\frac{T_i^m - T_i^c}{T_i^m} \right)^2 \tag{3}$$

From mechanical considerations, the authors identified that the most reasonable influencing parameters of cable forces and their domain space may be: the stiffness of the tower $E_{c,t} \in [30, 50]$ GPa, the abutments supports' stiffness $k_a \in [10, 500]$ kN/mm, the steel mass $\rho_s \in [75, 80]$ kN/m^3 and concrete mass $\rho_c \in [24, 30]$ kN/m^3 of the deck, and its stiffness $E_{c,d} \in [30, 50]$ GPa. The cables' geometry and material properties are accurately known, thus they were

Table 2. Sensitivity indicators S_1 for the error function Eq. (2) and for the cable forces.

	S_1 on (2) [%]	Mestre Side cables S_1 [%]									Venice side cables S_1 [%]								
		1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
$E_{c,t}$	5.14	**87.13**	**38.14**	9.06	1.32	0.01	0.27	0.97	2.10	4.22	**82.85**	**30.49**	6.76	1.18	0.12	0.00	0.08	0.21	0.44
ρ_s	0.34	0.08	0.25	0.27	0.23	0.17	0.12	0.07	0.05	0.03	0.18	0.39	0.41	0.36	0.29	0.20	0.12	0.05	0.01
ρ_c	4.13	12.57	61.29	**86.05**	**78.93**	**55.23**	31.74	16.75	9.23	6.82	17.14	68.93	**93.46**	**94.99**	**78.15**	48.68	22.88	8.28	2.06
$E_{c,d}$	1.21	0.51	1.37	1.35	1.12	0.79	0.47	0.24	0.11	0.07	0.22	0.95	1.32	1.44	1.28	0.91	0.48	0.15	0.02
k_a	93.14	0.48	0.69	4.79	19.18	43.59	**66.41**	**80.52**	**86.86**	**87.17**	0.19	0.83	0.01	3.79	21.13	**50.04**	**75.34**	**89.66**	**95.70**

Table 3. Sensitivity indicators S_1 for $f(\boldsymbol{x})$, $f_1(\boldsymbol{x})$ and $f_2(\boldsymbol{x})$, and for the frequency of each modes (see Fig. 2).

	S_1 on $f(\boldsymbol{x})$ [%]	S_1 on $f_1(\boldsymbol{x})$ [%]	S_1 on $f_2(\boldsymbol{x})$ [%]	S_1 on each frequency mode [%] (see Fig. 2)										
				1	2	3	4	5	6	7	8	9	10	11
$E_{c,t}$	0.30	0.60	0.40	3.20	**94.40**	17.00	3.80	0.10	0.00	0.00	1.40	0.00	1.90	0.00
ρ_s	0.50	0.90	0.70	0.30	0.00	5.30	17.80	0.70	1.20	0.50	3.90	5.30	4.30	2.00
ρ_c	3.70	61.40	1.30	**42.20**	4.40	**75.40**	**52.90**	**48.90**	**65.40**	**49.30**	**65.80**	**60.20**	**54.80**	**52.00**
$E_{c,d}$	0.00	0.10	0.00	0.10	0.00	0.60	0.70	0.10	0.10	0.10	0.10	0.60	0.00	0.80
k_a	**94.60**	41.60	**97.20**	**54.60**	4.40	**23.30**	**39.20**	**53.20**	**33.80**	**51.00**	**34.10**	**52.30**	**48.30**	**51.90**

excluded from the SA assessment. The SA permitted to decompose of the model output variance into fractions related to each analyzed mechanical parameter [18]. Saltelli's sampling scheme has been adopted [20] to define the total number of simulations required. The variance-based SA provides the first-order (not accounting for input variables' interactions) Sobol sensitivity indicators S_1 [18], which have been reported in Table 2 and also depicted in Fig. 3. These outcomes proved that k_a mainly affects the cable forces estimated by (2), thus being the most influential parameter in the subsequent FE-MU. $E_{c,t}$ and ρ_c also fairly affects the cable forces by (2). From the cable forces point of view, three main trends may be evidenced from the SA results. k_a affects at the most the extreme cables (6–9), whereas $E_{c,t}$ plays a significant role for cables closer to the tower (1–2). The intermediate cables (3–5) appeared to be mainly affected by ρ_c. In summary, the SA results reported in Table 2 and also depicted in Fig. 3 aided to define the optimal set of parameters to be considered in the FE-MU procedure. Specifically, it is also possible to redefine the parameter space domain as follows: $E_{c,t} > 30\text{MPa}$, $\rho_c < 25\,\text{kN/m}^3$, and $k_a < 100\,\text{MN/mm}$.

On the other hand, the SA has been also conducted considering the modal parameters influence according to the second term of (1), since numerical modal parameters (ω^c, ϕ^c) are functions of modeling parameters $\boldsymbol{x}$. The second term of (1) can be synthetically rewritten as $f(\boldsymbol{x}) = f_1(\boldsymbol{x}) + f_2(\boldsymbol{x})$. $f_1(\boldsymbol{x})$ denotes the part depending on the angular frequencies of (1), whereas the $f_2(\boldsymbol{x})$ the MAC-related part. The Sobol sensitivity indicators have been reported in Tables 3 and 4.

Inspecting Table 4, ρ_c generally appears as the most influential parameter in terms of natural frequency, immediately followed by k_a. Conversely, inspecting 3, k_a appears to be the most influential with respect to mode shapes. As expected both mass and stiffness parameters play a crucial role in the dynamic part of the FE-MU problem (1). Focusing on mode 2, it is the only case where the sensitivity indicators showed a strong influence of $E_{c,t}$ in terms of frequencies. With deeper insights, modes 2–4 in Table 4 report comparable values of $E_{c,t}$, ρ_c, and k_a, and

Table 4. Sensitivity indicators S_1 for for the MAC of each modes (see Fig. 2).

	S_1 on MAC of each mode [%] (see Fig. 2)										
	1	2	3	4	5	6	7	8	9	10	11
$E_{c,t}$	2.80	**49.60**	41.50	24.30	1.40	1.60	0.00	1.60	0.00	0.60	0.00
ρ_s	2.60	0.20	16.30	**58.30**	3.80	**48.80**	0.00	0.60	0.90	0.60	0.60
ρ_c	2.20	**25.40**	**57.70**	**41.60**	**11.60**	**24.20**	0.40	4.80	1.60	0.70	1.70
$E_{c,d}$	0.00	0.00	0.20	0.40	0.00	0.10	0.00	0.20	0.00	0.00	0.00
k_a	**95.70**	**74.10**	**30.20**	**36.30**	**97.90**	**87.20**	**99.60**	**98.50**	**99.40**	**98.40**	**96.90**

in modes 4 and 6 also ρ_s is quite influential. In conclusion, on average, the SA provided a ranking from the most to the less influential selected parameters: k_a, ρ_c, $E_{c,t}$, $E_{c,d}$, ρ_s.

5 Finite Element Model Updating

It is worth mentioning that the preliminary model already approaches the agreement with experimental modal information, thus any MU only driven by modal parameters may produce an identity of the updated parameters. On the contrary, considering both mass and stiffness parameters would be an indeterminate problem. Moreover, the possible discontinuities in the natural frequency or mode shape parameters' subspaces, may prevent an effective meta-heuristic optimization process. Therefore, the FE-MU driven by both cable forces and modal characteristics would be beneficial. Specifically, due to the uncorrelation of the above-selected parameters with respect to the cable forces (see Tables 2, 3 and 4), a lower number of parameters may be considered for FE-MU such as:

1. Assuming an $E_{c,t}$, the optimization refers only to ρ_c and k_a for cables from 3 to 9, using the OF in (2).
2. Assuming ρ_c and k_a from the previous step, the optimization is limited to $E_{c,t}$ for cables 1–2 and mode shape 2, using the OF in (1) limited to the just mentioned conditions.
3. Assuming ρ_c, k_a, and $E_{c,d}$ from the previous steps, a final optimization involving deck's $E_{c,d}$, using the general OF statement of (1).

The authors adopted metaheuristic global optimization algorithms, i.e. the particle swarm optimization (PSO) [14] and the differential evolution (DE) [25] by their Python implementations, leveraging the SAP2000-OAPI. No significant discrepancies were obtained between the two algorithms, thus the authors reported only PSO results. The three optimizations led to the final values of the OFs 0.4306, 0.0347, and 1.0296, and the final optimal results are reported in Table 5.

The optimum values are still consistent with the engineering judgment, except for the tower stiffness which appears slightly overstated than usual values. However, it is worth noting that beyond its physical meaning, Young's

Table 5. Cable forces and modal parameters associated with the optimum set of parameters and percentage error before and after the updating. In the bottom right part of the table, the optimum parameters are listed with the upper (U.B) and lower (L.B.) bounds. In the cable notation, M indicates the Mestre side, whereas V the Venice side.

Cable Label	Exp. [kN]	Num. [kN]	Error	Initial error	Mode Label	Exp. [Hz]	Num. [Hz]	MAC	Freq. error	Initial MAC	Initial freq. error
M1	458	408	11%	52%	V1	0.635	0.699	97.10%	-10.1%	97.41%	-6.5%
M2	757	1228	-62%	-77%	V2	0.996	0.975	93.79%	2.1%	93.06%	2.1%
M3	2359	2372	-1%	-2%	V3	1.143	1.226	82.41%	-7.3%	85.58%	-7.3%
M4	3715	3852	-4%	5%	T1	1.387	1.395	95.03%	-0.6%	95.26%	-0.5%
M5	3842	4271	-11%	12%	M1	1.523	1.650	78.13%	-8.3%	80.01%	-8.1%
M6	4199	4453	-6%	29%	T2	1.602	1.513	75.38%	5.5%	75.56%	5.7%
M7	4828	4540	6%	48%	V4	1.963	2.073	97.04%	-5.6%	96.91%	-5.5%
M8	5289	5041	5%	56%	T3	2.646	2.559	94.04%	3.3%	94.19%	3.3%
M9	4771	4618	3%	58%	T5	4.072	3.995	89.03%	1.9%	89.10%	1.9%
V1	614	530	14%	43%	T6	4.951	4.826	93.29%	2.5%	91.61%	2.2%
V2	860	1279	-49%	-86%	T7	5.625	5.539	94.48%	1.5%	94.48%	1.5%
V3	2381	2460	-3%	-19%							
V4	3704	3872	-5%	-10%							
V5	3961	4284	-8%	0%							
V6	4352	4563	-5%	18%							
V7	4698	4573	3%	40%							
V8	5310	5229	2%	57%							
V9	4655	4791	-3%	76%							

Optimized parameters

Param.	Unit	L.B.	U.B.	**Optimum**
ρ_c	kN/m^3	23	30	**24**
k_a	kN/mm	100	10000	**1350**
$E_{c,d}$	GPa	30	1	**40**
$E_{c,t}$	GPa	30	70	**51.1**

modulus acts as a modeling parameter in FE-MU procedures, governing global dynamic properties, and thus it is affected by a high level of uncertainties [22]. These uncertainties may be mainly related to modeling errors, due to complex structure simplifications or even meshes discretization, or to modeling parameters intrinsic errors due to material and geometric properties uncertainties. As demonstrated in [13], the herein obtained results are still reasonable. Furthermore, the FE-MU results are consistent with the ones discussed in [3]. It is worth noting that the analyses also revealed that the agreement between modal parameters does not improve significantly, since the average percentage error remains almost equal before and after the updating. Conversely, the cable forces exhibited a noteworthy consistent improvement.

6 Conclusions

In this study, a finite element model updating procedure is discussed, especially contextualized on the Marghera curved cable-stayed bridge case study. The authors adopted a model updating procedure involving both cable forces estimates and modal parameters in order to overcome the indeterminate MU modal-based standard problem when dealing with stiffness and mass parameters simultaneously. This optimization problem is usually challenging, especially concerning large-scale structures with numerous degrees of freedom. Therefore, the authors carried out a preliminary variance-based sensitivity analysis to evidence and select the most influencing parameters for the subsequent model updating process. Specifically, five parameters were selected: the concrete mass (ρ_c), Young's modulus of the concrete deck ($E_{c,d}$), Young's modulus of the concrete tower ($E_{c,t}$), and the bearing stiffness (k_a). The sensitivity indicators were obtained for both the objective function related to the cable forces and to the one related to the experimental-numerical discrepancy of natural frequencies and mode shapes. This analysis revealed that the tower's stiffness played a crucial role in the cables closer to the tower. Conversely, the extreme cables appeared influenced the most by the abutments bearing stiffness. For the intermediate cables, a major influence of the concrete mass parameter. Regarding the modal features, the strongest influence was provided by the bearing stiffness and the concrete mass parameter, except for mode 2 in which also the stiffness of the tower presented a significant sensitivity indicator. Therefore, the authors accomplished an almost complete finite element multi-objective model updating procedure with a simplified step-wise procedure, i.e. by solving in sequence simplified single-objective sub-problems. The global optimization was conducted with the meta-heuristic particle-swarm (PSO) and differential evolution (DE) algorithms. This study also revealed that meta-heuristic optimization algorithms can be challenging to use in finite element model updating of cable-stayed bridges, especially when many parameters must be contradictorily optimized simultaneously. However, the sensitivity analysis represents a critical step to correctly identify the most relevant parameters which deserve to be considered in the finite element model updating procedure of complex large-scale structures.

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