

Experimental and Numerical Characterization of the Dynamic Behaviour of a Historic Suspension Footbridge



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Abstract This paper investigates the dynamic characteristics and behavior of a historic suspension footbridge through experimental and numerical studies. Ambient vibration tests were performed on the footbridge to extract the modal parameters of the structure such as natural frequencies, damping ratios, and mode shapes. The modal properties were identified from ambient vibration tests adopting the Stochastic Subspace Identification (SSI) technique. The availability of a numerical model reproducing accurately the dynamic characteristics of the footbridge is essential to carry out numerical studies on the footbridge under different dynamic loading scenarios. Due to the lack of the original technical drawings of the footbridge, a geometrical survey was carried out in order to determine the geometric characteristics of the structural elements. Furthermore, the deformed configuration of the main cable under dead load was experimentally measured during the field survey. The results of field vibration tests were used to calibrate and validate the numerical model of the footbridge, e.g., boundary conditions, and initial cable tension. The present study reports the results of the geometrical survey, of the operational modal analysis, and of the numerical modeling of the footbridge. Moreover, the 3-D Finite Element Model of the footbridge and its calibration with respect to ambient vibration tests are reported. After calibration of the finite element model, a good agreement was observed between computed and measured natural frequencies and mode shapes.

Keywords Ambient vibration tests · Finite element modeling · Modal identification · Suspension footbridges · Geometrical nonlinearity

1 Introduction

Suspension bridges have been widely utilized from ancient times until now due to their advantages to build long, light, and slender bridges. There are many suspension bridges in the world built in the 19th Century that are still in use (see, e.g. [1–4]).

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Fig. 1 Different views of the footbridge

These bridges as historical structures have usually uncertain conditions regarding their current structural properties and serviceability for the loading scenarios. This is due to the fact that these bridges were designed based on loads and methods that might be different from the current service loads and approaches that are used to design new suspension footbridges. For instance, the Ramello footbridge (Fig. 1) that was completed in 1954 and located in the countryside of La Spezia in Italy, has been still employed for crossing pedestrian and light vehicular traffic until 2019. To continue using this historic footbridge, it is essential to investigate its current structural properties to ensure current serviceability condition of the footbridge against dynamic loadings. The dynamic characteristics of the footbridge such as natural frequencies, mode shapes, and damping ratios can be estimated experimentally by using modal identification techniques [3]. These dynamic properties serve as a basis to build a reliable Finite Element Model (FEM) of the footbridge for further analytical studies such as vibration serviceability assessment of the footbridge under human and wind loadings [5]. Ambient vibration testing is a very common technique to identify modal parameters, particularly for historic structures since it does not require excitation equipment. However, in the case of ambient vibration testing, only the response of the structure is measured and the loading condition is unknown [4]. Therefore, a modal parameter identification technique such as Peak Picking (PP), Frequency Domain Decomposition (FDD), Stochastic Subspace Identification (SSI), should be used to perform an operational modal analysis on the output measurement data to extract modal parameters of the structure [6]. The present paper aims to describe the dynamic characterization of the Ramello footbridge in several tasks. Firstly, field surveys that have been conducted on the footbridge to estimate geometric properties of the footbridge are described. Secondly, the details of four ambient vibration tests

with different measurement setups performed on the footbridge are reported. Then, the identified modal parameters of the footbridge from operational modal analysis using the SSI technique are presented. Finally, a 3D FE model for the footbridge is developed and the numerically-obtained dynamic properties are compared with those derived from operational modal analysis.

2 Description of Footbridge

The Ramello suspension footbridge, shown in Fig. 1, that was built in 1954, is located in the countryside of La Spezia in Italy and crosses over the Vara River. As the design information concerning the geometry and material properties of structural elements was not available, some field inspections were performed on the footbridge to obtain the geometrical properties of the structure using station theodolite and vernier caliper. According to conducted field surveys, the geometric properties of the footbridge and its elements can be described as shown in Fig. 2. The suspension footbridge has a single span with a length of 90 m and a width of 2.28 m. The footbridge comprises two main suspended cables which connect two reinforced concrete pylons from one side of the river to the opposite side. The pylons have a height of 8.2 m with respect to the bridge deck that provide a cable sag of 7.05 m at the middle of the footbridge span. The ends of main cables are anchored into the ground at distances of 7.9 m and 7.2 m from the left and right pylons, respectively, as shown in Fig. 2. Each main cable is composed of three individual spiral strands with a nominal diameter of 4 cm and 61 galvanized steel wires per strand in each cable plane. There are 89 hangers made of rolled steel with a C-shaped cross-section to connect the main cables to the steel floor beams with a step of one meter. The bridge deck as shown in Fig. 3, includes a grid of steel floor beams and stringers, and timber planks. The transverse and longitudinal timber planks which have a square cross-section with dimensions around 80 mm, are used to provide more connection surfaces with steel floor beams to convey pedestrian loads as well as providing a walking surface for the pedestrians. The bridge deck consists of two rolled steel stringers with I-shaped cross-sections that have a center-to-center distance of 1.78 m from each other. In addition, 89 rolled steel floor beams with an I-shaped cross-section with lengths of 2.4 m are used in the bridge deck to transmit the loads from the deck to the hangers. Concerning the connection between stringers and floor beams, a welded connection is used to link the bottom flanges of stringers to the top flanges of floor beams. The ends of floor beams are directly joined to the bottom ends of hangers by using bolted connections;

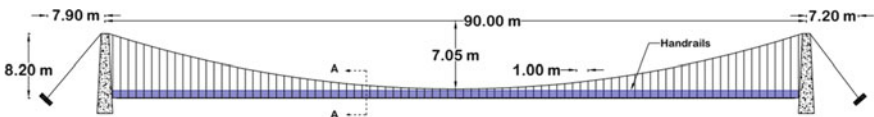


Fig. 2 Elevation of the footbridge

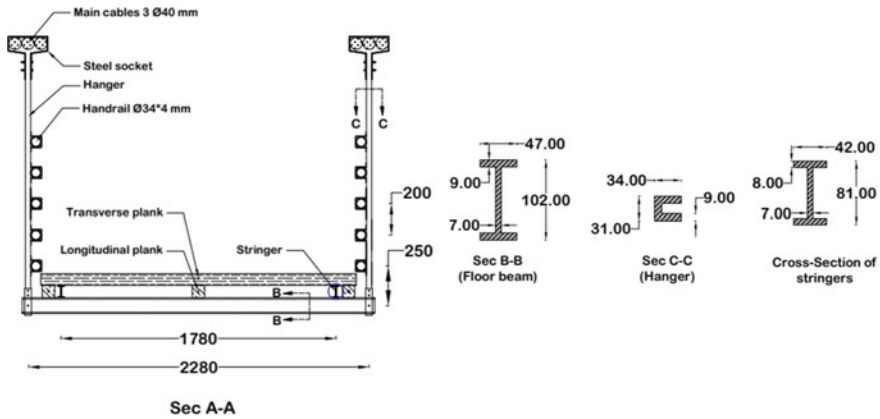


Fig. 3 Cross section and dimensions of the footbridge structural elements (in mm)

while the other ends of hangers are connected to the main cables by using bolted connections and steel sockets which keep the cables in contact with each other and avoid any relative displacements of cables. Handrails of the footbridge are made of circular hollow steel sections and connected to the hangers with joints that are able to restrain the relative translational movement between the handrails and the hangers in the vertical direction. More details regarding the dimensions of the footbridge elements which were obtained through the field survey are shown in Figs. 2 and 3. It should be noted that the tension force of main cables was not measured during the field tests and it is considered as an unknown parameter in the present study that will be estimated in the next sections using Finite Element (FE) modeling of the footbridge.

3 Ambient Vibration Testing

Field dynamic testing of structures such as ambient vibration tests can provide accurate and reliable data regarding current dynamic characteristics of structures. As shown in Fig. 4, four ambient vibration tests with different measurement setup arrangements were carried out on the footbridge to identify its dynamic characteristics. The first measurement setup arrangement for ambient vibration test was implemented for the footbridge in January 2019; while the other measurement setups were carried out in January 2021 to identify more in detail the mode shapes of the footbridge. Since the footbridge is a symmetric structure and also the first two ambient test setups have shown symmetric dynamic behaviour of the structure, the accelerometers in the third and fourth ambient tests were mounted only on one-half the footbridge deck to extract more precisely the vertical mode shapes of the bridge

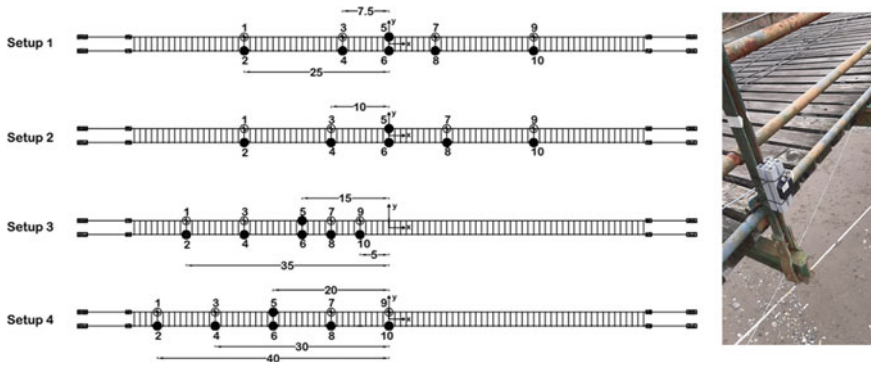


Fig. 4 Layout and location of accelerometers along the bridge deck for different measurement setups

deck. Ambient vibration tests were performed on the footbridge deck using a 14-channel data acquisition system with 10 low-cost MEMS triaxial accelerometers that are able to measure accelerations in $\pm 6g$ range with a sensitivity of $333mV/g$ and a nominal 0–200 Hz bandwidth. The dynamic response of the footbridge was measured at 10 different locations in each measurement setup including measurement of only vertical acceleration of all the locations and transverse accelerations of four locations (locations 1, 3, 7, and 9). In each measurement setup, the ambient vibrations were simultaneously recorded for one hour. Furthermore, the acceleration response was recorded with a sampling frequency of 500 Hz. As shown in Fig. 4, all the accelerometers were mounted on the hangers, close to the joint between floor beams and hangers.

4 Modal Identification of the Footbridge

The modal identification was carried out on the obtained raw data from ambient vibration tests using the Stochastic Subspace Identification (SSI) technique [7]. The data processing and modal identification were performed by using MACEC that is a MATLAB-based toolbox [8]. The order N of a structure’s model is usually selected in a wide range to construct a reliable stabilization diagram that allows recognizing the real structural modes (from noise modes) whose properties do not vary considerably for different model’s order. In the present study, stochastic state-space models are identified for different orders of the footbridge’s model, ranging from 2 to 200 for the data set of the first setup and 2 to 100 for the data set of the other setups, with an increment of 2. Figure 5 plots the extracted stabilization diagrams by applying the SSI technique to the obtained dataset from each measurement setup to identify stable modes. Furthermore, the power spectral density functions of the measured

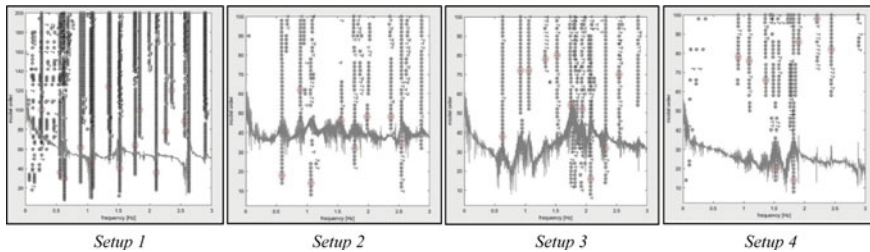


Fig. 5 Stabilization diagrams produced by using SSI method for 1–4 test setups

accelerations are superimposed on the stabilization diagrams, confirming that the identified poles correspond to peaks in the acceleration spectra.

Table 1 and Fig. 6 report, respectively, the natural frequencies and damping ratios and mode shapes of 11 natural vibration modes, that were identified by combining and averaging the obtained results from the implemented modal identification technique for different setups. The natural frequencies of identified mode shapes in the frequency range of 0.25–2.6 Hz are reported, that are of interest for possible vibration serviceability assessment of the footbridge in the vertical direction under walking load. Indeed different researches [9] have shown that the normal walking frequency of pedestrians is in the range of 1.6–2.4 Hz. The detected natural mode shapes of the footbridge include one Lateral mode (L), two Torsional modes (T), and eight Bending (B) modes that have Symmetric (S) or Asymmetric (A) shapes. According to Table 1, it can be seen that the identified frequencies greater than 1 Hz are quite stable and reliable since these frequencies were found in most of the vibration measurements. On the contrary, some modes were not consistently identified from all the measurement setups: this circumstance can be due to the fact that these modes were not significantly excited in some ambient tests. For instance, the first two modes were identified only from test setup 1 that was carried out on a different day with respect to setups 2–4. In addition, most identified modal parameters are related to bending modes in the vertical plane, showing that the lateral and torsional modes were not considerably excited in ambient vibration tests.

5 Finite Element Modeling of the Footbridge

In the present study, a 3D finite element model of the footbridge has been developed using ANSYS software [10] to conduct the numerical modal analysis of the footbridge. The model was built based on the geometry and structural properties measured from the field surveys and then updated according to obtained results from ambient vibration tests. Within the ANSYS code, the cables were modelled using the 3D spar element “LINK180” that is a uniaxial tension–compression element with three degrees of freedom at each node. According to technical data [11], the effective steel area, density, modulus of elasticity and Poisson’s ratio of each spiral strand was

Table 1 Identified modal parameters using SSI-DATA

Mode	Mode shape	Setup/test	Frequency (Hz)	Damping ratio (%)	Mode	Mode shape	Setup/test	Frequency (Hz)	Damping ratio (%)
1	L-S	1	0.259	2.051	7	B-S	1,2,3,4	1.531	1.730
2	B-A	1	0.560	2.462	8	B-A	1,2,3,4	1.803	1.946
3	B-S	1,2,3	0.612	3.040	9	B-S	1,2,3,4	1.980	1.050
4	T-A	3	0.922	3.600	10	B-A	1,2,3,4	2.310	0.766
5	T-S	1,2,3	1.062	2.500	11	B-S	1,2,3,4	2.520	0.177
6	B-A	1,3,4	1.344	2.160					

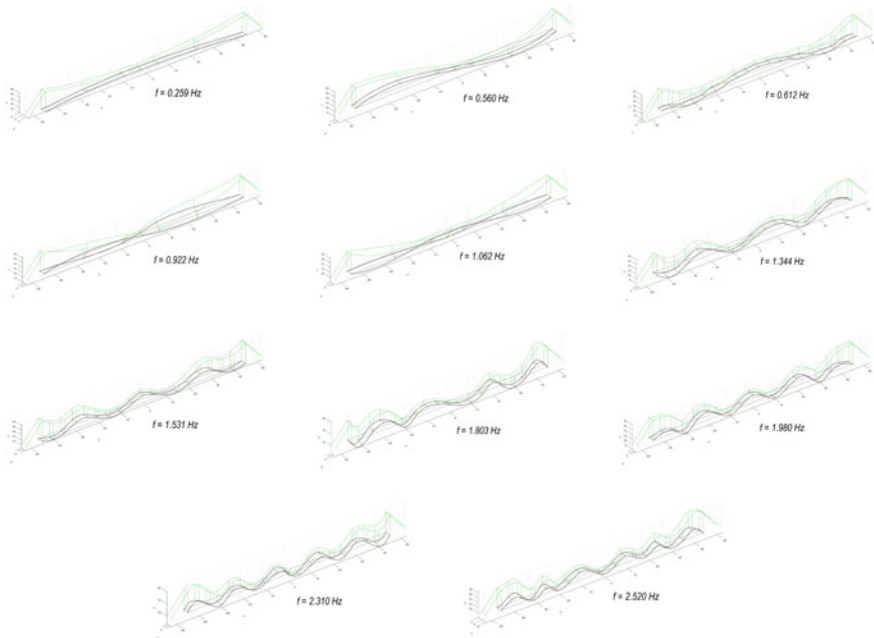


Fig. 6. 3D representation of identified mode shapes using SSI technique

taken as 940mm^2 , 8300kg/m^3 , 135GPa and 0.3 , respectively. Furthermore, the floor beams, stringers, and hangers were modelled using the 3D elastic beam element “BEAM 4” with six degrees of freedom per node that can be subjected to tension, compression, torsion, and bending. The modulus of elasticity and density for these structural elements were assumed as 210GPa and 7850kg/m^3 , respectively. The timber boards and handrails were assumed as nonstructural elements with considering their weights in the dead loads and their effects on the dynamic properties as lumped masses applied on the steel grid and hangers, modelled with the concentrated mass element “MASS 21”. The values of density for timber boards and handrails were taken as 700kg/m^3 and 7850kg/m^3 , respectively. Modeling of pylons was ignored with assuming high stiffness at the pylon saddles and the pylons were considered as a boundary condition for the cables; therefore, the cables were allowed to have only longitudinal sliding over the pylons. The anchor blocks have not been modelled and it was assumed that the ends of cables were restrained to the ground by pinned supports. According to Fig. 7, in the finite element modeling, it was assumed that the main cables were hinged to the hangers and floor beams. The bottom flanges of stringers were connected to the top flanges of floor beams with fixed joints and also the ends of stringers were fixed to the ground. A nonlinear static analysis (considering P-delta effect along with large deformation effect) was performed to estimate initial tension of main cables which has a significant effect on initial configuration and total stiffness of the footbridge [1, 12]. According to the finite element model, the



Fig. 7 Representation of boundary conditions of structural elements

initial tension in the main cables was obtained about 189 KN based on trial-and-error procedure to reach a convergence of the possible minimum vertical deflection for different points of the bridge deck. Following the completion of footbridge modeling in ANSYS, including geometry, materials, elements, cross sections, boundary conditions and applied loadings, modal analyses was performed on the footbridge model to extract dynamic properties of the structure. It should be mentioned that the modal analysis was conducted after the nonlinear static analysis of the footbridge, subjected to the dead loads and pretension of the cables, in order to determine the geometric tangent stiffness matrix which is used in the modal analysis. The general view of FE model of the footbridge is shown in the Fig. 8 and the natural frequencies of the first twenty modes obtained from FE modeling are summarized in Table 2.

Fig. 8 General view of finite element model of the footbridge

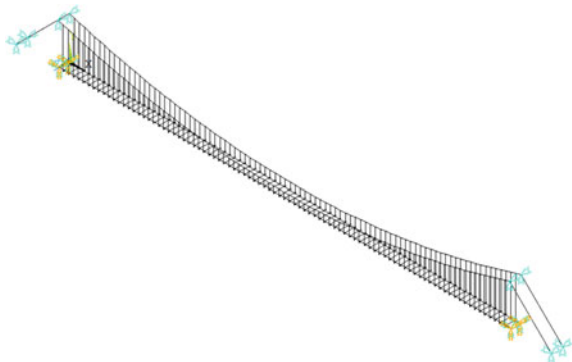


Table 2 Dynamic properties of the footbridge obtained through FE modeling

Mode	Mode shape	Frequency (Hz)	Mode	Mode shape	Frequency (Hz)	Mode	Mode shape	Frequency (Hz)
1	L-S	0.242	8	T-A	0.885	15	L-S	1.576
2	L-A	0.403	9	L-S	0.905	16	L-A	1.743
3	B-A	0.497	10	B-S	1.077	17	B-A	1.815
4	L-S	0.573	11	L-A	1.121	18	B-S	2.101
5	B-S	0.619	12	L-S	1.252	19	B-A	2.317
6	L-A	0.733	13	B-A	1.338	20	B-S	2.594
7	B-A	0.881	14	B-S	1.530			

The validation of the finite element model can be performed by comparing the natural frequencies and corresponding mode shapes obtained numerically and experimentally. In the present study, the bending vibration modes which were identified consistently from all ambient tests and also are important in terms of vibration serviceability assessment of the footbridge under human-induced excitation, are shown in Fig. 9 and compared with their equivalent mode shapes extracted from the ambient vibration tests in Table 3. The Modal Assurance Criterion (MAC) parameter is used to investigate the correlation of these calculated and identified mode shapes which is defined as [13]:

$$MAC(\phi_{F,i}, \phi_{N,j}) = \frac{(\phi_{F,i}^T \phi_{N,j})^2}{(\phi_{F,i}^T \phi_{F,i})(\phi_{N,j}^T \phi_{N,j})} \tag{1}$$

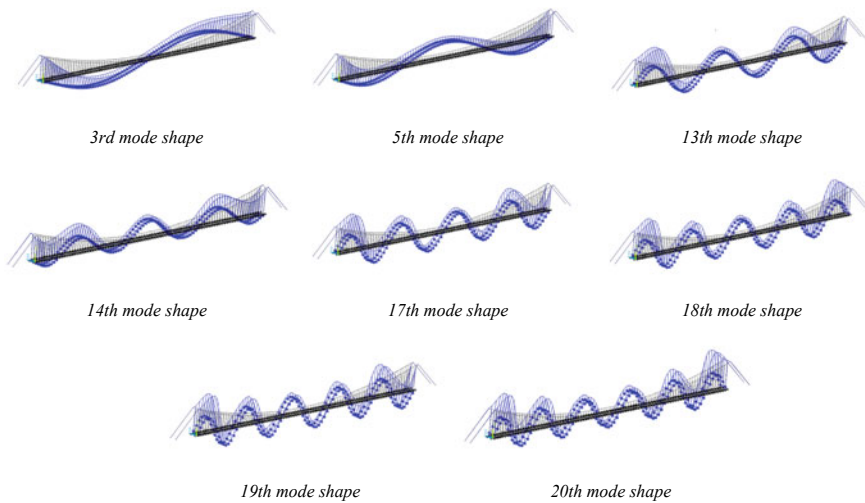


Fig. 9 Bending mode shapes obtained through FE modeling

Table 3 Comparison of numerical and experimental modal parameters for eight bending vibration modes

FE results		Experimental results		MAC values
Mode	Frequency (Hz)	Mode	Frequency (Hz)	
3	0.497	2	0.560	0.984
5	0.619	3	0.612	0.995
13	1.338	6	1.344	0.986
14	1.530	7	1.531	0.989
17	1.815	8	1.803	0.986
18	2.101	9	1.980	0.952
19	2.317	10	2.310	0.992
20	2.594	11	2.520	0.736

where $\phi_{F,i}$ is a vector which represents the i th mode shape extracted from field vibration tests, $\phi_{N,j}$ is a vector that represents the j th mode shape obtained numerically, and T stands for transpose. The MAC value equal to 1 shows a perfect correlation between the numerical and experimental vibration mode shapes; while the MAC value equal to 0 indicates that the mode shapes are completely uncorrelated. Generally, the MAC value greater than 0.8 shows a very good match between two mode shapes. According to Table 3, the MAC values for seven modes are very close to one which shows a very good match between numerical and experimental results; while the MAC value 0.736 for the 20th mode shape of numerical results, indicates that this mode does not completely match with its counterpart mode shape identified through ambient vibration tests. However, the obtained mode shapes and frequencies from FE modeling generally show a good agreement with the obtained results from conducted ambient tests on the footbridge.

6 Conclusion

In this paper, an experimental and numerical study on a historic suspension footbridge located in Italy was presented. A FE model was provided based on geometric field surveys and ambient vibration tests. Four ambient vibrations testing with different measurement setup arrangements were used to accurately identify modal parameters of the footbridge. Within the frequency range 0–2.6 Hz, eleven vibration modes including one lateral, two torsional, and eight bending mode shapes, were identified from different ambient tests using the SSI technique. However, some modes (specifically lateral and torsional modes) were not consistently detected from all ambient vibration tests, indicating that those modes were not significantly excited during ambient vibration testing. Results obtained from ambient tests were used to build a reliable FE model to reflect the dynamic behaviour of the footbridge with reasonable accuracy. The tension force of main cables was estimated numerically based on the

initial equilibrium configuration of the footbridge under dead loads obtained through the field surveys. This parameter has a significant effect on the dynamic characteristics of the footbridge during building and calibrating the FE model. Generally, a good agreement of natural frequencies and of mode shapes was found between the FE modeling and ambient vibration testing. The validated FE model of this historic footbridge can be used as a baseline model to investigate the structural performance and vibration serviceability assessment of the footbridge under different loading scenarios such as crossing pedestrians and wind loading.

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