SMAR 2019 – Fifth Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures

SMAR 2019

Structural health monitoring of “Artemio Franchi” Stadium in Florence, Italy: measurement using interferometric radar

Lapo MICCINESI [1], Massimiliano PIERACCINI [1], Gloria TERENZI [2], Iacopo COSTOLI [3], Paolo SPINELLI [2], Giulia MAZZIERI [2]

[1] Department of Information Engineering, University of Florence, Florence, Italy

[2] Department of Civil and Environmental Engineering, University of Florence, Florence, Italy

[3] Polytechnic Department of Engineering and Architecture, University of Udine, Udine, Italy

Contact e-mail: lapo.miccinesi@unifi.it

ABSTRACT: The “Artemio Franchi” Stadium in Florence, Italy, designed by Pier Luigi Nervi in 1929, was built from 1930 to 1932. The stadium has a reinforced concrete structure and it is composed by 24 stands, a 50-meter tower (“Maratona” tower) and a cantilever roof. In occasion of the World Cup in 1990 the stadium was renovated by adding seats at the ground level as retrofit. A study for seismic requalification is in progress and an interferometric radar was used for monitoring the architectural complex. In particular, the radar monitored the “Maratona” tower and some stands. In this paper, the preliminary results of this measurement campaign are reported. The wind action was exploited to test the “Maratona” tower and the measurement was performed both with an interferometric radar and a seismic accelerometer. Natural frequencies measured with both instruments substantially match.

The stands are too rigid to be appreciably excited by wind or vehicular traffic, hence the measurements were performed during football matches. The supporters’ movements were used as input action to measure the dynamic properties of stands. Unfortunately, this input was not enough high to allow the measurement of the natural frequencies of all the stands.

The experimental results have been then utilized to tune a finite element computational model for the simulation of the dynamic response of the tower and stands.

1 INTRODUCTION

The seismic protection and preservation of historic buildings is a priority in Italy (Sorace and Terenzi 2013, Sorace et al. 2016, Sorace and Terenzi 2016). After the most recent seismic events that hit the central Regions of Italy, many surveys have been carried out in order to identify the vulnerability of existing buildings and define retrofitting restoring, especially for those have a social role (Terenzi and Rossi 2018).

The investigation of "A. Franchi" Stadium in Florence should be included in this context. The stadium is a reinforced concrete (R/C) structure designed in the past century by the world-famous Italian engineer Pier Luigi Nervi. Built from 1930 to 1932, it was designed only by considering gravity loads, whereas most recent Italian Standards (Italian Council of Public Works, 2018) require a verification of the structural response to each type of the most significant dynamic actions (wind, supporters’ movements, seismic actions).

With reference to this structure, the vulnerability analysis was carried out in the following steps: 1) collection of the original design documentation in order to define its geometrical and structural characteristics;2) on-site experimental tests aimed at identifying mechanical properties of materials;3) definition of a computational model on the basis of the experimental results obtained in the previous phase;4) evaluation of the dynamic response of the structure and definition of interventions in order to improve its performances against most severe dynamic actions.

In the paper, a summary of the results concerning the first two steps is presented. The experimental campaign was performed using an interferometric radar (Pieraccini 2013), capable to detect the movements of the structure subjected to external actions, such as wind and crowd, and using a seismic accelerometer (Pieraccini et al 2007). The other steps of the assessment analysis on the structure will be the object of next communications by the Authors.

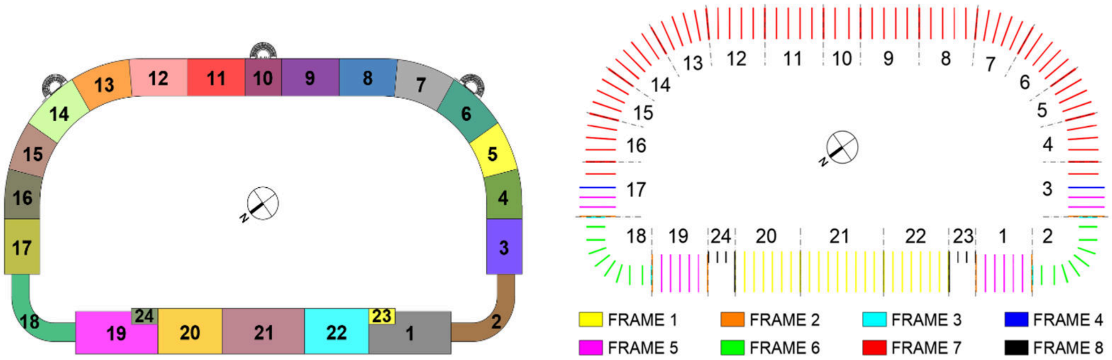
2 DESCRIPTION OF THE STRUCTURE

2.1 General characteristics of the Stadium

The Municipal Stadium of Florence, initially named "Giovanni Berta", is considered one of the most important projects of Pier Luigi Nervi built in the early days of R/C design. On December 4, 1930 excavations began for the construction of foundations and work ended with the last load tests, performed from 3 to 7 January 1933.

The R/C structure has a D shape consists of 24 blocks (Figure 1) separated by joints not more than 5 mm wide. The stadium consist in four main zones:1) the uncovered “Maratona” grandstand (blocks 8th to 12th); 2) “Fiesole” curve (blocks 14th to 17th); 3) Central covered grandstand (blocks 20th to 22th); 4) “train-rail” curve (blocks 3rd to 6th). Each block is composed by framed structures as shown in Fig. 2c (corresponding to the block 10th at the base of the Maratona tower). This kind of frame (“Frame 7” in Fig. 1b) is the most used among the eight typologies characterizing the stadium, being common to all blocks from 3th to 17th. Its upper profile has the shape of steps, the body of which extends on a single ring.

The experimental tests concerned all four zones of the Stadium but, for sake of brevity, in the following section the results of the preliminary experimental campaign of Maratona Tower and block 14th will be presented.



a. b.

Figure 1. Schematic representation of blocks and frames constituting the Stadium.

2.2 The Maratona tower and the blocks 10th and 14th

The Maratona tower is a 39.43 m height reinforced concrete structure, placed at the level of 14.25 m on the top of block 10th included in the uncovered grandstand zone of the stadium. As shown in Fig. 3, it reaches 53.68 m height. Its transversal section is composed by a perimeter rectangular R/C structure and a semi-elliptical glass surface. The external sizes of the R/C part are of $3.15 \times 2.15\ m \times m$ at the base and $2.75 \times 1.35\ m \times m$ at the top of the tower. Indeed, the tower's thickness starts from $500\ mm$ at the base, and it reduces to $300\ mm$ at the level of $28.15\ m$, and finally to $100\ mm$ from $41.18\ m$ till the top. The internal section has a constant size of $1.65 \times 1.15\ m \times m$. The semi-elliptical glass surface has a framed steel structure and internally hosts an elevator.

Block 10th, at the base of the tower, is composed by four seven-type frames as that detailed in Fig. 4a for block 14th, adjacent to which there are other four couple of columns with section of $700 \times 700\ mm \times mm$. As evidenced by the black rectangles in Figures 2b and 2c, these columns are transversally connected by three order of beams. A singular spiral shaped stair is connected on the top floor of block 10th. This stair is unsymmetrically placed with respect to the plan of this zone of the grandstand, and it determines a constraint to the dynamic behaviour of the structure.

Block 14th is part of the «Fiesole» curve. It is composed by six seven-type frames, equal to that constituting the 10th. As evidenced in Figure 4a, they are characterized by three columns the first of which have a section varying in elevation. At $7.20\ m$ height the first alignments of columns are divided in two parts. The columns in the other two alignments have sections varying in elevation, but with different geometry and sizes with respect to the first one as shown in Fig. 4a.

The 3D perspective views of the finite element model generated by SAP2000NL calculus program (CSI, 2018) for the block 10th - Maratona tower zone, and block 14th are shown in Fig. 3b a, Fig. 3c, and Fig. 4b, respectively. The frames constituting the structures of the blocks are made of frame-type elements.

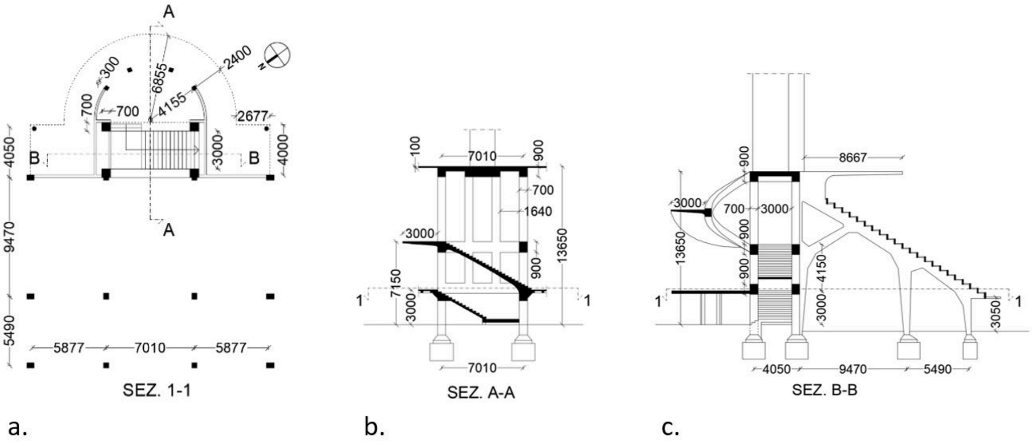


Figure 2. Horizontal (a) and vertical sections (b and c) of block 10th.

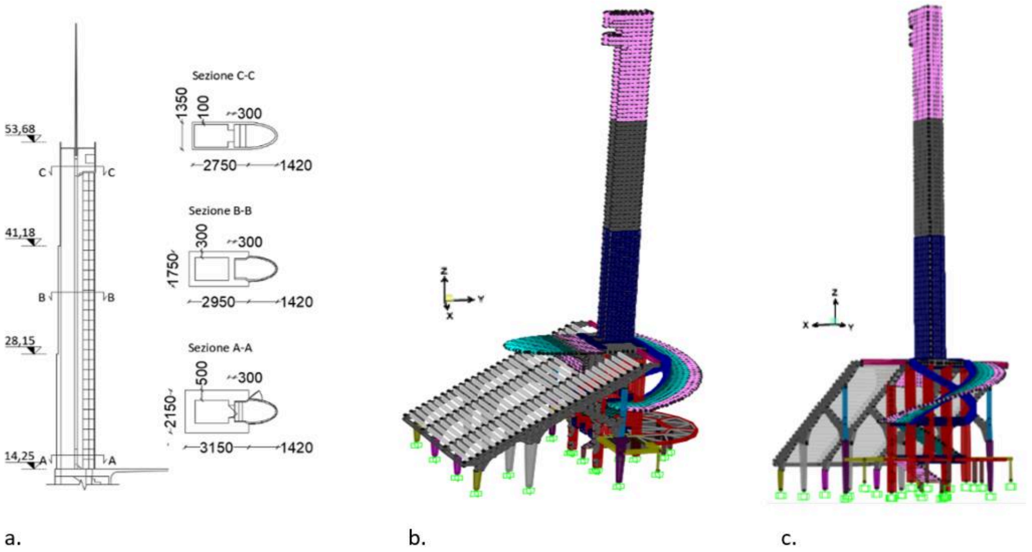


Figure 3. Vertical and cross sections of the Maratona tower (a); 3D perspective views of the finite element model of the tower and block 10th (b and c).

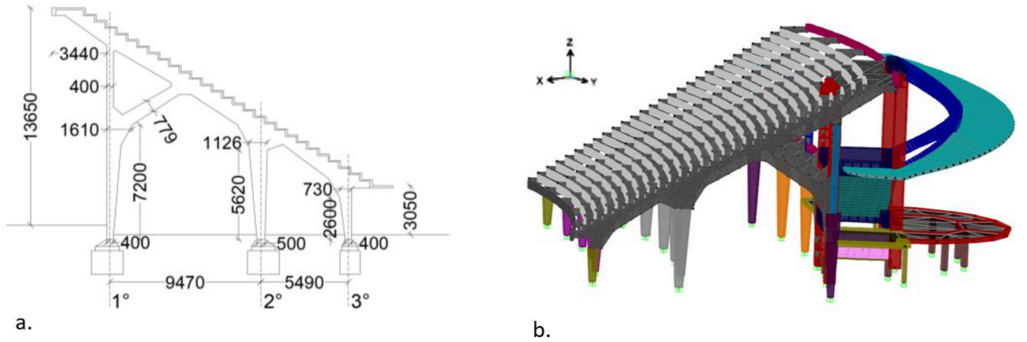


Figure 4. Vertical section of block 14th (a); 3D perspective view of the finite element model of block 14th (b).

The mean cubic compressive strengths of concrete for the stands, spiral stair, and tower are considered equal to 15.97 N/mm^2, 28.12 N/mm^2 and 40.83 N/mm^2 respectively; the yield stress and the tensile strength of steel are considered equal to 309.5 MPa and 441.68 MPa respectively. The cubic compressive strength values were utilized in order to estimate the corresponding elastic moduli to be attribute to the concrete in the finite element model. The following values were derived for the stands, spiral stair and tower: 25009 N/mm^2, 29635 N/mm^2, and 33143 N/mm^2, respectively.

3 THE EQUIPEMENT

3.1 Interferometric Radar

An interferometric radar is a remote sensor able to detect targets in his field of view by sending and receiving electromagnetic wave and it is able to detect the displacement by measuring differences of phase between two consecutive measurements. The natural frequencies can be detected by evaluating the Fourier transform of displacement. However, for large structures such as tower or stage, the Joint Time-Frequency analysis (JTFA) is preferable to assess the natural frequencies (Fratini et al. (2009) or Qian et al. (1999)). The JTFA evaluates the Fourier transform of displacement with a sliding time-window. The interval of time-window is shorter than the complete measurement and generally it is related to the coherence time of structure. The JTFA allows to evaluate the frequency spectrum during the time. The natural frequencies can be estimated by averaging on time the amplitude of JTFA.

The radar used for the measurements campaign operates a Continuous Wave-Step Frequency signal in K_u band and allows to detect natural frequencies between DC to more than $100\ Hz$ and it is described in Pieraccini et al. (2008). The radar can be installed close to the structure and it can perform measurements of different targets of the structure. Fig. 5 shows a possible setup of radar for measuring the tower displacement.

3.2 Seismic accelerometer

The seismic accelerometer is an accurate sensor able to measure acceleration of a structure. In order to perform reliable measurements, the accelerometer must be fixed on the structure under test. The natural frequencies can be retrieved by calculating the Fourier transform or the JTFA of the measured acceleration.

The accelerometer used was a PCB 393B31 produced by PCB piezotronics. The sensitivity of this sensor was $1.02\ \mathrm{V}/(m/s^2)$ with a typical resolution of $9 \cdot 10^{-5}\ m/s^2\ rms$. It is able to detect frequencies between $0.1\ Hz$ to $200\ Hz$. An example of the accelerometer setup is shown in Fig. 5.

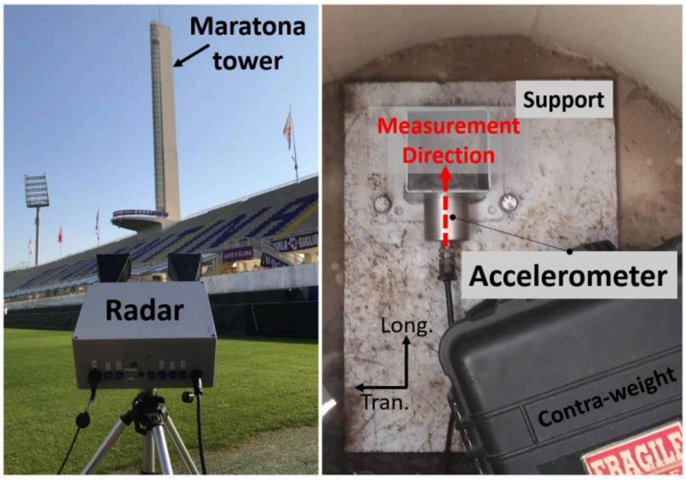


Figure 5. On the left a possible radar configuration for measuring displacement; on the right an example of accelerometer setup on the Maratona Tower.

The accelerometer was constrained to the structure by using a heavy support and it measured the acceleration in the horizontal plane.

4 EXPERIMENTAL RESULTS

4.1 Maratona Tower

The measurements of Maratona Tower was carried out under the wind action, both with the accelerometer and interferometric radar. The radar was positioned close to entrance gate of stadium as Fig 6 shows. From this position the radar was able to detect both longitudinal and transversal movement of the tower.

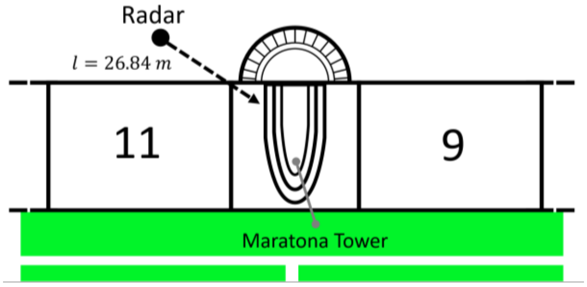


Figure 6. Radar position

Fig. 7 shows the radar plot projected on vertical direction. The Maratona tower starts form 13 m height. The target at 53.64 m height has been used to determinate the natural frequencies.

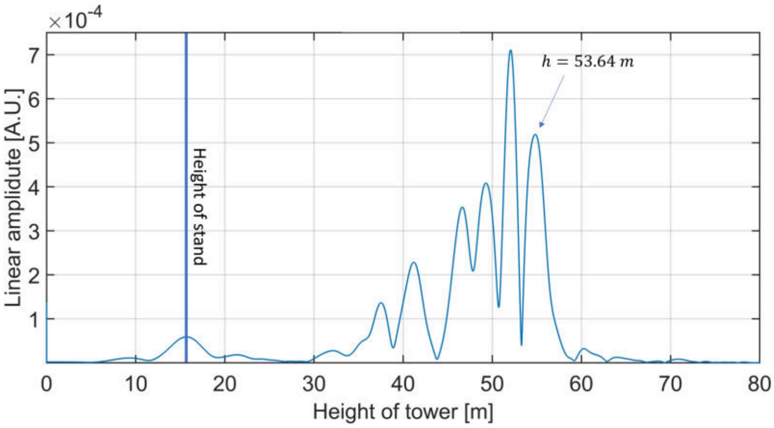


Figure 7. Radar plot projected on vertical direction. The stand was about in 15 m height.

The accelerometer operated in the tower's attic in three different setups as Fig. 8 shows. The position (a) was used to compere the measurement with interferometric radar while the position (b) and (c) ware used to discriminate the longitudinal and transversal mode.

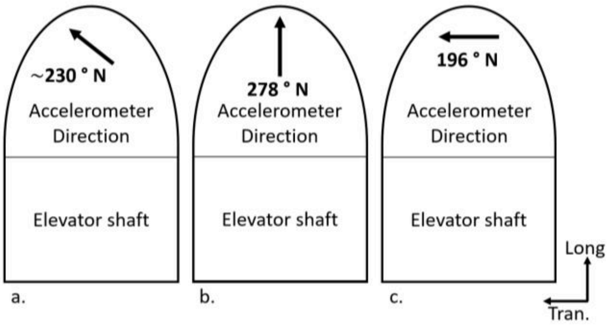


Figure 8. Measurement setup of accelerometer in the tower's attic. The position (a) was used for comparison with interferometric radar. The position (b) and (c) were used discriminate the longitudinal and transversal mode.

The measurements with interferometric radar and accelerometer were performed in different moments, but with similar wind conditions. Fig. 9 shows the frequency spectrum measured by the interferometer, and by the accelerometer in each of the three setups. The JTFA was applied for both cases with a time-window of 140 s for radar and 100 s for accelerometer. Frequencies estimated by the radar were: $f_1 = (0.685 \pm 0.007)\ Hz$, $f_2 = (0.809 \pm 0.007)\ Hz$ and $f_3 = (1.031 \pm 0.007)\ Hz$. The frequencies evidenced by the accelerometer were: $f_1 = (0.677 \pm$

$0.010)\ Hz$, $f_2 = (0.787 \pm 0.010)\ Hz$ for transversal direction and $f_3 = (1.013 \pm 0.010)\ Hz$ for longitudinal direction. The measurement uncertainties are estimated as the reciprocal of the used time-window. The agreement between both instruments is good.

The frequencies f_1 and f_3 measured by the radar correspond to the first two translational frequencies (determined by making use of a fixed constrain at the basement of block 10th) by considering a stiffness reduction of about 64% in X direction and 35% in Y with respect to the value estimated by material tests. This high discrepancy has to be investigated deeper. We think that the numerical model of the Maratona tower and block 10th has to be refined by considering the underground structures (swimming pool and gym) realized for the 1990 FIFA World Cup. As the real constraints of the tower basement are determined by these underground structures, further on-site inspections will be necessary for a more accurate refinement of the numerical model.

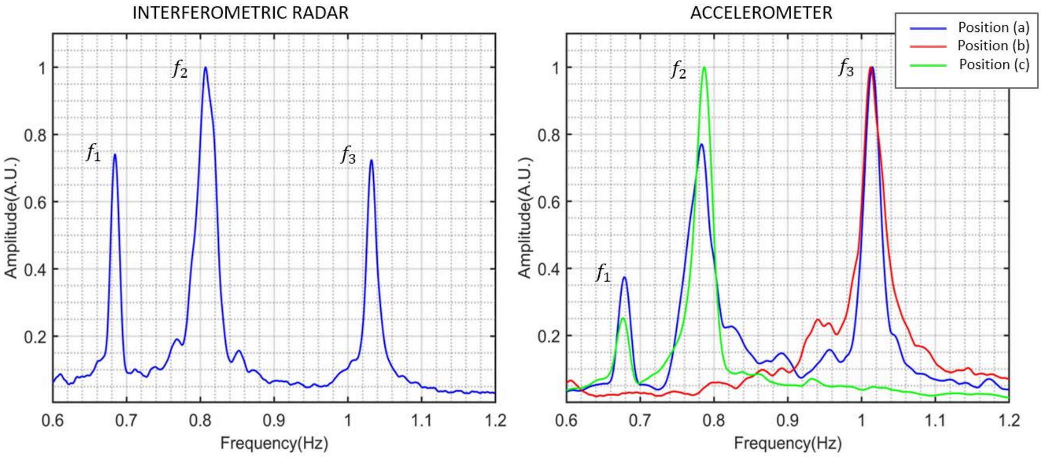


Figure 9. Frequency spectrum measured with interferometric radar (on the left) and with accelerometer (on the right) for all of three measurement setups.

4.2 *"Fiesole" curve – block 14th*

The measurements on the stages were performed during a football match. The movements of supporters were used as input action to measure the dynamic properties of stands. Unfortunately, this input was not enough to allow the measurement of the natural frequencies of all the stands. Here the authors report the results obtained on block 14th.

The JTFA was performed with time-windows of $35\ s$. The natural frequency spectrum is shown in Fig. 10. This spectrum is obtained by averaging the JTFA in full measurement interval ($800\ s$). The natural frequencies retrived were $f_1 = (2.83 \pm 0.03) Hz$ and $f_2 = (5.04 \pm 0.03) Hz$.

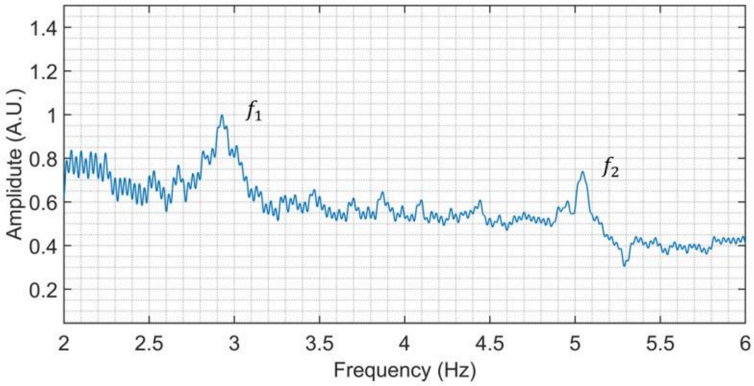


Figure 10. Natural frequency spectrum of "Curva Fiesole" stage.

For block 14th frequencies obtained by interferometer ($f_{1,exp} = (2.83 \pm 0.03)\ Hz$, $f_{2,exp} = (5.04 \pm 0.03)\ Hz$) substantially match with those corresponding to the 1st translational mode in Y direction, and 4th translational mode in X direction, deriving from the numerical model. In fact, the natural frequencies obtained for these two modes are: $f_{1,num} = 2.684\ Hz$ and $f_{4,num} = 4.928\ Hz$.

5 CONCLUSIONS

In this paper, a selection of results concerning an experimental campaign carried out on the "A. Franchi" Stadium in Florence is reported. On-site tests have interested particularly the "Maratona" tower and Block 14th of "Fiesole" curve. For investigating the Martona tower interferometric radar and accelerometer are used. Natural frequencies estimated for the tower by means of both instruments substantially match. Instead, the computational model of block 10th must be refined by changing its constraints at the base.

The Block 14th was investigated only by radar. Although Block 14th was exited only by action of supporters' movement, natural frequencies detected with the interferometer substantially match with the modal parameters resulting from the numerical model.

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