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Laser doppler and radar interferometer for contactless measurements on unaccessible tie-rods on monumental buildings: Santa Maria della Consolazione Temple in Todi

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Abstract. Non-contact measurements can be effectively used in civil engineering to assess the variation of structural performance with time. In the last decades this approach has received considerable interests from researchers working in the field of structural health monitoring (SHM). Indeed, non-contact measurements are very attractive because it is possible to perform non intrusive and non destructive investigations even being at a significant distance from the targets. Within this context, contactless measurements of the tie-rod vibrations in the Santa Maria della Consolazione Temple in Todi (Italy) are presented in this paper. In particular, laser vibrometer and radar interferometer measurements are used to estimate natural frequencies and mode shapes. This information is crucial to obtain the tensile axial force in the tie-rods, which can be used as an indicator of structural integrity or possible failure. Furthermore, a novel approach is proposed where drones (Unmanned Aerial Vehicles) can be successfully used to improve the effectiveness and the accuracy of the experimental activities.

1. Introduction

Structural Health Monitoring (SHM) of historical constructions is becoming one of the most important tools for safeguarding and preserving monuments and cultural heritage [1–4]. Italy is one of the countries characterized by the presence of a considerable number of historical constructions, which require important maintenance programs, significant restoration activities, and planning of emergency strategies in case of natural hazards.

The state of a structure can be altered in time by natural degradation of materials, severe isolated events such as earthquakes and thunderstorms, and background environmental loads such as synoptic winds or traffic. Within this context, SHM can provide crucial information about the ability of a structure to accomplish a required function in time. Modern static and dynamic monitoring techniques can be used both to provide information about the main mechanical and geometrical parameters used in the structural identification and to detect damage occurrence in time. In the last years, one of the most appealing monitoring technique is the one based on structural vibration [5–9], aimed to assess natural frequencies, mode shapes and associated damping ratio.

Figure 1. Temple of Santa Maria della Consolazione in Todi.

Tie rods are simple structural elements that have been commonly used throughout the centuries to improve stability of old masonry buildings. These elements, different in material, size and shape, are used as an effective connection in the structural system constituting elements, especially lateral walls or springing of arches and vaults. Stability of the whole construction and/or local structural elements is directly connected to the magnitude of the tensile axial force carried out by the tie-rods. A change in time in this tensile force might be associated to some kind of mechanical failure causing a new internal forces distribution among the structural elements. As an example, cracks in the masonry walls or differential settlements, which can compromise the stability and the integrity of the whole building, can initiate this process of change in the internal forces in the structural elements, including the tie-rods.

The evaluation of the axial internal force time histories in the tie-rods, e.g. with periodic measurements, can be used as an effective monitoring tool in order to predict structural failures. This evaluation has to take into account all the uncertainties in the geometrical and mechanical properties due to both the use of hand made iron elements and the different constraint boundary conditions.

Measurements of tie-rods vibrations can be obtained using contact and non-contact vibration techniques. The development of non-contact measurement systems has received a considerable interests from researchers in the last decades (e.g. [10,11]). Non-contact measurements are very attractive because it is possible to perform non intrusive and non destructive investigations even being at a significant distance from the target.

In this paper, contactless measurements of tie-rod vibrations in the Santa Maria della Consolazione Temple in Todi (Italy) are presented. Laser Doppler Vibrometer and Radar Interferometer tests are compared, showing both ambient vibration and induced free vibrations. A novel usage of Unmanned Aerial Vehicles (UAV), commonly known as drones, to support the experimental tests is also described together with a set of thermografic survey in order to estimate the tie-rod temperature during the measurements. This information is crucial for estimating the tie-rod axial tensile force variation with time.

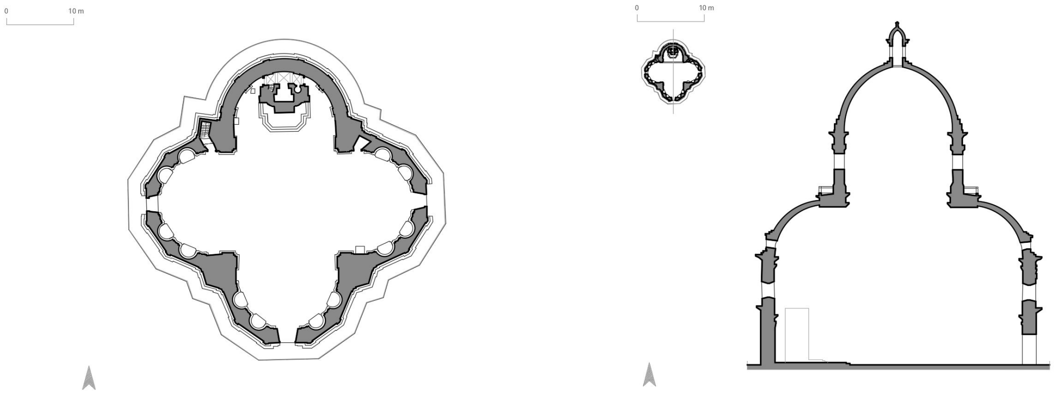


Figure 2. Temple of Santa Maria della Consolazione in Todi: plan and longitudinal section (Courtesy of Biondini & Corradi Associati - Studio di Ingegneria e Architettura.)

2. Santa Maria della Consolazione Temple

2.1. The Temple

The Santa Maria della Consolazione Temple (Figure 1), one of the most important monumental buildings in Umbria Region, in Central Italy, is located in the South West Area of Todi's city. It is a Renaissance style church and it was built between the 16th and the 17th centuries. Although direct evidence is lacking, the first design of the structure can be assigned to Bramante [12].

The church consists of a greek cross plan, with 42 m and 48 m dimensions, with a tall central dome, which rises to a total height of about 50 m from the temple floor, and four semi-shells on the lateral sides. The dome consists of a single shell with ogival shape [13], it rests on a circular drum, is surmounted by a lantern and reinforced with ribbs. Figure 2 shows the plan and the longitudinal section of the temple carried out after a recent architectural survey.

The main bearing structure consists of 4 pillars with an height of about 25 m and a thickness of about 2 m. The base of the pillars lays on a square central area of 25 m^2. The North apse, the first to be built, is semi-spherical, while the others are polygonal. The apse walls thickness is of about 2 m. The foundations reach a depth of 4 m. All the structure is made of ashlar and mortar. The exterior of the temple is made of the white limestone blocks from the local quarries. The dome and the apses shells are covered with lead sheets.

Since its construction, dated back to 1509, the Temple revealed structural problems and local collapses. The first consolidation work began at the end of 1800s. Four tie-rods were installed: each element was connected to the spring line of the vaults and directly fixed to stonework by bolts and plates. At the same time, a retaining wall was built in the South area. In the second half of the 20th century drilling holes in concrete foundations and cement grouting were carried out in order to strengthen foundations and masonry walls. A drainage wall was also completed in order get the water out from the structure [14]. In the eighties it was discovered that the cause of instability was a landslide on the South West side, due to the differential sliding of clay and sands. Because of this reason, a consolidation work began in 1990, where 232 micropiles and 257 large diameter piles were built [15]. After the recent Umbria-Marche earthquake in 1997, the temple was subjected to other phases of strengthening. Seismic safety was improved by confinement measures on the apses and dome internal side and on the drum external side.

2.2. The tie-rods

The four tie-rods in the Santa Maria della Consolazione Temple (Figure 3(a)) appeared for the first time in a picture dated back in 1890 (Figure 3(b)). During the years these metallic elements


(a) (b)

Figure 3. (a) Bottom view of the central dome. (b) Historical picture (1890) of the tie-rods.

experienced failures and replacements. The North and the East tie-rods were replaced in 1905 and 1959, respectively; the former after breaking, while the latter because of the instability problems involving the whole structure.

As of today, the geometrical and mechanical properties of the tie-rods are unknown so that every analysis has to consider uncertainties on several parameters such as bar length, cross section size, mass density, elastic properties, and support conditions. Furthermore, each of the tie-rods is equipped with a tightening device made with iron eyelets in order to adjust the rod tension in time to accommodate slight changes in the structural geometry. The position and the masses of the tightening systems are further unknown parameters to be considered in future structural global and element identification.

3. Experimental Tests

A laser vibrometer and a radar interferometer have been used to measure tie-rod vibration time histories. This choice finds its main reason on the difficulty in placing commonly used contact sensors, such as accelerometers and strain gauges, on the unaccessible tie-rods located at the height of about 16 m. The obtained measurements can be used to estimate natural frequencies and mode shapes that are directly related to the tensile axial force.

3.1. Brief description of the measuring system

The laser doppler vibrometer used in this work is a Polytec OFV 3001 - OFV 303, controller and sensor head(Figure 4(a)), with resolution 0.25 nm, constant in the whole frequency range from 0 Hz to 250 kHz.

In order to improve signal quality it was decided to use reflecting targets to be applied on the target positions in the unaccessible tie-rods. This issue was overcome designing a suitable drone (UAV) equipped with a carbon fiber mechanical arm as shown in Figure 5(a). Figure 5(b) shows the reflecting target, correctly positioned by the drone, and the vibrometer measurement point on the South tie-rod.

The main features of the IBIS-FS ground based radar interferometer are summarized in Table 1.

3.2. Experimental layout

Figure 6 (a) shows the laser vibrometer (blue circles) and the radar interferometer (white squares) positions used in the experimental measurements. It is worth noting that the target surfaces are located at a height over 16 m (Figure 6 (b)). A drone (UAV) was used to place

(a) (b)

Figure 4. (a) Laser Doppler vibrometer system. (b) Radar Interferometer.

(a) (b)

Figure 5. (a) Drone at work. (b) Reflecting target on the South tie Rod.

Table 1. Features of IBIS-FS 010-14-000301 ground based radar interferometer.

Center frequency f_0	17.2 GHz
Frequency Bandwidth	200 MHz
Range resolution ΔR	0.75 m
Maximum EIRP Power P_0	26 dBm
Maximum unambiguous displacement	4.36 mm

reflecting targets on the unaccessible tie-rods avoiding time consuming and costly scaffolding or moving platforms.

4. Experimental Results

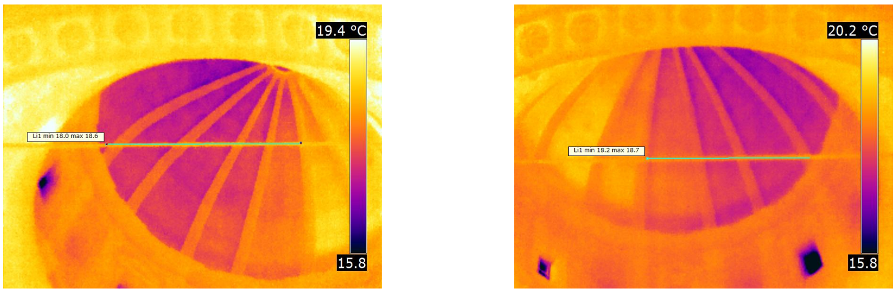
4.1. Temperature measurements

The tie-rod temperature was measured using thermal images. This information is crucial to distinguish tensile force variation that can be due both to geometrical and to temperature changes. Figures 7 (a) and (b) show the thermal images used to estimate the temperature in the East and West tie-rods. Maximum, minimum and mean temperature values are summarized in

(a) (b)

Figure 6. (a) Plan view of the laser vibrometer (blue circles) and radar interferometer (white squares) positions. (b) Tridimensional view of the North Apse with the tie-rod height.

Table 2.



(a) (b)

Figure 7. Thermal image of the East (a) and West (b) tie-rod.

Table 2. Maximum, minimum and mean temperature values in the four tie-rods.

Tie Rod	Tmin[°C]	Tmax[°C]	Tmean[°C]
North	18.40	19.00	18.70
East	18.00	18.60	18.30
South	18.60	19.00	18.80
West	18.20	18.70	18.45

4.2. Ambient vibration measurements

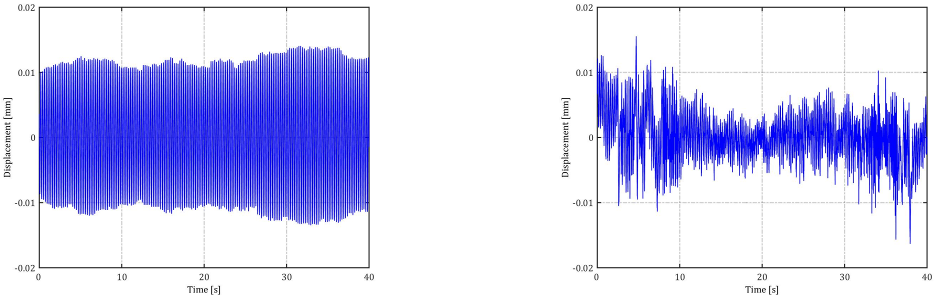
Ambient vibrations were recorded in all the tie-rods with a sampling rate set to 200 Hz. Figure 8 shows the displacement time histories obtained by the laser vibrometer and radar interferometer in the East tie-rod.

Figure 9 shows the power spectral densities estimated from 100 s of the displacement time histories in the East (upper panels) and North (lower panels) tie-rods. The left and right panels report estimates from the laser vibrometer and radar interferometer measurements, respectively.

4.3. Free Vibrations

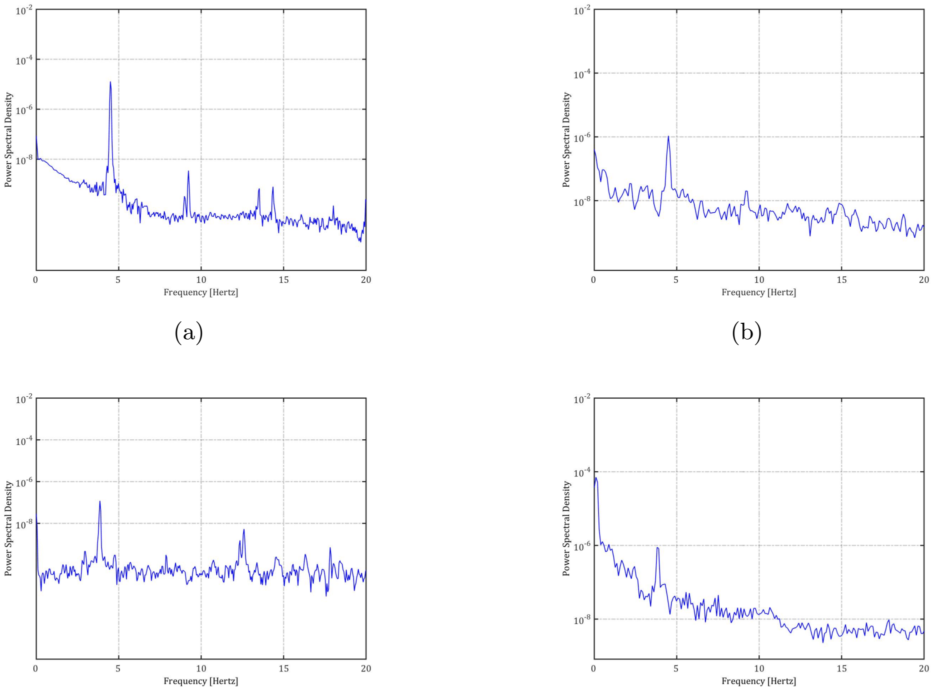
Free vibrations were induced giving a force pulse with a thin rope. Then, 100 s displacement time histories were recorded with sampling rate set to 200 Hz. A drone (Figure 5(a)) was used to overpass the thin rope over the four tie-rods. The thin rope was suitably linked to the drone using a special connection system in order to avoid instability problems.

Figure 10 shows the displacement time histories obtained by the laser vibrometer and radar interferometer in the West and North tie-rods, respectively. Left panels refer to laser vibrometer, while right panels report radar interferometer measurements. The different shape of the North



(a) (b)

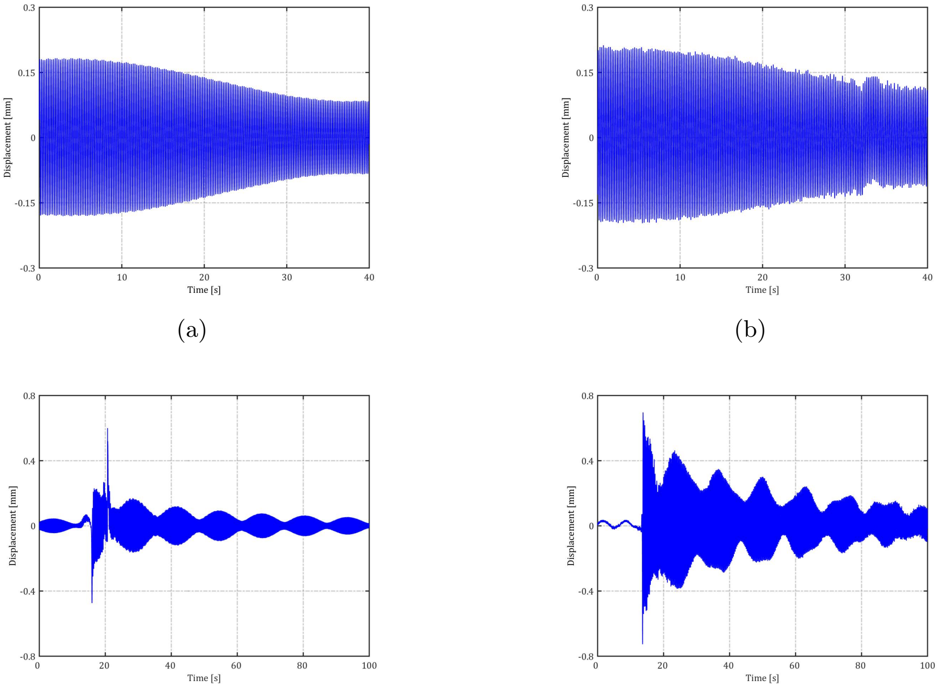
Figure 8. East tie-rod displacement time histories: (a) laser vibrometer (b) radar interferometer.



(a) (b)

(c) (d)

Figure 9. Power spectral densities estimated from the laser vibrometer (left panels) and radar interferometer (right panels) measurements in the East (upper panels) and North (lower panels).



(a) (b)

(c) (d)

Figure 10. Displacement time histories from the laser vibrometer (left panels) and radar interferometer (right panels) in the East (upper panels) and North (lower panels).

tie-rod vibrations is due to three hanging candle holders playing the rule of pendulous.

Figure 11 shows the power spectral densities estimated from 100 s of the displacement time histories in each tie-rod. The left and right panels report estimates from the laser vibrometer and radar interferometer measurements, respectively.

More information can be obtained by the radar interferometer since it is possible to record simultaneous displacements in a finite number of sample points located along its line of sight. As an example Figure 12 (a) shows the measured point locations on the North tie-rod, while Figure 12 (b) reports the displacement time histories at these locations.

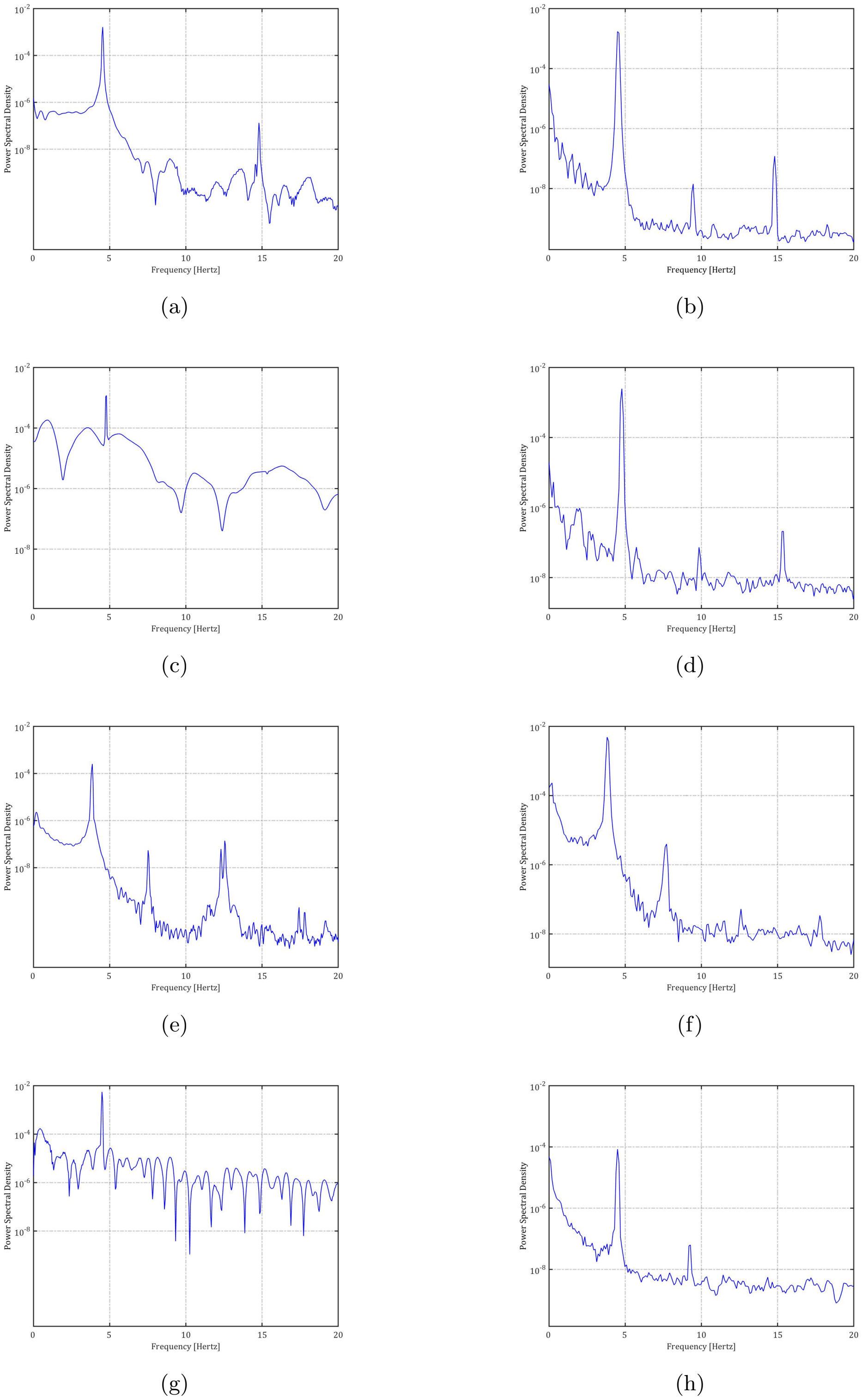
Figure 13 (a) and 13 (b) show the maximum and minimum displacement (blue) obtained at the different measured positions, together with the tie-rod geometry at two time istants (red).

4.4. Tie-rods natural frequencies

The tie-rods natural frequencies can be easily estimated by performing a peak picking in the frequency domain (e.g. Figures 9 and 11). The first natural frequency value for each tie-rod is summarized in Table 3 both for laser vibrometer and radar interferometer data. The results comparison demonstrate that both the instruments provide the same values in the East and West tie-rods. A slight difference, less than 2%, is found for the North and South elements.

5. Conclusions

Laser vibrometer and radar interferometer vibration measurements of unaccessible tie-rods on the Santa Maria della Consolazione Temple in Todi were presented and compared in this paper. It was shown that both measuring techniques give satisfactory results in terms of the first natural frequencies and can be an effective alternative to contact sensors such as accelerometers and



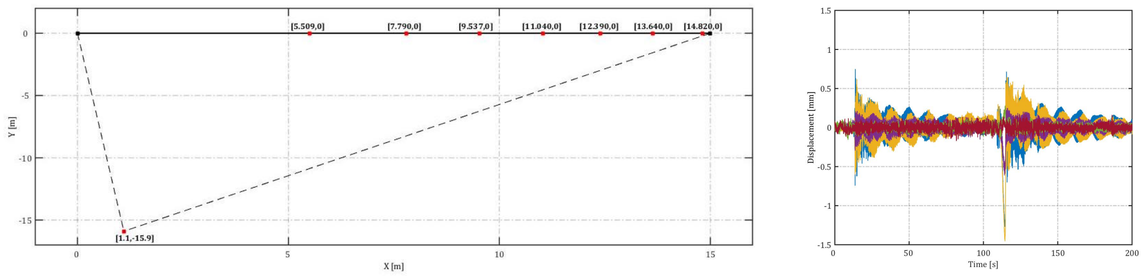
(a) (b)

(c) (d)

(e) (f)

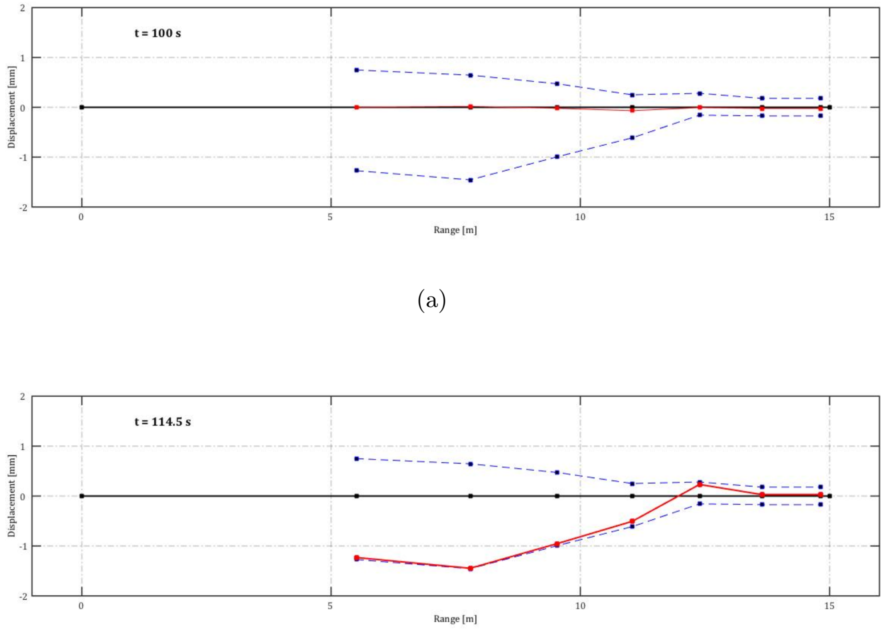
(g) (h)

Figure 11. Power spectral densities estimated from the laser vibrometer (left panels) and radar interferometer (right panels) measurements in the South, West, North, East tie-rods (top to bottom panels).



(a) (b)

Figure 12. (a) Sampling locations and radar interferometer position used for the North tie-rod. (b) Displacement time histories recorded by the radar interferometer at the sampling points on the North tie-rod.



(a)

(b)

Figure 13. Maximum and minimum displacements at the sampled points (blue) of the North tie-rod recorded by radar interferometer. The red line shows the tie-rod shape at two time instants: (a) 100 s and (b) 114.5 s.

Table 3. Tie-rod natural frequencies obtained by laser vibrometer and radar interferometer.

Tie Rod	Vibrometer (Hz)	Interferometer (Hz)
East	4.785	4.785
West	4.875	4.875
North	4.541	4.491
South	3.875	3.809

strain gauges. Furthermore, a novel methodology was proposed to improve the effectiveness and the accuracy of the experimental activities by the use of drones (Unmanned Aerial Veichles) to place reflecting targets on suitable locations and to position thin ropes for inducing free vibrations of the structural elements.

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