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STRUCTURAL MONITORING OF MONUMENTAL BUILDINGS: THE BASILICA OF SANTA MARIA DEGLI ANGELI IN ASSISI (ITALY)

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Abstract. *The preservation of architectural heritage and monumental structures is an important challenge of the scientific research, especially for the countries where cultural heritage is of primary concern and, at the same time, there are significant risk factors due to natural hazards as earthquakes. In this perspective, structural health monitoring systems can improve the protection of structures by providing real-time diagnostic data together with suitable procedures, which are able to identify possible occurring problems. In this work the first results given by a monitoring system placed in the Basilica of Santa Maria degli Angeli in Assisi will be presented. Data recorded by nine linear variable displacement transducers (LVDTs) are shown together with power spectral densities of acceleration time histories measured during ambient vibration tests. The spectral analysis results are compared with the natural frequencies given by a numerical model of the Basilica structural system.*

Figure 1: Basilica of Santa Maria degli Angeli in Assisi.

1 INTRODUCTION

Structural health monitoring can give crucial information on the variation in space and time of the main mechanical features of existing buildings. These information assume significant meaning especially when dealing with historical and monumental constructions where it is important to preserve architectural and cultural heritage [1],[2].

Within this context, monitoring systems can be used to provide real-time diagnostic data together with all the relevant information that can be useful to detect changes is structural parameters, often associated with some kind of structural damage.

In order to obtain such information a research program has been recently started to monitor two relevant historical constructions in the center of Italy: the bell-tower of the Basilica of San Pietro in Perugia [3] and the dome of the Basilica of Santa Maria degli Angeli in Assisi.

In this paper the first results obtained by the monitoring system placed in the Basilica of Santa Maria degli Angeli in Assisi are presented.

The Basilica of Santa Maria degli Angeli (Fig. 1) is located in the center of Italy. Over the years the structural system has been affected by significant seismic events, among which the earthquakes in 1832 and in 1997 were the most severe. In particular, the event in 1832 caused the collapse of the nave and the left aisle, together with a wide spread damage scenario, which also involved the drum-dome system.

The seismic event of 1997 induced damages only in a few parts of the structural system, nevertheless, after a set of strengthening and rehabilitation works, a ”static” monitoring system consisting of nine linear variable displacement transducers (LVDTs) has been installed.

In the first part of the paper, after recalling the main historical and geometrical features of the Basilica, the data of the LVDTs recorded in the years 2001-2003 are presented. This system

(a)  (b) 

Figure 2: (a) Image of the drum-dome structural system. Three orders of steel rings can be easily seen. (b) Line-engraving of the damage conditions after the 1832 earthquake. *Prospetto delle ruine del famoso Tempio di Santa Maria degli Angioli di Asisi*, by Cilleni Nepis.

failed after a severe thunderstorm and it was possible to restart it only at the beginning of 2015.

The research program has started in 2014 with a preliminary investigation using two accelerometers installed at the base of the dome to detect the first modal frequencies. The acceleration time histories together with their spectral representation are shown in the second part of the paper and compared with the modal analysis of a preliminary numerical structural system.

These results will be used to design a permanent ”dynamic” monitoring system and to calibrate a numerical finite element model (FEM) that can be used to assess the spatial and time variation of the main mechanical features of the Basilica of Santa Maria degli Angeli in Assisi.

2 THE BASILICA OF SANTA MARIA DEGLI ANGELI IN ASSISI

The Basilica of Santa Maria degli Angeli in Assisi was built between 1569 and 1679. Its original drawing is attributed to the architect Galeazzo Alessi, even if the philological respect of the design is controversial, since the structure was completed many years after the Architect’s death. The basilica has a latin cross plan, with 126m and 65m dimensions, with a nave and two aisles and a semicircular apse. The central core, at the intersection between the transept and nave, consists of the four pillars which bear the triumphal arches, the drum and the dome. At the vertical axis of the dome’s lantern is located the Porziuncola, a little ancient chapel, heart of the basilica and symbol of Franciscan spirituality.

The current architectural configuration of the façade is quite recent. It was designed by Cesare Bazzani with the aim to confer just the right monumental dignity to the Basilica. It was built at the beginning of the 20th Century and inaugurated in 1930. The actual configuration hides the original façade, more simple and poor, and seems to balance the visual attraction, which was previously dominated only by the drum-dome system.

The dome of the Basilica is majestic and impressive, and is characterized by a singular slenderness due to the lightness of the drum (Fig. 2 (a)) [4]. The inner diameter is of about 20m and the variable thickness of the unique shell starts from 1.60m to 0.70m. The inner perimeter of the drum is circular, while the outer is octagonal; the coupled pilasters at the angles of the

(a) (b) (c)

Figure 3: (a)-(b) Vertical cracks between the new and the old fașdes. (c) Major through crack of the drum-dome system.

octagon become stiffening ribs which join at the *oculus*, the base of the lantern, that gives a total height of about 75m to the structure.

Throughout its history the structure has been subjected to significant seismic events that have compromised also the structural integrity of the Porziuncola. Historical documents describe the damages due to the earthquake of 1832, that caused the collapse of the nave and of a portion of the left aisle (Fig. 2 (b)). The drum-dome system did not collapse, but was severely damaged. Date back to this event the strengthening measures of the drum with three orders of steel rings (Fig. 2 (a)). After the Umbria-Marche earthquake of 1997 the basilica has been subjected to several rehabilitation and strengthening measures [5]. The works have mainly concerned the façade stability, the strengthening of the transepts and aisle vaults and the reinforcement of the drum. The kinematic mechanisms related to these crucial aspects can be detected by the evident cracks, especially for the façade and the drum (Fig. 3).

The cracks and micro-cracks pattern which affects the drum-dome system has been recently surveyed (Fig. 4) [7]. The widespread cracks type and configuration suggest that they are imputable both to seismic and static loads acting over the years. The most significant cracks are located above the north-east wall, due to the presence of internal staircases and a door on extrados of the dome (Fig. 4(a)-(c)), and the west wall of the drum (Fig. 4(b)-(d)).

3 STATIC MONITORING SYSTEM

In 2001 a continuous static monitoring system, consisting of nine linear variable displacement transducers (LVDTs), was installed in order to record displacement time histories as follows (Fig. 5):

- LVDT 1. Installed across the joint between the old façade and the vault of the nave. The sensor monitors the overturning of the façade after consolidation, which has consisted of the foundation's strengthening by means of a series of micro-poles, in addition to the

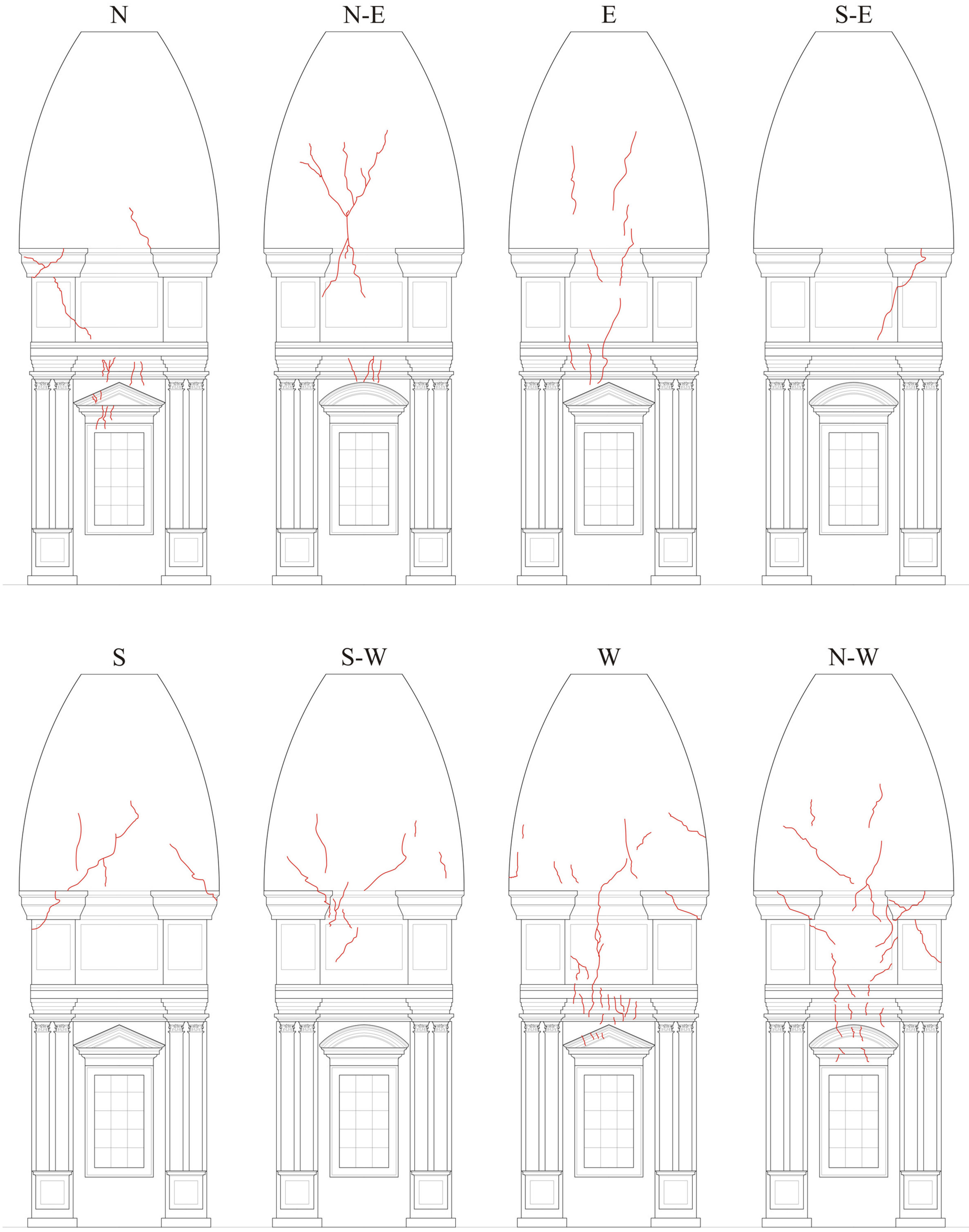

Figure 4: Survey of the cracks pattern at the dome intrados [7].

installation of four orders of couple tie rods to anchor the façade to the lateral walls of the nave.

- LVDT 2-4. In the following they will be identified as “wire-sensor”. The wires are fixed at the nave vault imposts. The LVDT 2 is located at the beginning of the nave, near to the entrance, and LVDT 3 at the end, near to the drum. The wire-sensor LVDT 4 is fixed at the triumphal arch imposts, in the intersection between the nave and the transept. The LVDT 4 has recorded very few good data, so it will not be shown in the following.

- LVDT 5. Installed at the base of the drum, across a crack over the triumphal arch at the

(a)

(b)

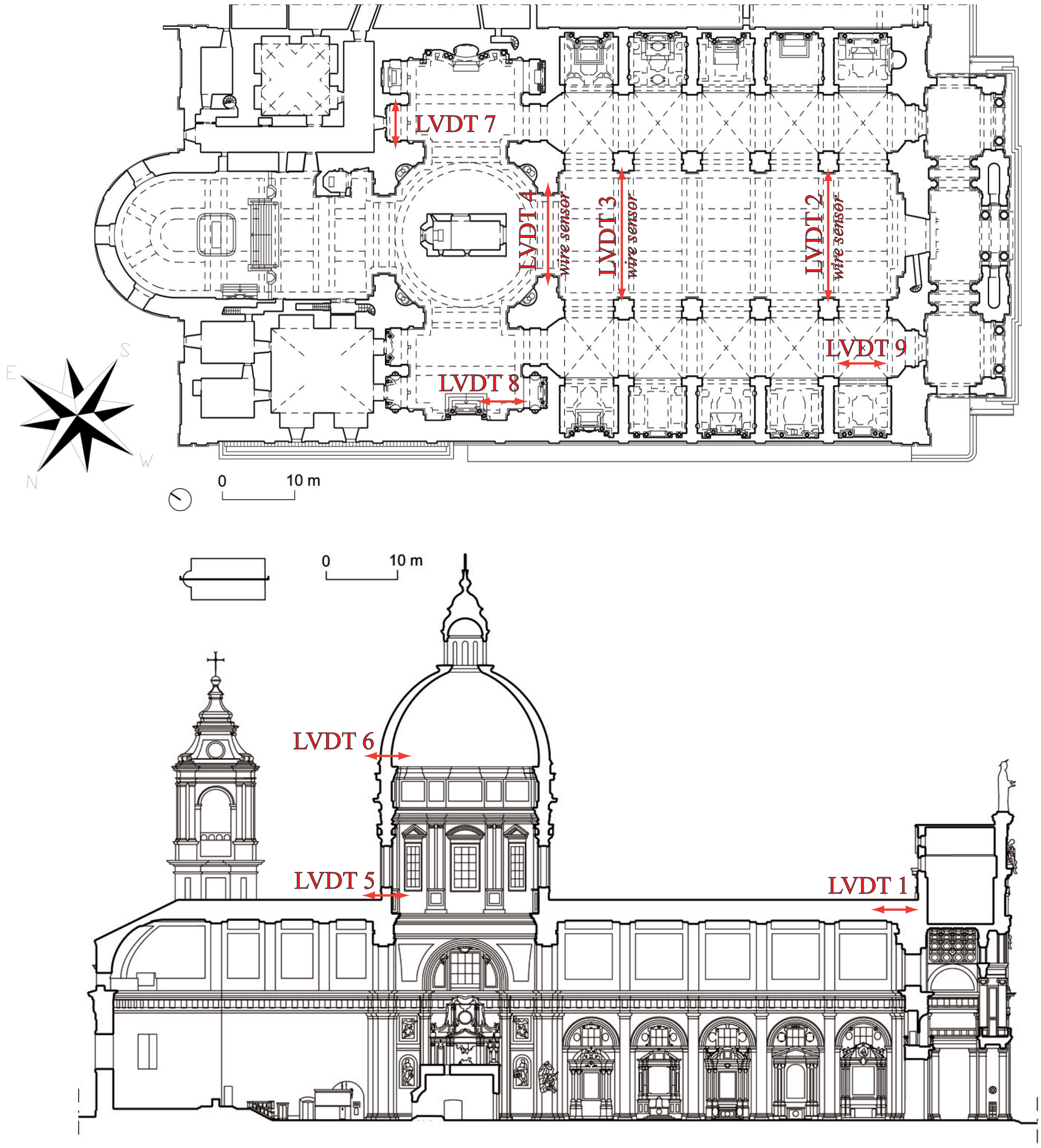

Figure 5: LVDTs' installation layout. (a) Plan. (b) Longitudinal section.

intersection between the nave and the right transept.

- LVDT 6. Installed across the major dome's crack. This critical point is evident both from inside and outside the structure. The importance of this crack is related to a weak section of the wall due to the presence of inner spiral staircases.

- LVDT 7. Installed over the sacristy arch. The monitored crack is linked to an important structural settlement which involves all the right transept.

- LVDT 8. Installed on the vault crown of the left transept.

- LVDT 9. Installed across a significant crack on the vault of S.Diego chapel. Owing to its position, the crack behaviour can be related to the overturning of the façade, and then to the LVDT 1.

The recorded data are continuously available from April 13th 2001 to September 28th 2003. On that day the system was shut down. After three years, in 2006, it was started again, but crashed after only a few months, maybe because a severe thunderstorm. The system has been repaired and restarted in March 2015.

Figures 6 and 7 show the time evolution of the data recorded by the LVDTs in the period 2001/04/13-2003/09/28. All the data highlight the classic seasonal trend, given by ambient conditions, such as temperature and moisture.

Moreover, some aspects are noteworthy. In particular, LVDT 1-2-3-5-9 seem to show an increasing or decreasing trend, which could be related to ongoing motions. As said before, LVDT 1 and 9 are consistent, since S.Diego chapel is the near to the façade. At the same time, LVDT 2 and 3 describe the same phenomenon viewed by two different points, as the realtive motion between the walls of the nave.

Specific attention must be given to the LVDT 6, which path is related to the lateral thrust of the dome. The occurrence and the slow opening of the meridian cracks at the base of a dome describe a physiological static response of such structures [7]. Nevertheless, more investigations are needed to give proper interpretation of the data.

4 DYNAMIC INVESTIGATIONS AND NUMERICAL MODEL

4.1 Ambient vibration test

Ambient vibration testing is considered a reliable method for assessing modal parameters also for historical constructions. In this chapter, the results of a first dynamic investigation are shown. In particular two accelerometer sensors have been installed at the highest reachable level (about 50m high), at the base of the dome (Fig. 8).

Two ambient vibration tests have been carried out by using different types of sensors: form January 29th to February 5th 2015 by using piezoelectric uni-axial accelerometers model PCB 393C (1 V/g sensitivity); form February 17th to 24th 2015 by using high sensitivity piezoelectric uni-axial accelerometers model PCB 393B12 (10 V/g sensitivity). Data have been recorded continuously with a sampling rate of 100 Hz and stored with a time length of 30 minutes. Moreover a weather station is installed nearby the Basilica and the main wind and temperature data are also available.

Both the tests have been characterized by a quite fast wind speed. In particular, wind gusts of 66.6 km/h and 57.4 km/h have been recorded on January 30th and February 18th, respectively. In these days the data recorded by the different sensors are similar. Figure 9 shows the acceleration time histories (Fig. 9(a)) and related frequency spectra (Fig. 9(b)) of the latter event. Form the frequency analysis the first natural frequencies of the structure can be estimated: it should be noted resonant peaks for both Acc1 and Acc2 sensors for $1.7 \div 1.8$ Hz, a peak at a frequency of about 3.0 Hz only for Acc2 and for both the sensors in the ranges of $3.5 \div 4.0$ Hz, $4.0 \div 4.5$ Hz and $6.0 \div 6.5$ Hz. However, an in-depth dynamic identification analysis is necessary to better understand the complex dynamic behaviour and the modal structural properties.

In both the tests has been also observed a significant contribution of vibration, in the range of $10 \div 15$ Hz, due to the traffic during daytime. Moreover, another interesting phenomenon is

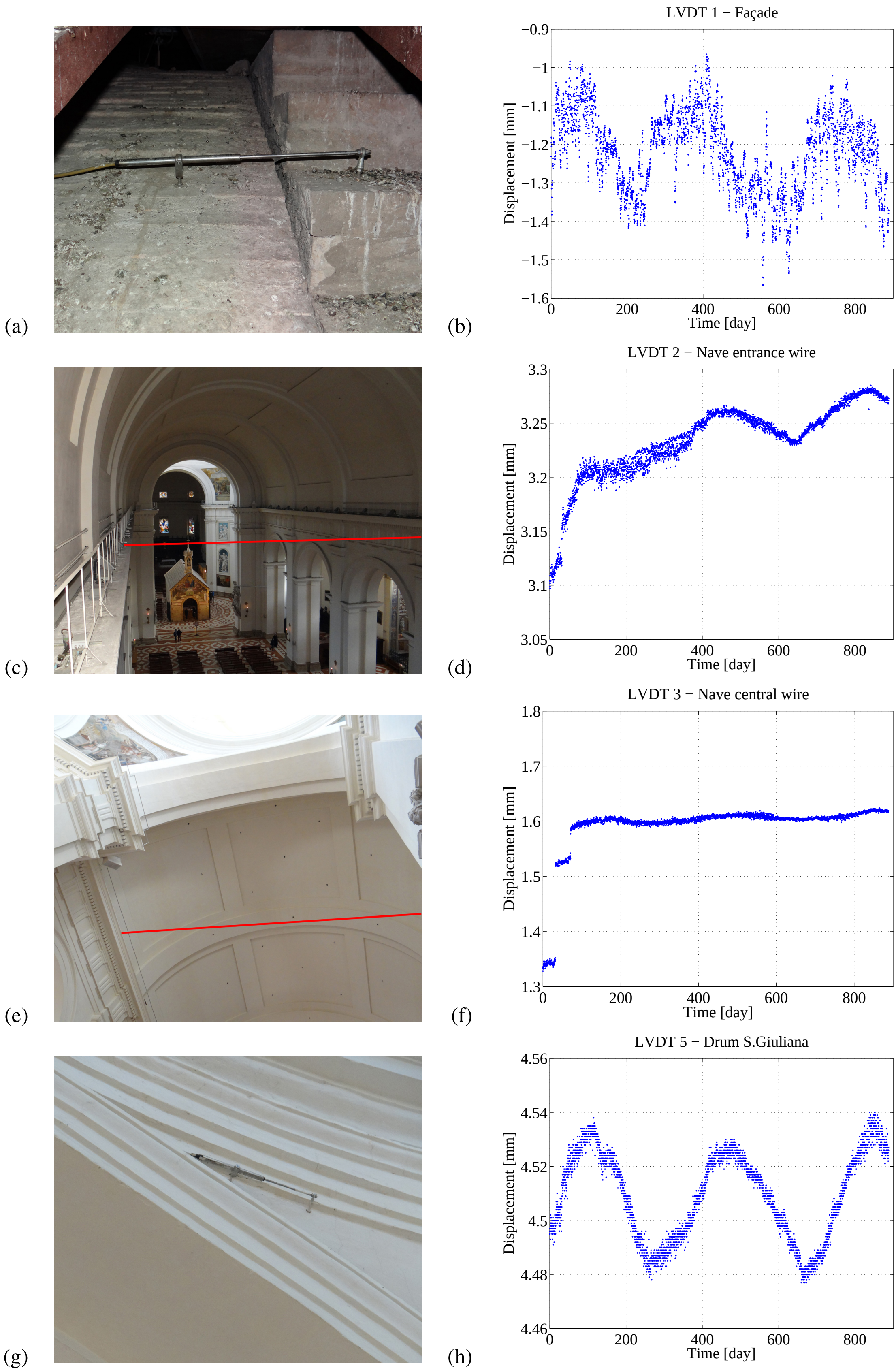

Figure 6: Images (a-c-e-g) and timeline (b-d-f-h) of the displacement transducers n. 1, 2, 3 and 5.

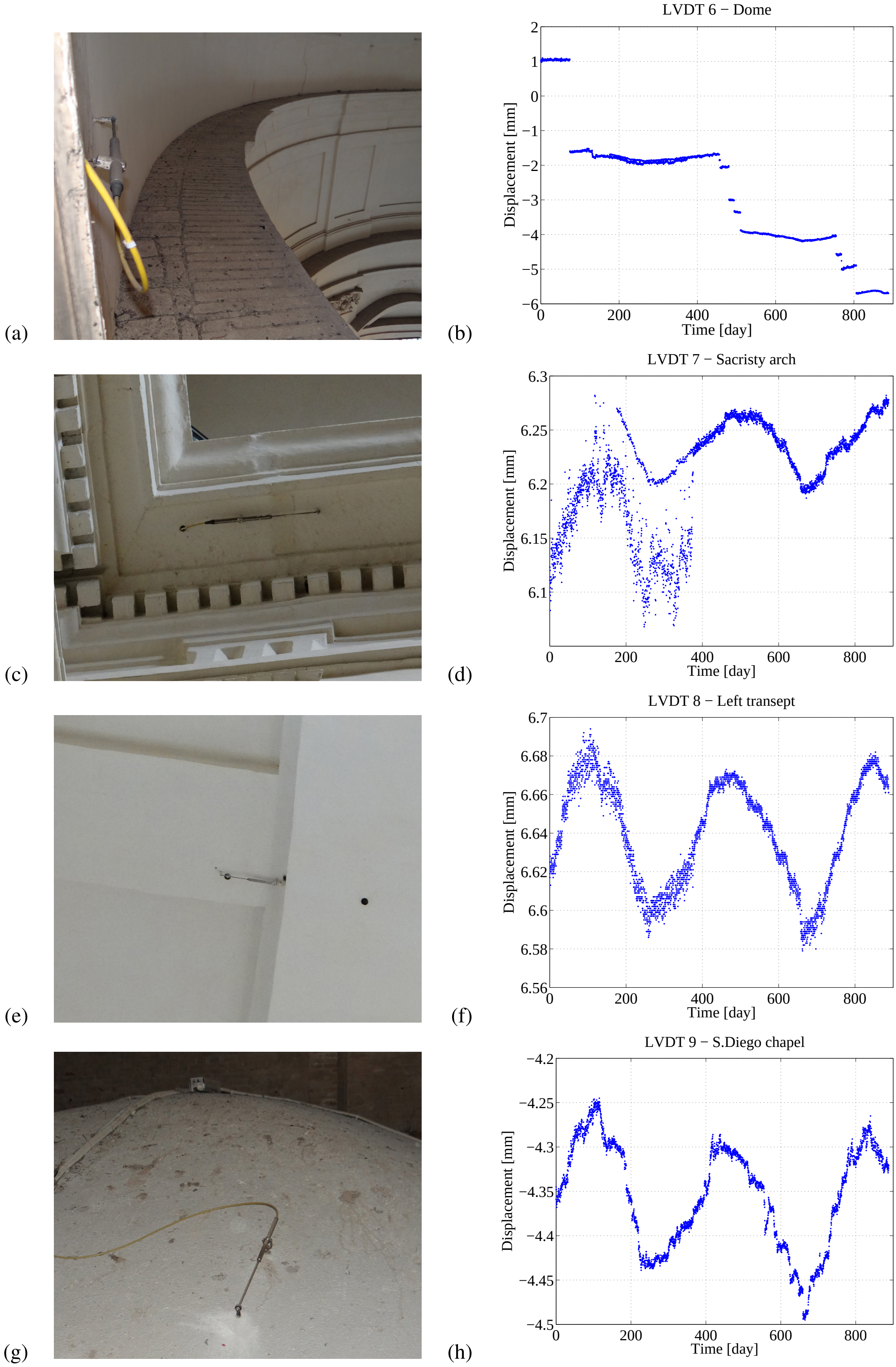

Figure 7: Images (a-c-e-g) and timeline (b-d-f-h) of the displacement transducers n. 6, 7, 8 and 9.

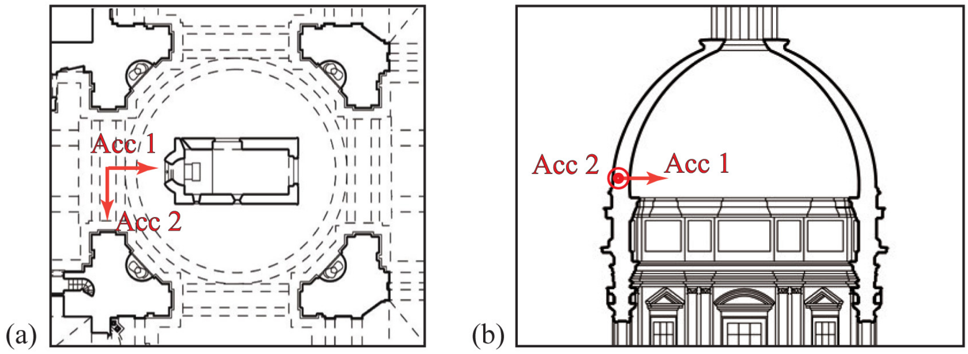

Figure 8: Instrumentation layout used in the ambient vibration tests.

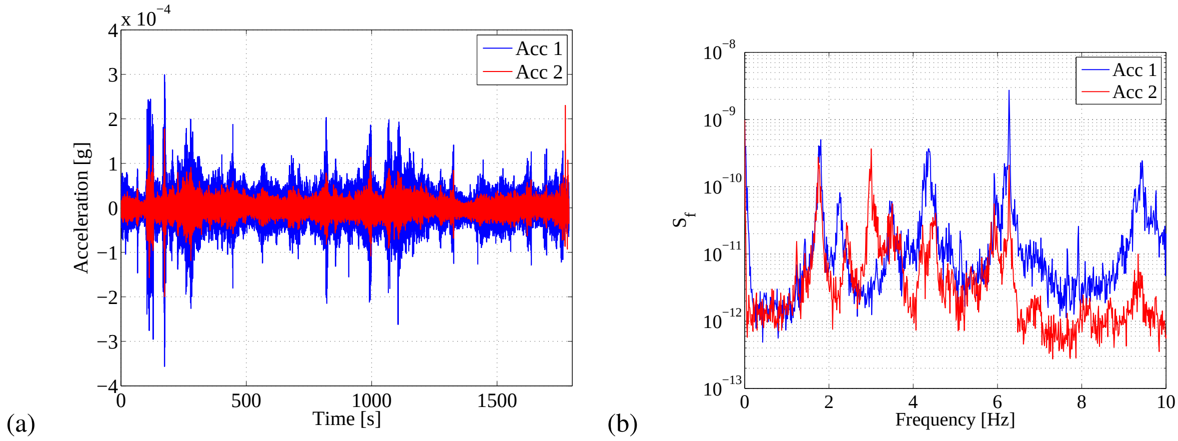

Figure 9: Output signals (a) and frequency analysis (b) of acceleration sensor recorded on February 18th under wind excitation.

related to the driven oscillations due to the bell-tower motion, which can be reached whenever the bells sound.

4.2 Numerical model

A numerical FE model has been performed by means of a commercial code. The model has been focused on the central core of the basilica, i.e. the triumphal arches, the drum and the dome. However, sketch models of the nave, the transepts and the apse have been introduced to attain a better modeling of the lateral restraints. Due to the lack of knowledge concerning the mechanical parameters of the materials, a probabilistic approach has been used in the estimation of the natural frequencies in function of the variability of the elastic moduli of the materials [7].

The constituent material is brickwork everywhere, excepting for the stone pillars of the nave. An homogeneous material with orthotropic elastic behaviour has been considered. The values of stiffness, and their lognormal distribution parameters, proposed by the recent Italian instructions [8] have been used (Tab. 1). A set of 1000 samples have been generated for both the Young's modulus (E) and shear modulus (G) of the brickwork (Fig. 10), and then multiplied by a coefficient α=1.5 which takes into account the good condition of the mortar.

Figure 11 shows the first seven modal shapes obtained by the eigenproblem solutions with the respective range and distribution of frequencies related to the variability of the elastic properties.

	ρ [ton/m^3]	μ_E [MPa]	$\sigma_{ln,E}$	μ_G [MPa]	$\sigma_{ln,G}$
Brickwork	1.8	1500	0.2	500	0.2
Stone masonry	2.2	2800	-	860	-

Table 1: Mechanical material properties: mass density (ρ); mean value ($|mu_E$) and standard deviation of the logarithm ($\sigma_{ln,E}$) for the elastic modulus; mean value (μ_G) and standard deviation of the logarithm ($\sigma_{ln,G}$) for the shear modulus

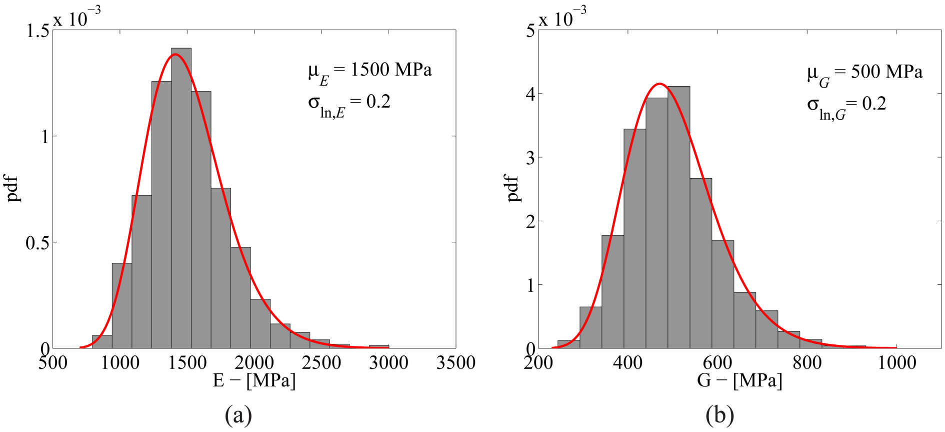

Figure 10: Generated values of Young's modulus (a) and shear modulus (b) from the statistical moments of the related distributions [7].

It can be observed a link with the resonant peak ranges reached by experimental tests (Fig. 9(b)). Further dynamic investigation will allow to identify the actual modal parameters of the structure and to obtain a tuned numerical model.

5 CONCLUSIONS

In this paper the first results obtained by the monitoring system placed in the Basilica of Santa Maria degli Angeli in Assisi have been presented.

A static monitoring system, consisting of 9 LVDTs, was installed during the rehabilitation works after the seismic events of 1997. The available data, recorded in the years 2001-2003, have been presented and discussed, even if more investigations are needed to give proper interpretation of them.

Moreover, some preliminary dynamic investigations have been performed by using two accelerometers installed at the base of the dome to detect the first modal frequencies. The spectral representation of the acceleration time histories has been compared with the modal analysis of a numerical FE model. The modal analysis has been applied to a series of FEM samples, by varying the mechanical characteristics of the constituent materials. The comparison between the experimental data and the numerical results is of interest to calibrate the FE model.

These results will be used to design a permanent dynamic monitoring system of the Basilica of Santa Maria degli Angeli in Assisi.

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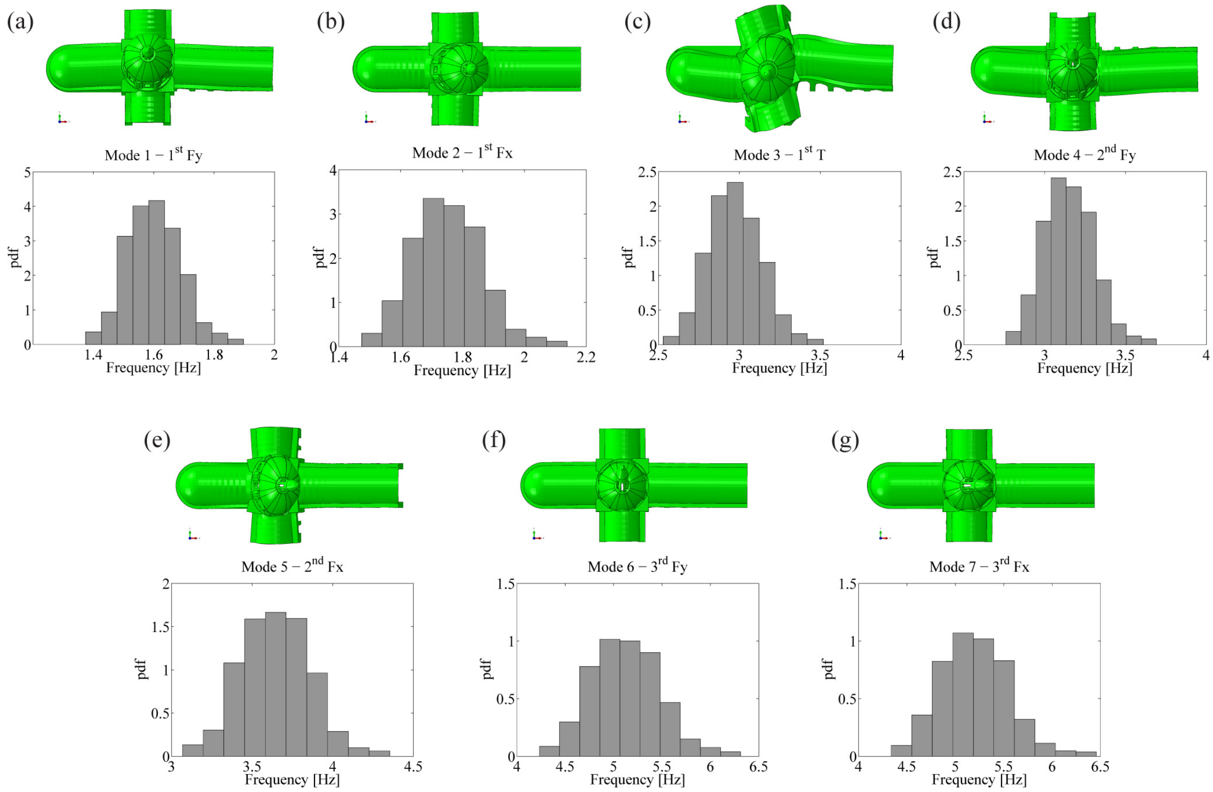

Figure 11: Modal shape and distribution of the related frequencies of the first seven modes derived by FE model by varying material stiffness.

protection of the Cultural Heritage: the bell-tower of the Basilica of San Pietro in Perugia and the dome of the Basilica of Santa Maria degli Angeli in Assisi" (Project Code 2014.0266.021).

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