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DYNAMIC MONITORING AND NONLINEAR ANALYSIS OF THE DOME OF THE BASILICA OF S.MARIA DEGLI ANGELI IN ASSISI

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Abstract. *During the last years, the application of Structural Health Monitoring (SHM) systems to heritage constructions has received a great interest due to the low invasiveness and low-cost of the necessary equipment. When applied to monumental structures and, more in general, to cultural heritage ones, such SHM systems represent an effective solution for preventive conservation against both material degradation and damages derived by natural hazards, such as earthquakes. Among the various technical solutions currently available for SHM, vibration-based systems deserve a special attention, but their application in the context of historical constructions is still quite rare and challenging, with very few documented applications, mostly limiting to masonry towers and bell-towers for their slenderness properties.*

In this work, the first months of continuous vibration monitoring of the dome of the Basilica of Santa Maria degli Angeli in Assisi are presented. At first, a dynamic identification has been carried out using five high-sensitivity accelerometers, three of them installed at the base of the drum and two at the base of the dome. Then, a fully automated identification technique has been used to extract time series of natural frequencies during the monitoring period. Moreover, some statistical tools have been applied in order to select the best configuration, in terms of number and position of sensors, necessary to obtain a continuous frequency tracking of the first natural modes in view of the use of this information for rapid post-earthquake structural assessment.

Moreover, a preliminary investigation about the seismic assessment has been carried by means of a Finite Element (FE) nonlinear dynamic analysis. The damage map obtained by the numerical simulation has been compared with the actual crack scenario present on the structure, giving further information about the structural dynamic response.

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1 INTRODUCTION

In the last decades the structural monitoring of constructions has received great interest from both scientific community and professional engineers, with special attention to the identification of damage scenarios occurred after seismic events. Within this framework, the dynamic monitoring of architectural heritage can be still considered as a challenge, due to the complexity of the structures and of their behaviour [1, 2, 3, 4]. In particular, vibration-based SHM techniques applied to historical constructions are giving interesting results in terms of damage detection especially after earthquakes of even small intensity [5, 6, 7, 8, 9].

The seismic events that stroke the centre of Italy during the second half of 2016 have affected a large part of the national area, in which several monuments and historical constructions of relevant interest are placed. Even if the distance from the epicentre of a strong motion determine a significant reduction of the energy and the accelerations of the ground motions, continuous input of small and medium intensity could cause cumulative damage scenario on a structure that are not always directly visible by a fast visual inspection.

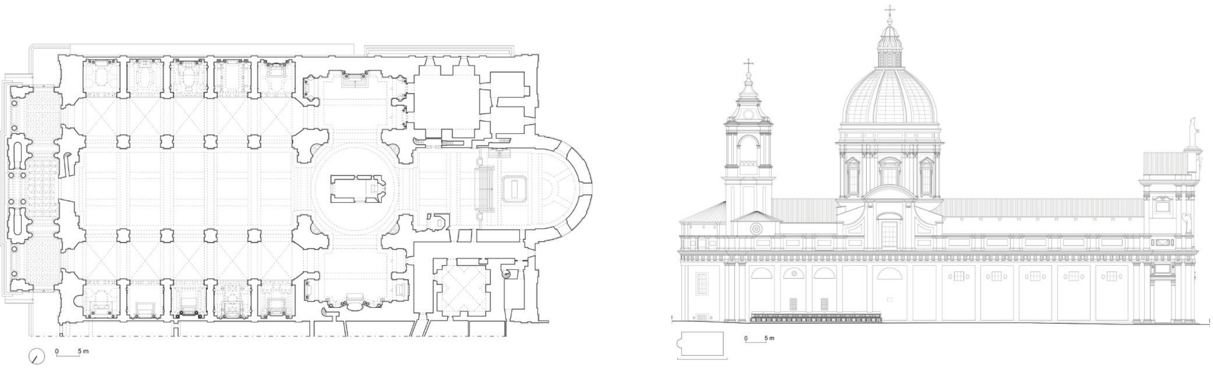
In this work, the dynamic response of the dome of the Basilica of Santa Maria degli Angeli in Assisi is presented. The slenderness of the drum-dome system gives to the structure particular features making it a quite interesting case of study and research. At first, a dynamic identification has been carried out using five high-sensitivity accelerometers, three of them installed at the base of the drum and two at the base of the dome. Then, a fully automated identification technique has been used to extract time series of natural frequencies during several months of monitoring period. A numerical FE model has been tuned on the natural frequencies and related mode shapes extracted by the experimental data. On the base of the tuned numerical model, nonlinear dynamic analyses have been performed by applying a seismic input recorded by a near station belong to the accelerometric national network and the numerical response, in order to assess the damage scenario observed on the structure. The reliability of the results have allowed to carry out vulnerability investigations in order to identify critical situations.

2 THE BASILICA OF SANTA MARIA DEGLI ANGELI IN ASSISI

The Basilica of Santa Maria degli Angeli in Assisi, built between the 16th and the 17th centuries, consists of a latin cross plan, with 126m and 65m dimensions, with a nave, two aisles and a semicircular apse. The Basilica contains the Porziuncola, a little ancient chapel representing a symbol of Franciscan spirituality and an important pilgrims destination. This chapel is located at the intersection between the transept and nave. Figures 1(a) and 1(b) show the plan and the lateral perspective drawings of the Basilica [10].

A great importance is given to the basilica from the inner presence of the Porziuncola, a little ancient chapel placed in the central part of the structure under the dome. The presence of the Porziuncola inside the basilica has always attracted thousands of pilgrims every year from all over the world. For this reason, the need of providing a well visible sign for pilgrims has induced the architect to design an uncommonly high drum-dome system. The dome is characterized by a single shell with a inner diameter of approximately 20m and a variable thickness of the unique shell from 1.80 m at the bottom up to 0.90 m at the top. The inner perimeter of the drum is circular, while the outer one is octagonal; the coupled pilasters at the angles of the octagon become stiffening ribs over the dome's extrados, joining at the oculus, the base of the lantern, that gives to the architectural complex an overall height of approximately 75 m.

The singular slenderness of the drum-dome system appears more evident if compared with the roles of constructions reported in the architectural treatises of the 17th and 18th centuries,



(a) (b)

Figure 1: Basilica of Santa Maria degli Angeli in Assisi: (a) plan; (b) lateral perspective.

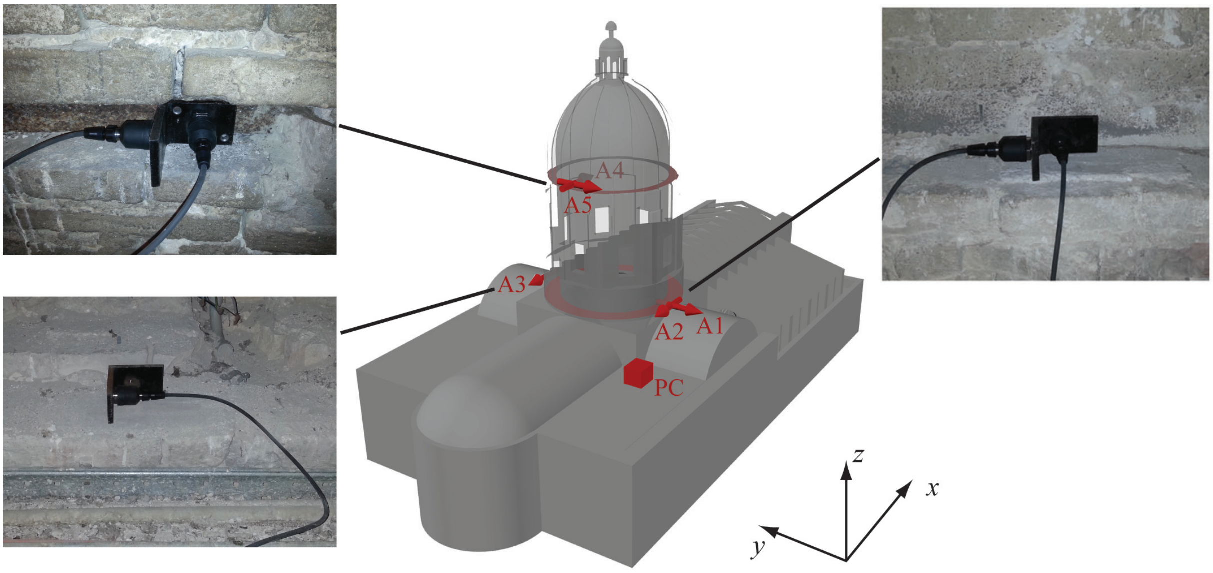


Figure 2: Dynamic monitoring system installed on the drum-dome system of the basilica.

e.g. the treatise of Carlo Fontana [11, 12]. A close comparison between the section of the case of study and the drawings of the architectural treatise highlights that the drum is high almost twice than the roles proposed by Fontana, conferring to the structure a really unusual slenderness and unique architectural feature. This significant slenderness motivated the authors towards the implementation of a vibration-based monitoring system for the dome.

3 DYNAMIC MONITORING SYSTEM AND DATA PROCESSING

3.1 Dynamic investigations

The dynamic monitoring system consists of five high-sensitivity (10V/g) uni-axial accelerometers installed at the base of the drum and at the base of the dome, as illustrated in Figure 2 [13]. In particular, the sensors A1, A2 and A3 have been placed on the easily accessible external side of the drum base, while the sensors A4 and A5 in the highest accessible location inside the dome structure, at the top of the drum, in the space of the internal staircases (Figure 2).

The vibration data have been continuously recorded in operational condition by using a multi-channel system (carrier model cDAQ-9188 with NI 9234 data acquisition modules, 24-

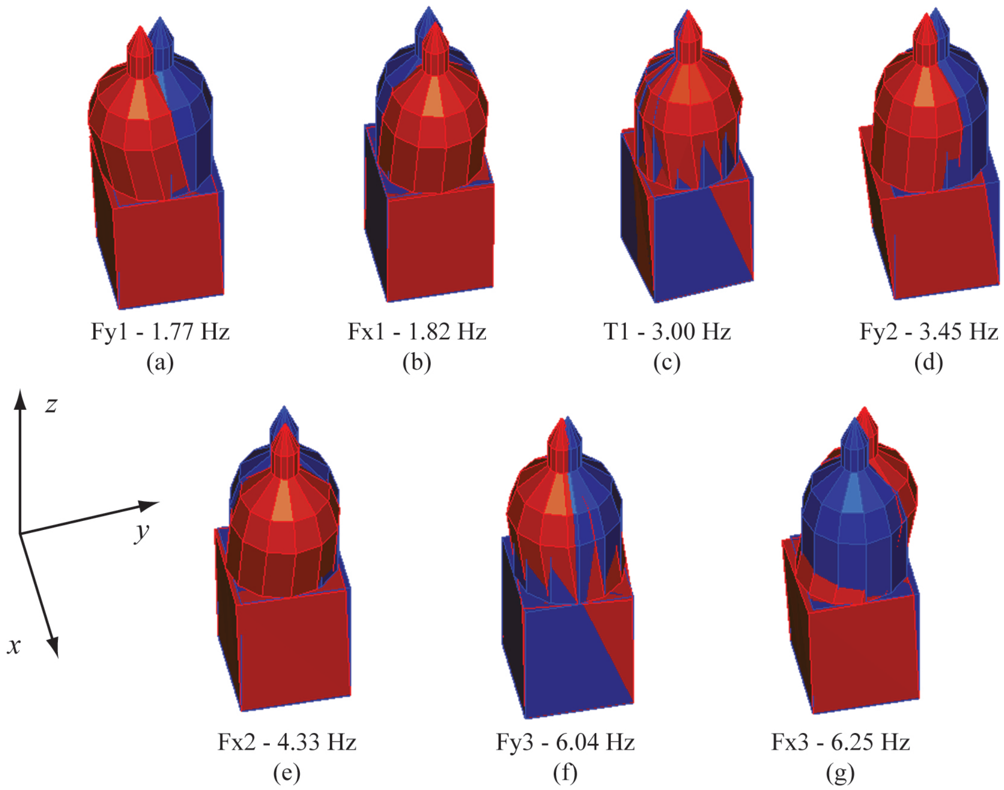


Figure 3: Representation of the identified mode shapes.

bit resolution, 102 dB dynamic range and anti-aliasing filters), with a sample rate of 100 Hz and stored in 30-minutes long time histories, representing the data sets. The monitoring system has started since October 16th of 2015 up to the end of May 2016. The operational conditions of the structure are mainly characterized by wind and traffic actions and, periodically, by the vibrations induced by the swinging bells of the adjacent bell-tower.

By analysing a data-set corresponding to a particular wind storm action (October 23th 2015, 03:00-03:30) a preliminary dynamic identification of the structure has been carried out by means of the Frequency Domain Decomposition technique, from which seven modes have been extracted (Figure 3). In particular the first two are flexural in y (Fy1) and x (Fx1) directions respectively, i.e. across and along the nave direction, the third is torsional (T1) and the others are flexural alternatively in y and x direction of second (Fy2, Fx2) and third order (Fy3, Fx3).

3.2 Automated frequency tracking

The dynamic monitoring system has been installed on the structure with the purpose of investigating the evolution in time of the natural frequencies of the structure in order to have an effective system to use for early damage detection. Owing to technical problems the system stopped on May 2016. Modal parameters of the drum-dome system have been continuously extracted from the acquired data by using a fully automated Stochastic Subspace Identification (SSI) technique [14]. Among the seven modes previously identified, the fourth, the sixth and the seventh mode cannot be consistently identified, due to the low level of vibration.

A first contribution given in this paper is to compare the frequency tracking obtained by using all the five sensors installed on the structure (see Figure 2) and a reduced number of sensors, in

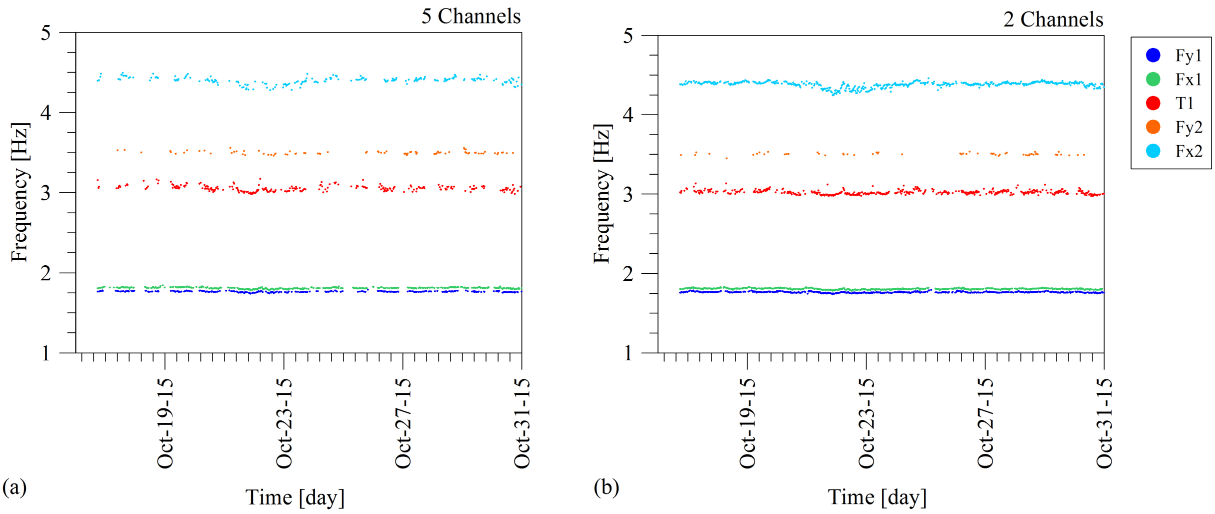


Figure 4: Time histories of the first five natural frequencies of the drum-dome system identified using five (a) and two (b) accelerometers, having A1-A2-A3-A4-A5 and A4-A5 layout respectively, with reference to Figure 2.

order to install a permanent system constituted by a small number of accelerometers. The comparison has been made by using only the accelerometers A4 and A5 as the alternative sensors layout. In Figure 4 the time histories of the first five frequencies obtained by the application of the SSI techniques with the complete layout of sensors (Figure 4(a)) and the reduced one (Figure 4(b)) are compared. The plot is limited to the first days of acquisition, in order to give a more clear visualization.

In Figure 4 is evident as the low level of vibration of the drum base (related to the sensors A1, A2, and A3) does not allow to obtain a consistent identification also for the first modes. However, a statistical comparison between the data identified in the two sensor layouts have been made in terms of mean and standard deviation of the time histories, for each natural frequency. Figure 5 summarizes the comparison for the first three modes, from which it should be noted that a vibration-based dynamic monitoring can be effectively carried out by using a small number of sensors even for historical constructions generally unusual for such applications.

4 NUMERICAL ANALYSIS

4.1 FE modelling

The numerical model, elaborated by means of a Finite Element commercial code, comprises both hexahedral and tetrahedral finite elements, necessary for the modelling of some irregular structural geometries. More in detail, a structured mesh has been used in the pillars, some regions of the drum and the dome, and a free mesh in the remain parts. Particular attention has been devoted to the modelling of the internal staircases of the drum, which play a fundamental rule in the results of the nonlinear analysis for the localization of damage regions. The near structural elements, such as the nave, the apse and the lateral transepts have been modelled only to confer a consistent lateral stiffness to the central part. A sketch of the numerical model and a detail of the internal staircases of the drum are shown in Figures 6(c) and 6(b) respectively.

Four main different regions can be identified in the model of the drum-dome system: the pillars, the triumphal arches and the drum-dome structure. The choice of these regions is related to the tuning operations for the correlation between the experimental and numerical modal characteristics. Homogeneous isotropic material have been used in all the parts of the model.

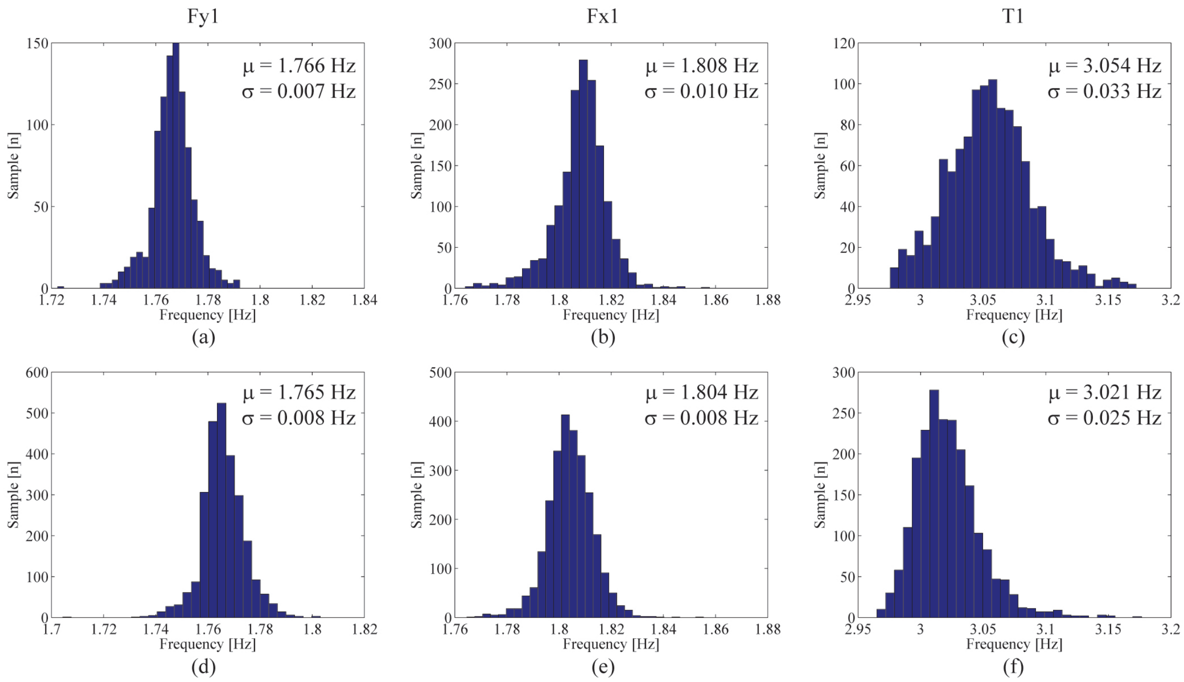


Figure 5: Statistical distributions of the first three natural frequencies (Fy1, Fx1 and T1) identified by using five sensors (a-c) and only two sensors (d-f).

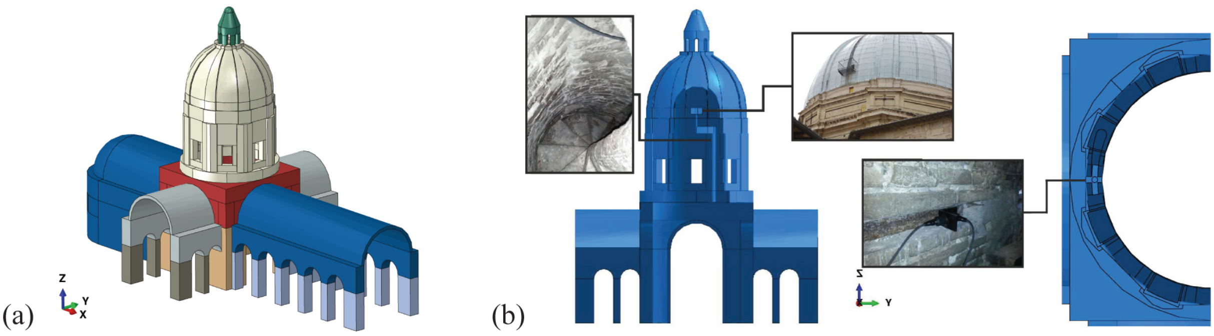


Figure 6: (a) Sketch of the 3D model. (b) Details of the drum internal staircases model.

Considering that all the structure has been mainly constructed by using brick masonry in a quite good condition, as a first attempt, the elastic parameters have been taken in the range proposed by the Italian code for brickwork [15], in exception of the pillars, which are made by stone masonry. In addition, the corrective multiplicative coefficients suggested by the standard in the case of good conditions of mortar have been considered for brickwork material ($\gamma_b = 1.5$), while the case of thin thickness of mortar joints ($\gamma_s = 1.2$) for stone masonry. By varying the mechanical parameters of the materials, a modal sensitivity analysis has been carried out to perform a model updating. By a few steps of manual tuning, a consistent numerical model has been obtained. Tables 1 and 2 summarize the results of the model updating process regarding the elastic properties of the materials and the frequencies derived by the modal analysis. Figure 7 shows the modal shape of the first five modes obtained by the numerical model.

Structural part	Young's modulus [MPa]		Poisson's ratio [-]		Weight [kN/m^3]	
	before tuning	after tuning	before tuning	after tuning	before tuning	after tuning
Drum-dome	2700	1400	0.15	0.30	18	20
Triumphal arch	2700	1400	0.15	0.30	18	20
Pillars	3850	4000	0.15	0.15	22	23

Table 1: Elastic parameters of the isotropic constitutive model before and after model tuning.

Mode	f^{exp}	f^{FEM}	$\Delta f\%$
Fy1	1.763	1.767	0.198
Fx1	1.811	1.883	3.968
T1	3.056	3.134	2.555
Fy2	3.498	3.644	4.187
Fx2	4.407	4.486	1.794
Fy3	5.903	5.624	4.732
Fx3	6.039	6.057	0.299
		$\Delta\bar{f}\%$	2.534

Table 2: Comparison between experimental and numerical structural frequencies after tuning.

4.2 Nonlinear numerical analysis

A consistent FE model allows to perform predictive analyses of the structural response both to assess possible damage scenarios already present on a structure and to predict critical situations related to the occurrence of particular damage conditions. In the following the results of a first dynamic investigation regarding the nonlinear response of the structure is presented. It should be noted that both the drum and the dome are characterized by a complex damage pattern due to several earthquakes occurred during the last centuries. The most important seismic event is dated back to 1832, which caused the collapse of the central nave. No specific interventions have been made on the structural masonry of drum-dome system other than an overall confinement of the drum through three orders of iron tension rings, after the event of 1832. Also the recent seismic sequence occurred in the central Italy in the second half of 2016 did not cause new relevant damage pattern.

The main purpose of the following study is to achieve a consistent interpretation of the state of damage, by means of a nonlinear dynamic analysis. The earthquake of Umbria-Marche of 1997, occurred on September 26th at 9:40 UTC, has been used as seismic input, due to the fact that a near seismic station has recorded the local ground motion (Figure 8). A concrete damage plasticity (CDP) model has been used in the numerical analysis to reproduce the behaviour of the masonry material beyond the elastic field, considering damage effects in both tension and compression. The CDP model consists of a modification of the shape of the yield surface of the well-known Drucker-Prager criterion by means of specific parameters and allows to describe the behaviour of quasi-brittle materials, such as concrete, rock and masonry. The damage parameters are locally defined as mainly functions of the equivalent plastic strain, with different behaviour in tension from compression.

Figures 9 and 10 show a comparison between the localization of damage obtained by the numerical simulations and a cracks survey made on the structure by using photo images on the eight internal sides of the drum and the above dome slice. The results highlights that the complex damage scenario is mainly due to dynamic actions, being the most damaged zones concentrated in the walls parallel to the y direction, i.e. the direction of the first natural mode and

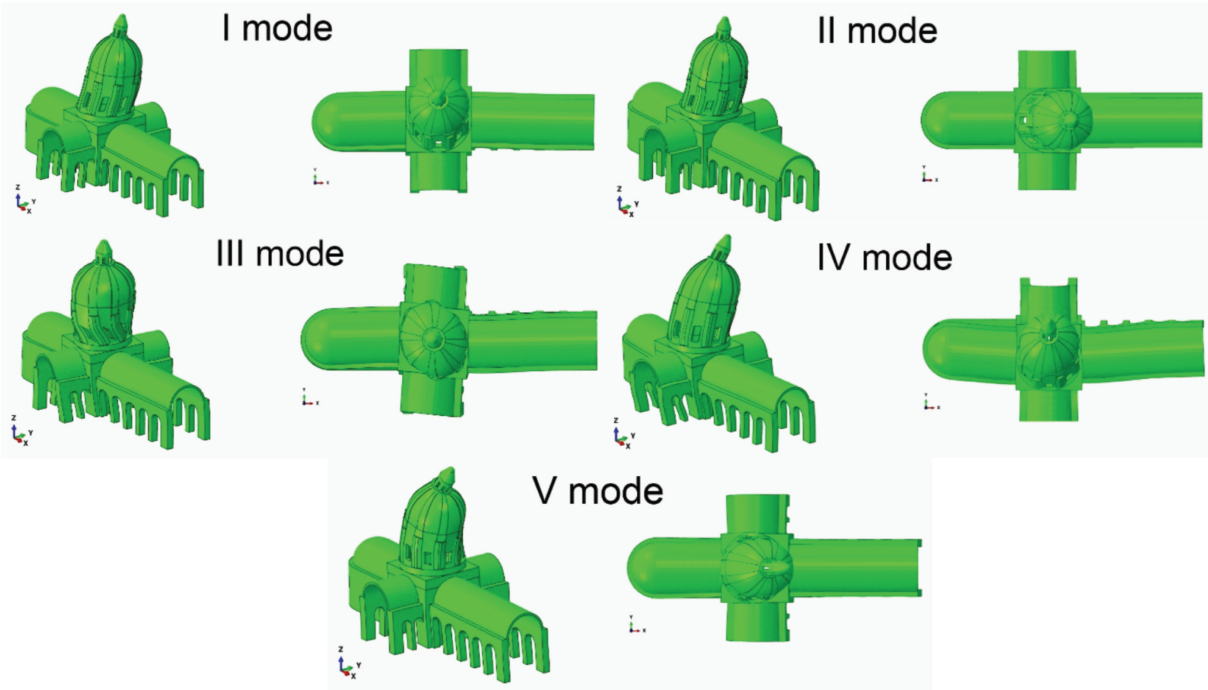


Figure 7: Mode shapes of the first five modes obtained by the numerical model.

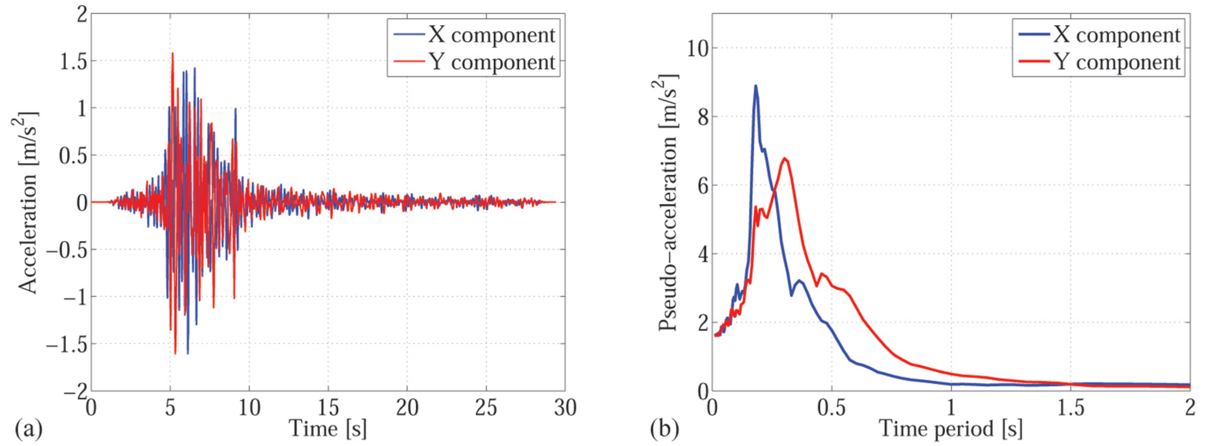


Figure 8: Umbria-Marche earthquake of 1997 (September 26th at 9:40 UTC) recorded by the Assisi station. (a) Acceleration time histories in x and y directions. (b) Pseudo-acceleration spectra of the acceleration signals.

then the most stressed. The numerical results are in a good agreement with the actual scenario while further investigations are needed to analyse the level of damage in order to predict critical situations.

5 CONCLUSIONS

In this paper a dynamic investigation of a historical masonry dome have been carried out, with the purpose of the definition of a right sensor layout constituted by a small number of accelerometers. Seven month of continuous dynamic monitoring have been performed using five high-sensitivity accelerometers installed a the base of the drum and at the base of the dome. A detailed dynamic identification has allowed to estimate the modal parameters of the structures and, by means of a fully automated dynamic identification procedure based on the SSI tech-

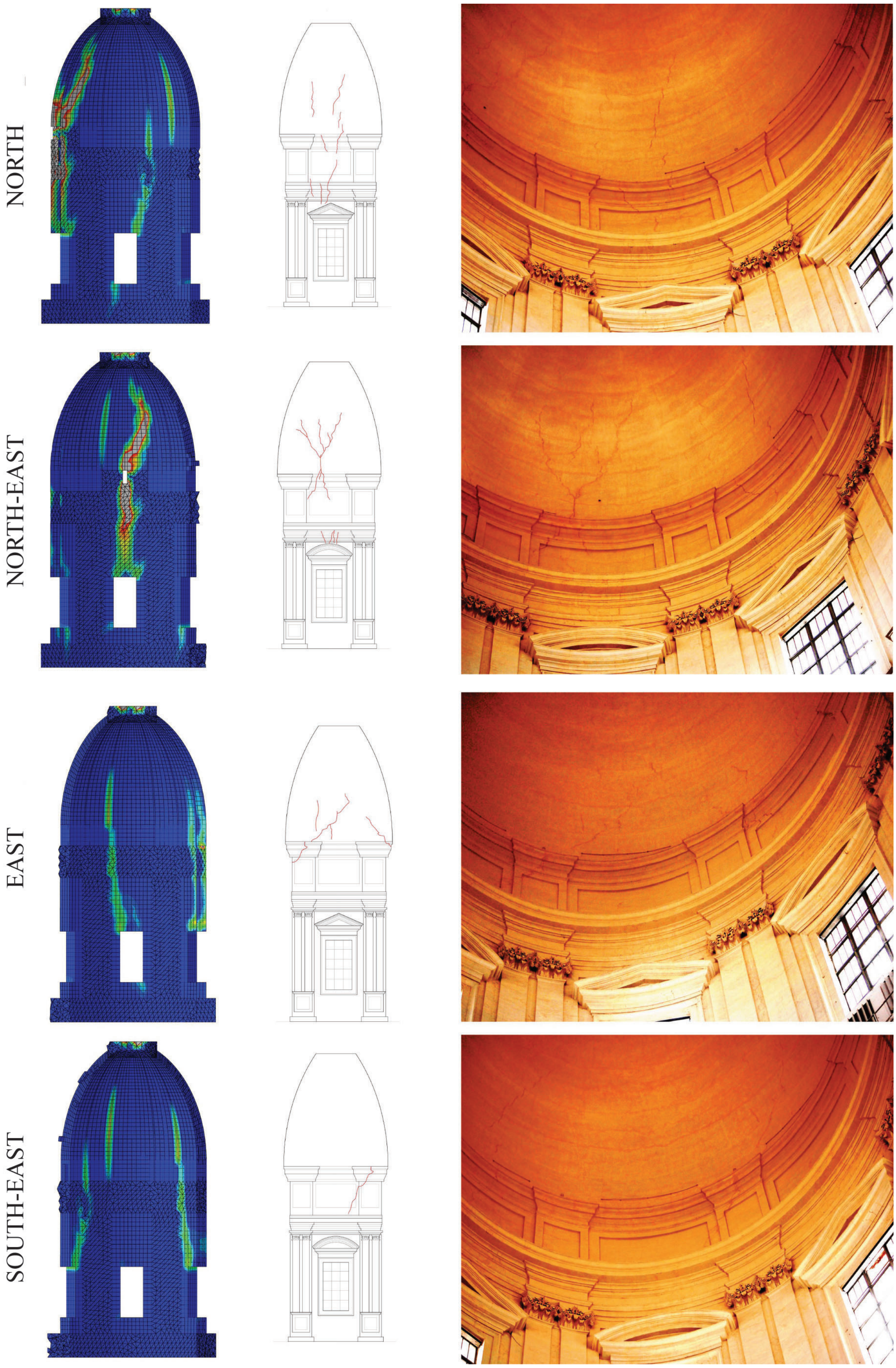


Figure 9: Maps of the damage parameter obtained by FE nonlinear dynamic analysis after the application of the Umbria-Marche earthquake (1997 September 26th) compared with the actual damage state in the North, North-East, East and South-East sides.

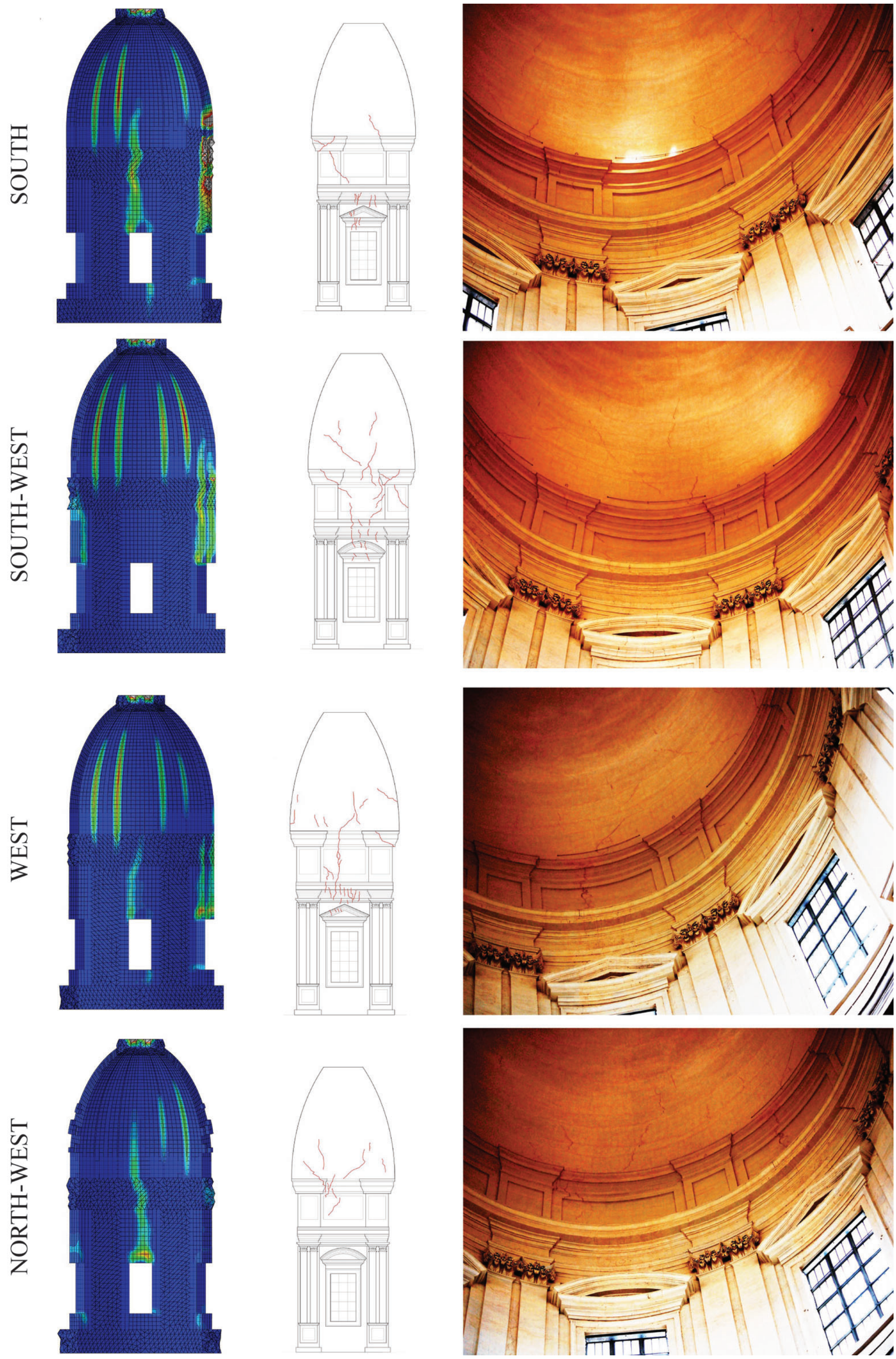


Figure 10: Maps of the damage parameter obtained by FE nonlinear dynamic analysis after the application of the Umbria-Marche earthquake (1997 September 26th) compared with the actual damage state in the South, South-West, West and North-West sides.

nique, the time histories of the first five natural frequencies of the structure have been traced. The frequency tracking has been made by using both all the sensors and only the two sensors placed in the highest part, at the base of the dome. The statistical analysis of the samples obtained during the first months of dynamic monitoring have highlighted that using even a small number of sensors it is possible to consistently identified the first natural modes.

Moreover, a FE numerical model has been constructed and tuned on the identified natural frequencies and a nonlinear dynamic analysis has been carried out using as seismic input the data recorded in a near station during the Umbria-Marche earthquake of 1997. The damaged zone obtained by the numerical analysis has confirmed that the complex crack pattern observed in the dome can be mainly associated to seismic actions. Further investigation are needed in order to perform the damage assessment and to predict critical scenario by numerical simulations.

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