Safety assessment of the Sanctuary of Vicoforte, Italy

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Abstract: In order to evaluate safety assessment of the Sanctuary of Vicoforte, Italy, a series of non-destructive tests were carried out for diagnostic inspection of its deterioration. Delamination of stone finishing and fresco painting were detected. Dynamic ambient vibration test was carried out and the relevant modes of vibration were identified resorting to the stochastic subspace identification method. The first two natural frequencies of the Sanctuary of Vicoforte were estimated to be about 1.93 Hz and 2.07 Hz in East-West and North-South directions, respectively. Therefore, the dome seems to be vulnerable to severe earthquakes characteristic of the local seismicity such as we experienced in recent years.

Keywords: Sanctuary of Vicoforte; elliptical masonry dome; diagnostic inspection; deterioration; brick; material tests; compressive strength; Young's modulus; dynamic ambient vibration test; stochastic subspace identification; natural frequency; mode shape; safety assessment; Italy; non-destructive test.

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1 Introduction

The elliptical masonry dome of the Sanctuary of Vicoforte located near Mondovì in Northwest Italy was built in 1731 as religious monument. It became one of the most important buildings representing the period, city, style, and culture (Figure 1). The major and minor axes of the dome are 37.15 m and 24.80 m respectively and it is the largest of its kind. The height of the sanctuary is about 84 m. Unfortunately, however, the stability of the sanctuary is now threatened by progressive fractures due to aging and chemical degradation of materials, the static and dynamic effects by dead loads and ambient actions, differential settlement of foundations and so on. The higher the historic value of structures is the more prohibitive core extraction and other partially destructive tests become. Therefore, for the maintenance and repair of the sanctuary, non-destructive static and dynamic tests became the only way to get a reliable material characterisation and the evaluation of the actual structural behaviour.

Figure 1 The Sanctuary of Vicoforte, (a) external view (b) internal view (see online version for colours)

(a) (b)

The project relating to monitoring, rehabilitation and structural strengthening was started in 1976 (Pizzetti and Fea, 1988; Chiorino et al., 1993). Then the five-year research project named 'Vicoforte 2002–2006' started in January 2002, aiming to control the structural stability of the monument and to establish the correct criteria for its future maintenance and restoration. Based on the experience acquired in the experimental investigation of Hagia Sophia in Istanbul, Turkey (Aoki et al., 1992, 1997, 2000), in order to contribute to this research project six objectives have been set as follows:

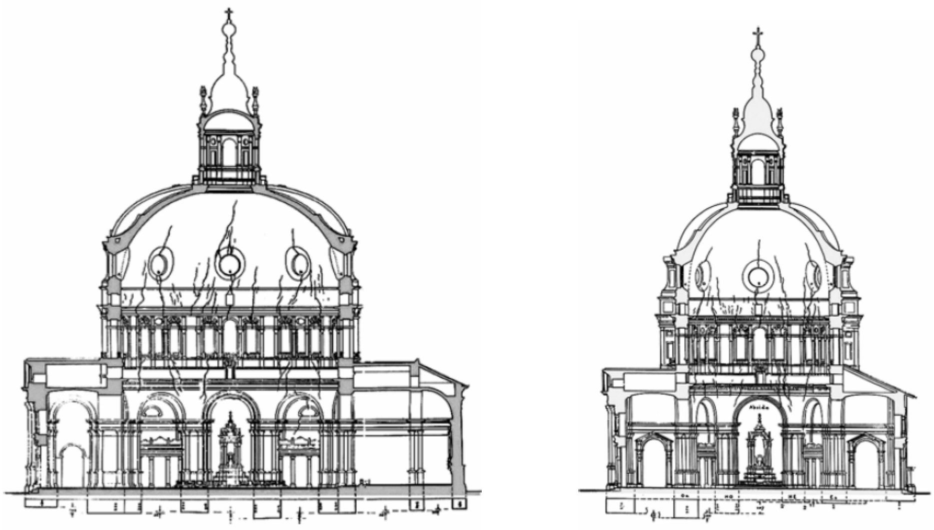
1. diagnostic inspection of deterioration by means of non-destructive tests (Aoki et al., 2004a)
2. investigation of the mechanical continuity of the three sets of annular iron ties embedded at the base of the main dome by architect Francesco Gallo in 1734
3. estimation of compressive strength and Young's modulus of the brick and the mortar (Aoki et al., 2004a)
4. identification of fundamental frequencies and mode shapes by ambient vibrations
5. interpretation of the static and dynamic behaviours of the dome and of the monuments by means of finite element three-dimensional elastic-plastic analyses and also considering the information about the soil foundations layers (Aoki et al., 2003, 2004b; Chiorino et al., 2008)
6. proposals for structural conservation and restoration.

In this paper, the results obtained from the above objectives one to four are discussed from a view point of its safety assessment.

2 The Sanctuary of Vicoforte

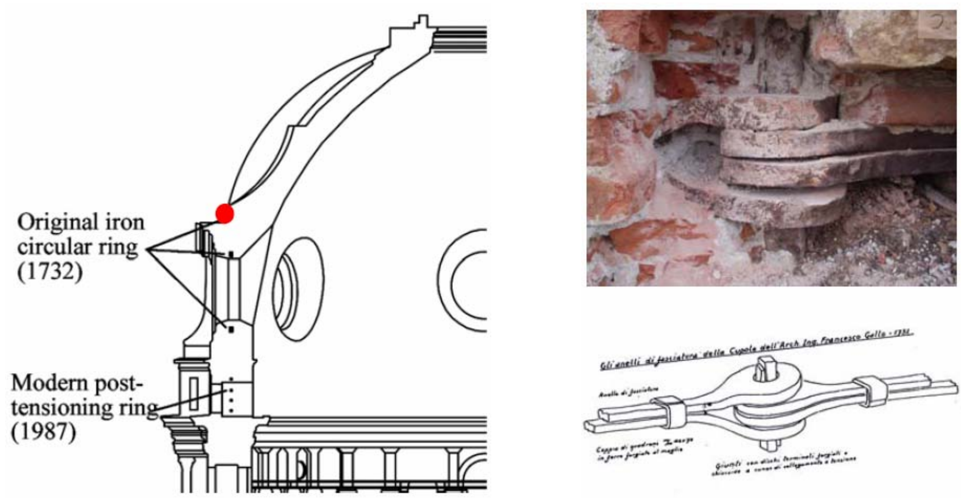
Carlo Emanuele I of Savoia (1562–1630) gave the order to build a sanctuary to Ascanio Vitozzi (1539–1615). The construction was started in 1596 and it should have become the official mausoleum of the dynasty. Due to an inadequate choice of the site, 1/3rd on consistent marl in the north-east side and the remaining 2/3rd on compressible clay-silt layers of variable thickness up to 3.5 m, large differential settlements took place. The construction at an elevation of 10 m height was abandoned at the end of 16th century. However, the drainage works in the clay layers continued during the first part of 17th century.

Figure 2 Crack pattern in the dome and the drum, (a) West side (b) North side



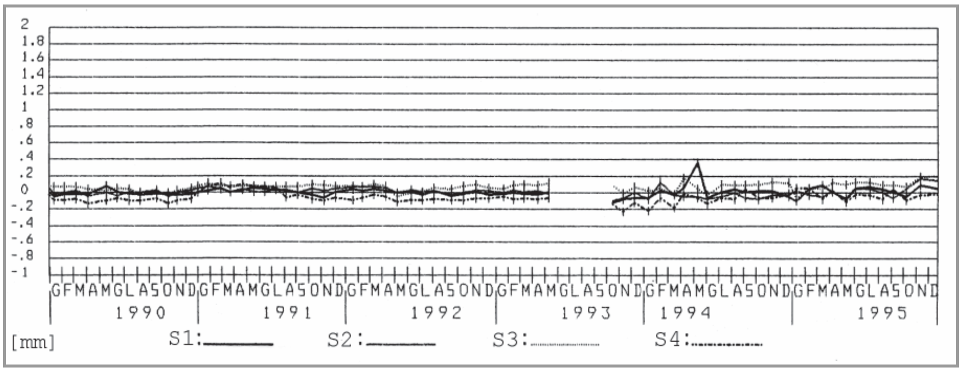
(a) (b)

Figure 3 Original iron circular ring and modern post-tensioning ring strengthening system, (a) position of tension ring (b) joint of original ring (see online version for colours)

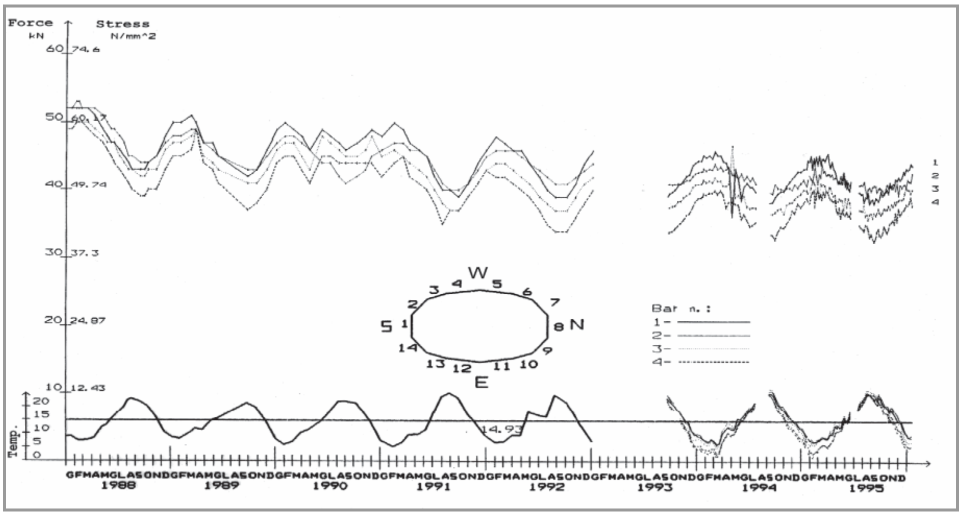


(a) (b)

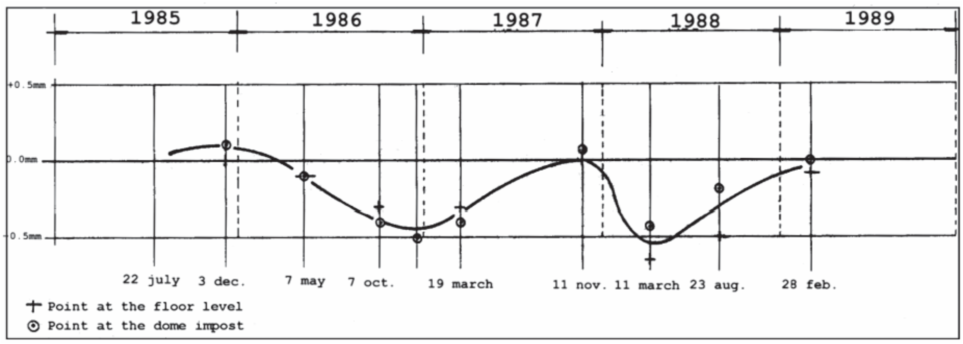
Figure 4 Monitoring system data charts, (a) crack width variations (b) pulling force applied by circulate bars (c) height variation over time of two points at floor level and at the impost of the dome



(a)



(b)



(c)

Source: Chiorino et al. (2008)

The construction started again in 1701 after compensation of settlements at the base of the drum under the guidance of architect Francesco Gallo (1672–1750) who realised the baroque dome. Differential settlements developed again due to the weight of the complete structure and cracking of the dome and the drum started developing and progressively increased (Figure 2). In 1985 to 1987, a strengthening of the dome was realised consisting of 14 groups of post-tensioned tangential ties. Each group made up of four superimposed Dywidag 32 mm bars of high-strength steel (Figure 3). The force in the tie-bars may be regulated at any time by jacks and the stress is constantly monitored by load cells. No substantial increases in the crack widths were observed afterwards (Figure 4).

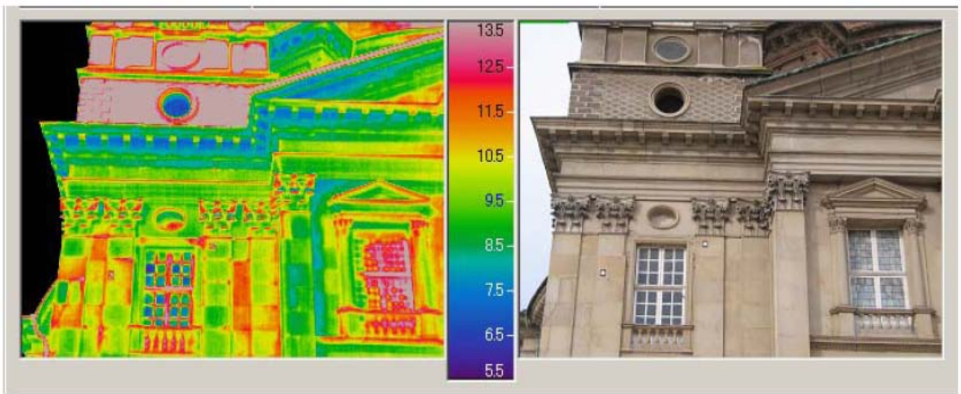
3 Safety assessment of the sanctuary by non-destructive static tests

3.1 Non-destructive inspection of cracks and delamination of stone finishing and fresco painting by using infrared thermography

Deterioration of the stone finishing and fresco painting such as cracks and delaminations were detected by infrared thermography. Delaminations of stone finishing at façade are seen in Figure 5. The state of delamination of stone finishing is very dangerous. One year later of this investigation, some peaces of stone finishing were fallen down and a repair work was continued during the following years.

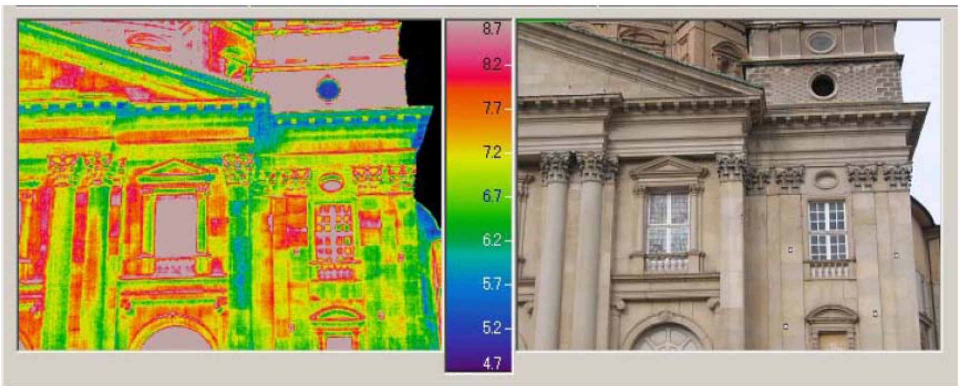
The active hearting infrared thermography method was applied for the detection of delamination and/or water leakage of fresco painting. Figure 6(a) shows delamination of fresco painting in the northwest chapel. Delaminations of fresco painting of the main dome at both north and west sides are shown in Figures 6(a) to 6(e).

Figure 5 Delamination of stone finishing at façade, (a) infrared image (b) visual image (c) infrared image (d) visual image (e) integrated infrared and visual images (see online version for colours)

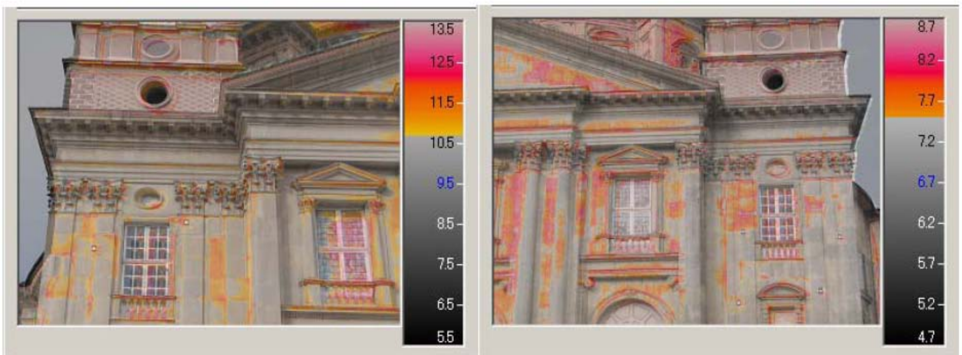


(a) (b)

Figure 5 Delamination of stone finishing at façade, (a) infrared image (b) visual image (c) infrared image (d) visual image (e) integrated infrared and visual images (continued) (see online version for colours)

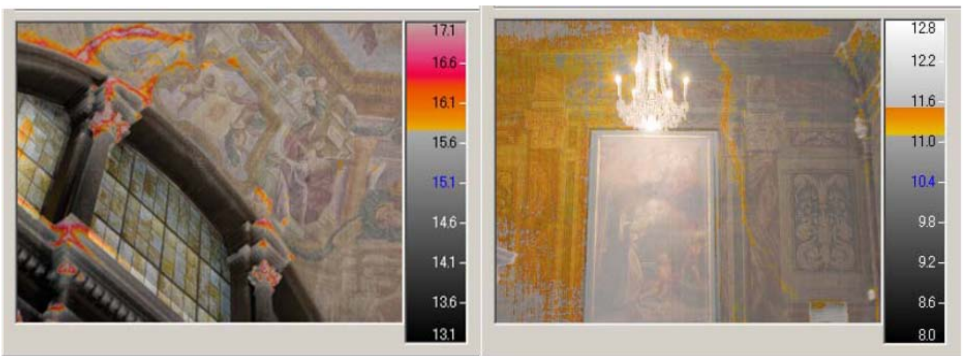


(c) (d)



(e)

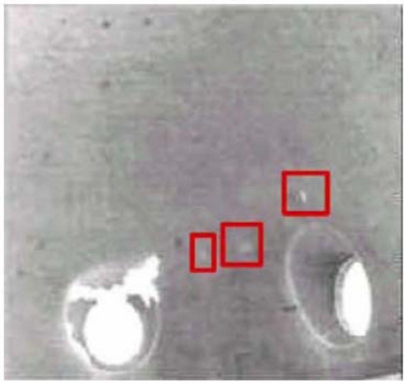
Figure 6 Delamination of fresco painting in the chapel and the main dome, (a) integrated infrared and visual images in the chapel (b) visual image at north side (c) infrared image at north side (d) visual image at west side (e) infrared image at west side (see online version for colours)



(a)

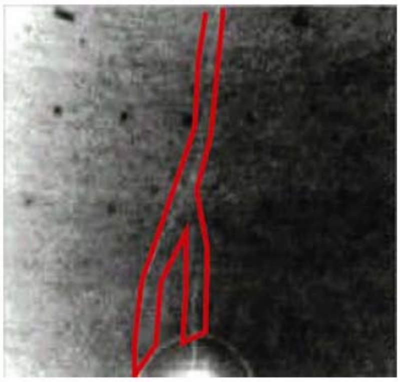
Figure 6 Delamination of fresco painting in the chapel and the main dome, (a) integrated infrared and visual images in the chapel (b) visual image at north side (c) infrared image at north side (d) visual image at west side (e) infrared image at west side (continued) (see online version for colours)

(b)



(c)

(d)



(e)

Delamination of stone finishing and fresco painting is dangerous from the view point of safety assessment related to non-structural members.

3.2 Subsidence of ground level and cornice levels and inclination of buttress piers by level survey and 3D laser scanning

The measurement of subsidence of ground level and dome cornice level verifies that there is a little difference between the measured values and those measured by Eng. Garro from 1935 to 1945 (Figure 7) (Garro, 1962). The subsidence is bigger in the north-western direction, and differential settlement occurs towards this direction. This tendency corresponds to the occurrence of the enormous crack of the wall surface as well (Figure 2). The result of level survey is accordance well with the construction history of the sanctuary as mentioned above in Section 2.

Figure 7 Level survey (see online version for colours)

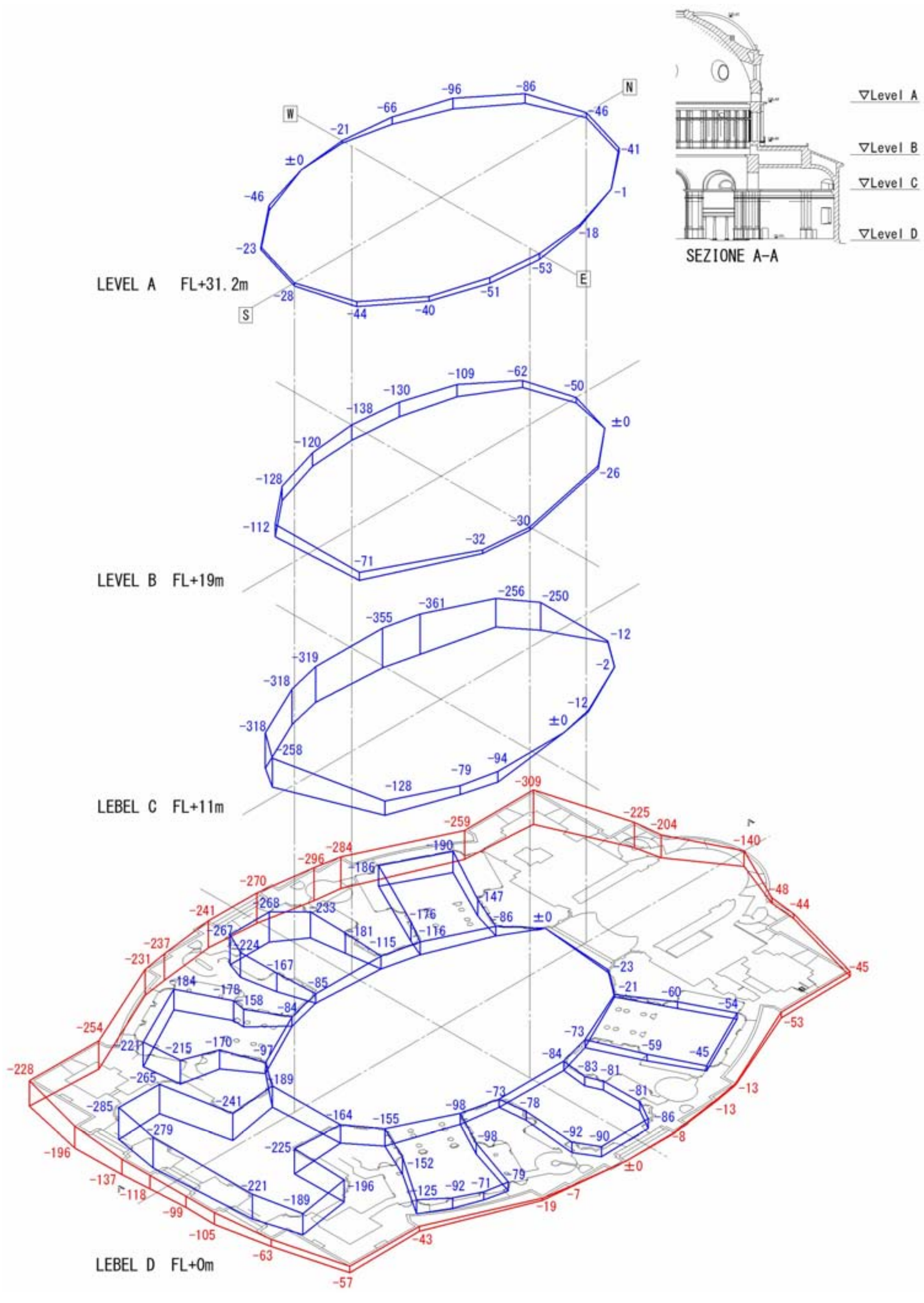
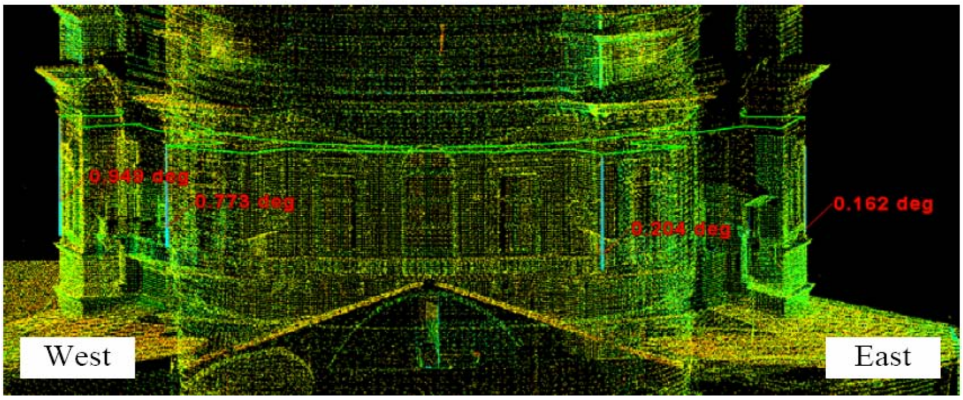
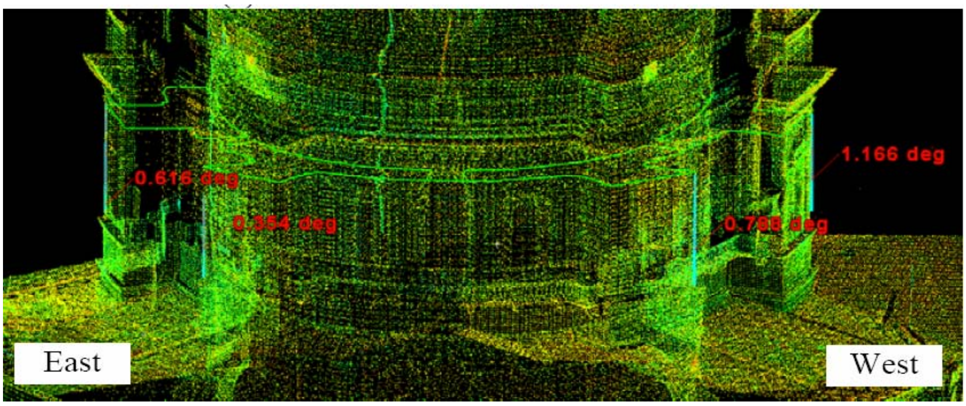


Figure 8 shows the inclination of the buttress piers obtained from 3D laser scanning. All buttress piers incline towards north-western direction due to subsidence.

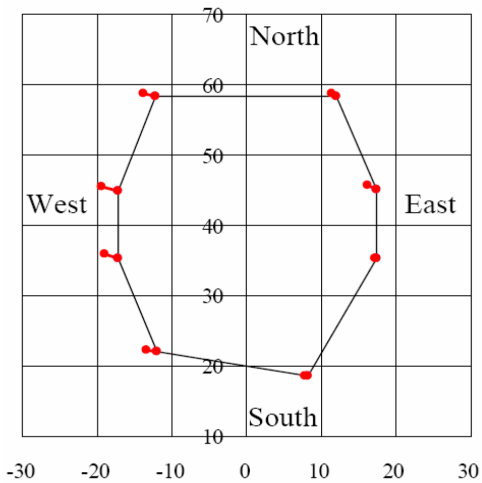
Figure 8 (a) Inclination of buttresses from south (b) inclination of buttresses from north (c) inclination of buttress piers obtained from 3D laser scanning (see online version for colours)



(a)



(b)



(c)

3.3 Detection of discontinuity of circular ring by using elastic wave

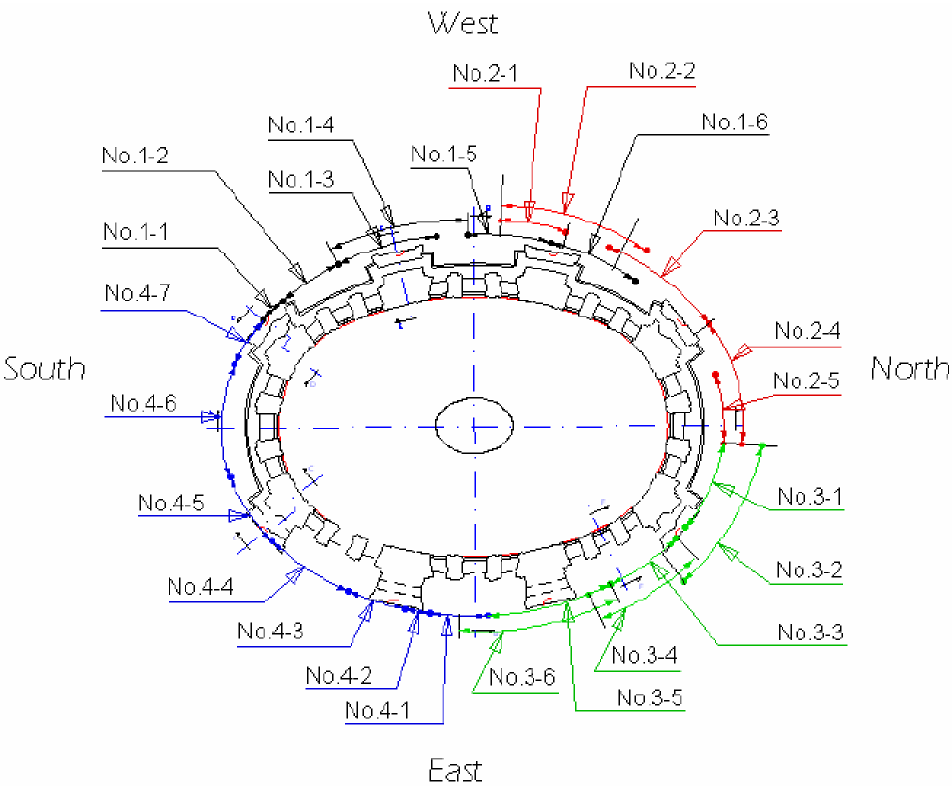
There are three sets of iron ties embedded at the base of the main dome by Eng. Gallo in 1734 (Figure 3). Figure 3(b) shows the detail of the original iron circular ring. The main dome is restricted by several iron rings; the original and the strengthening post-tensioning ones. The discontinuity of these rings may cause serious instability of the main dome. Therefore, a non-destructive testing aiming the detection of the discontinuity of the circular ring was carried out. The position of the ring tested is shown in Figure 3(a).

A bar and hammer were used in order to give a strong pulse wave into the circular ring and the elastic wave transmitting through the ring was received by dry coupling sensors. If a discontinuity of the ring was detected, the location of the defects must be determined. Therefore, the test was done in short ranges shown in Figure 9(a).

The velocity around 4,000 m/s of the elastic wave transmitted through the circular ring was detected at every measurement point. Therefore the discontinuity of the ring is estimated to not exist. The sample of elastic waves received by the sensors is shown in Figure 9(b).

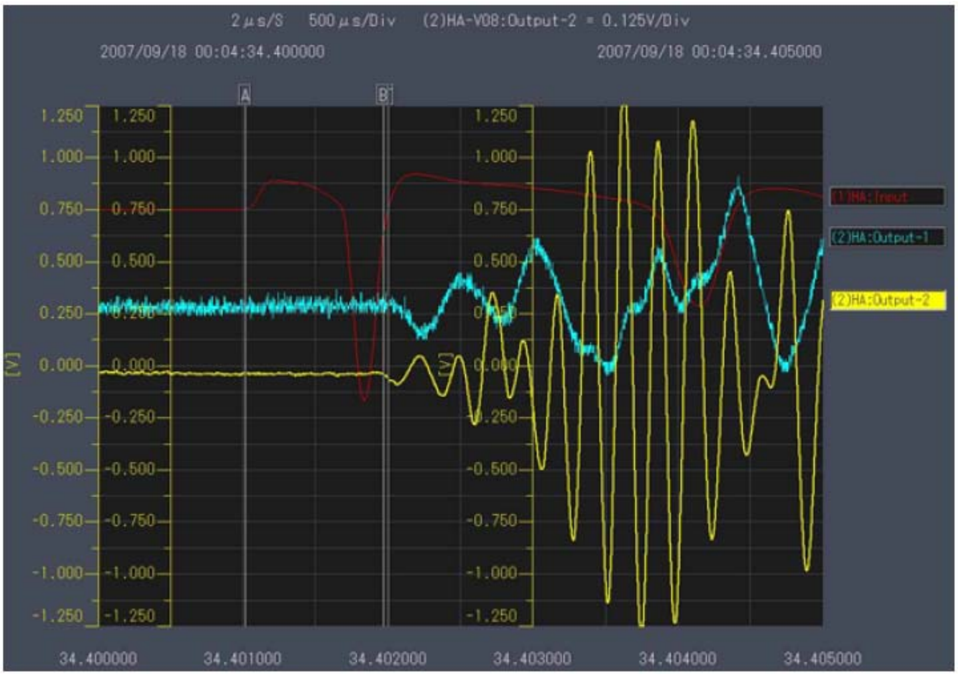
It is interesting to note that the iron reinforcements embedded at the base of the dome of San Pietro in Rome have been broken.

Figure 9 Measurement of elastic wave, (a) measurement points of elastic wave (b) sample of elastic waves received by the sensors (see online version for colours)



(a)

Figure 9 Measurement of elastic wave, (a) measurement points of elastic wave (b) sample of elastic waves received by the sensors (continued) (see online version for colours)



(b)

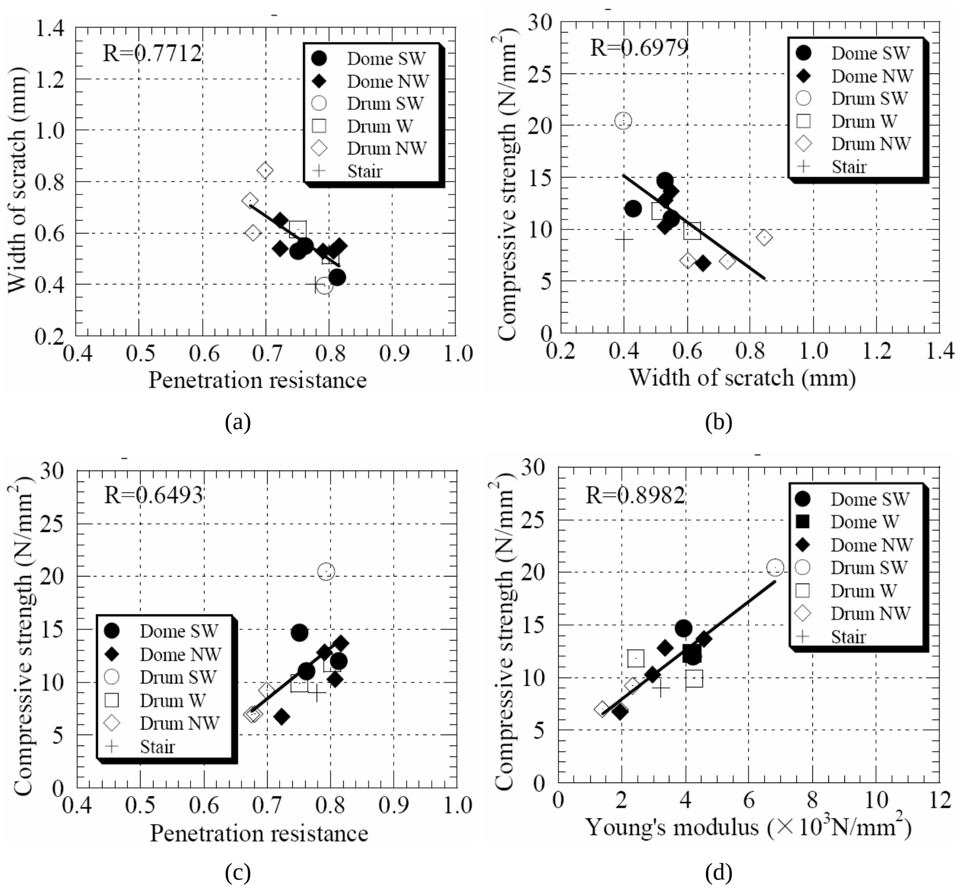
3.4 Compressive strength and Young's modulus of the brick

In order to estimate the compressive strength and Young's modulus of the brick and the mortar, both scratch tester and Windsor Pin System are applied (Yuasa et al., 2003; Rodio SpA, 1983). The scratch tester measures the width of scratch and Windsor Pin System uses the penetration resistance defined as micrometer reading, in other words 1 inch minus penetration depth.

Compression test of small sample for the brick and the mortar is necessary to estimate their compressive strength. The dimension of the brick specimen is about ϕ33 mm × 50 mm. The number of specimens is three for each measurement. The compressive strength test is carried out according to JIS A 1108.

Results of laboratory tests of the brick are shown in Figure 10. Figure 10(a) shows the relationship between the width of scratch and the penetration resistance. Figures 10(a) and 10(c) show the relationship between compressive strength and the width of scratch and the penetration resistance. As the width of scratch becomes larger, compressive strength becomes lower. On the other hand, as the penetration resistance becomes larger, compressive strength becomes higher. The relationship between compressive strength and Young's modulus is shown in Figure 10(d). As the compressive strength becomes higher, Young's modulus also increases proportionally. Judging from these figures, it is verified that there is a good correlation among the outcomes of the tests.

Figure 10 Compressive strength and Young's modulus of the brick, (a) relationship between width of scratch and penetration resistance (b) relationship between compressive strength and width of scratch (c) relationship between compressive strength and penetration resistance (d) relationship between compressive strength and Young's modulus



4 Safety assessment of the sanctuary by non-destructive dynamic test

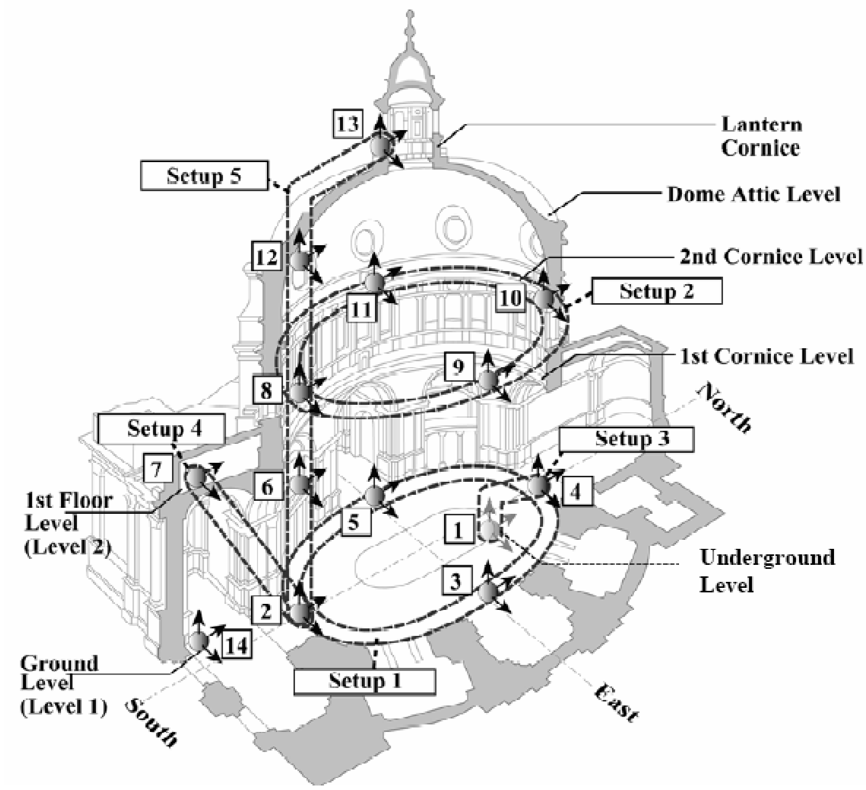
4.1 Dynamic tests

In order to characterise the dynamic behaviour of the Sanctuary of Vicoforte, ambient vibration was measured. Six different measurement setups were set and each setup designed to investigate expected specific features of the global structural dynamic behaviour. All the setups are listed in Table 1 and illustrated in Figure 11: here, 'North-South direction (N-S)' and 'East-West direction (E-W)' were assumed to be the major and the minor axes of the elliptical dome, respectively. Sampling frequency was 100 Hz and record duration was 300 seconds. Time history was obtained through the low-pass filter of 30 Hz.

Table 1 Measurement setups and sensor's position

Setup	*Level*	*Position*	*Direction*	*Objective*
Vico 1	1	N, S, E, W	N-S, E-W, up-down	Rocking behaviour
Vico 2	2nd cornice	N, S, E, W	N-S, E-W, up-down	Drum mode shapes
Vico 3	Basement	N	N-S, E-W, up-down	Swaying behaviour
	1	N	N-S, E-W, up-down	
	1	S, E, W	Up-down	
Vico 4	1	S	N-S, E-W, up-down	Outer structure
	2	S	N-S, E-W	
Vico 5	1	S	N-S, E-W, up-down	Drum and dome mode shapes
	1st cornice	S	N-S, E-W, up-down	
	2nd cornice	S	N-S, E-W, up-down	
	Dome attic	S	N-S, E-W, up-down	
	Lantern cornice	S	N-S, E-W, up-down	
Vico 6	Ground	W	N-S, E-W, up-down	Soil foundation natural frequencies

Figure 11 Measurement setups

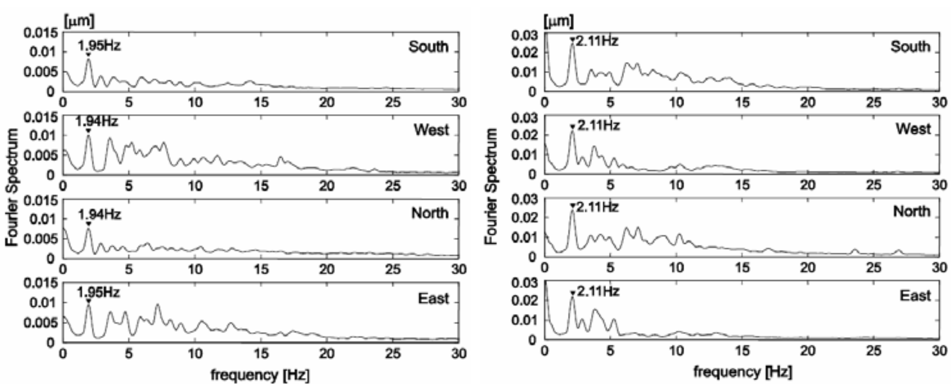


4.2 Preliminary dynamic characterisation

On the basis of the Fourier spectra of the measured signals, a preliminary identification of the structural modal properties was performed. This stage produces a first insight on the frequency band of interest and on the relevant features of the measured vibration signals.

The natural frequencies were chosen among the peaks of the spectra and the corresponding deformed shapes were detected by band-pass filtering around a natural frequency and evaluating the signal phase differences among the sensors. Figure 12 shows an example of the Fourier spectra of the horizontal motion acquired at the 2nd cornice level (setup 'Vico 2').

Figure 12 Fourier spectra of the horizontal micro-tremors (setup 'Vico 2'), (a) E-W direction (b) N-S direction

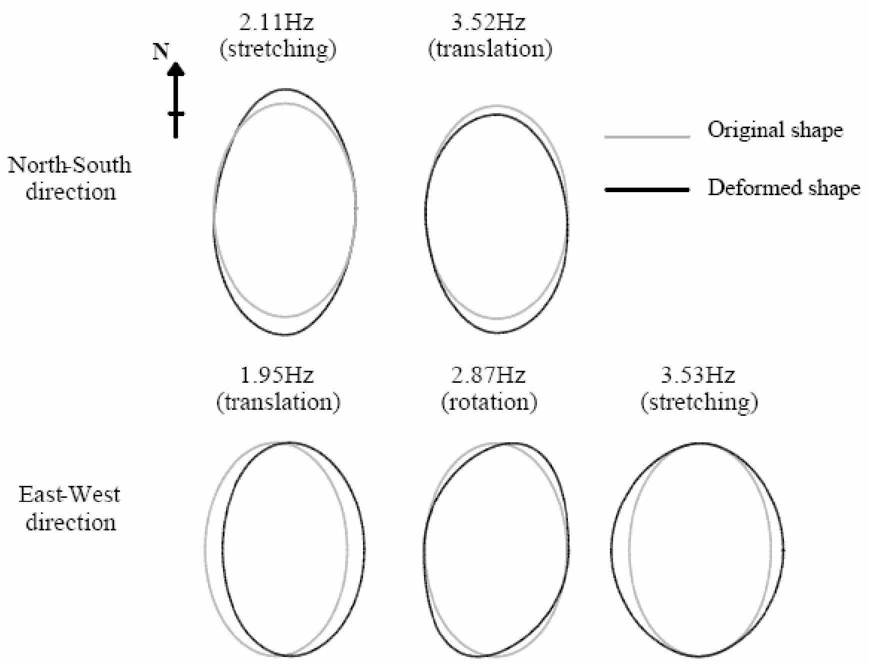


(a) (b)

From the vertical signal acquired through setup 'Vico 1' allowed for detecting some rocking behaviour since micro-tremors of up-down direction often shows inverse phase between the North-East and the South-West sides; on the contrary, micro-tremor of horizontal direction shows almost the same phase.

From the horizontal signal acquired through the 'Vico 2' setup, the first natural frequencies in E-W and N-S directions are 1.95 Hz and 2.11 Hz, respectively (Figure 12). Higher natural frequencies are not so sharp and their identification is more uncertain. The deformed shapes at the 2nd cornice level are depicted in Figure 13: the first natural frequency in E-W direction indicates a translational mode, while in N-S direction a stretching behaviour is the relevant feature of the deformed shape. At higher peak frequencies, possibly related to higher modes of vibration, the mode shapes are characterised by a predominant translation component in N-S direction and by rotation and stretching in E-W direction.

Figure 13 Mode shapes at 2nd cornice level (setup 'Vico 2')



For the detection of the higher natural frequencies, the ratio between the Fourier spectra of the signal acquired at different positions with those related to the signals at Level 1 have been calculated. Figure 14(a) shows the ratio between the horizontal signals Fourier spectra acquired respectively at the basement and Level 1 (setup 'Vico 3'). They reveal that the structure and foundation behaves almost as one unit without amplification in N-S direction and with a little bit amplification in E-W direction. From the Fourier spectrum ratio of Level 2/Level 1 it is possible to identify that the natural frequencies of the ensemble outer structure-drum structure are determined to be 4.47 Hz and 4.69 Hz in E-W and N-S directions, respectively [Figure 14(b)]. The ratios between the Fourier spectra of each of the signals acquired through the 'Vico 5' setup and that of Level 1 confirm that the first natural frequency in N-S direction is 2.11 Hz, while in E-W direction it is comprised in 1.95 to 2.10 Hz interval [Figure 14(c)]. The data acquired through the 'Vico 5' setup allowed for the estimation of the mode shapes in the vertical plane as represented in Figure 15. In particular, the first mode in the E-W direction has a deformed shape that does not show any significant modal displacement below the 1st cornice; this feature reveals the effect of outer structure surrounding the dome and drum structure as an effective constraint for the vibration in E-W direction.

Figure 14 Fourier spectrum ratio, (a) Level 1/basement level, (b) Level 2/Level 1, (c) setup 'Vico 5' levels/Level 1

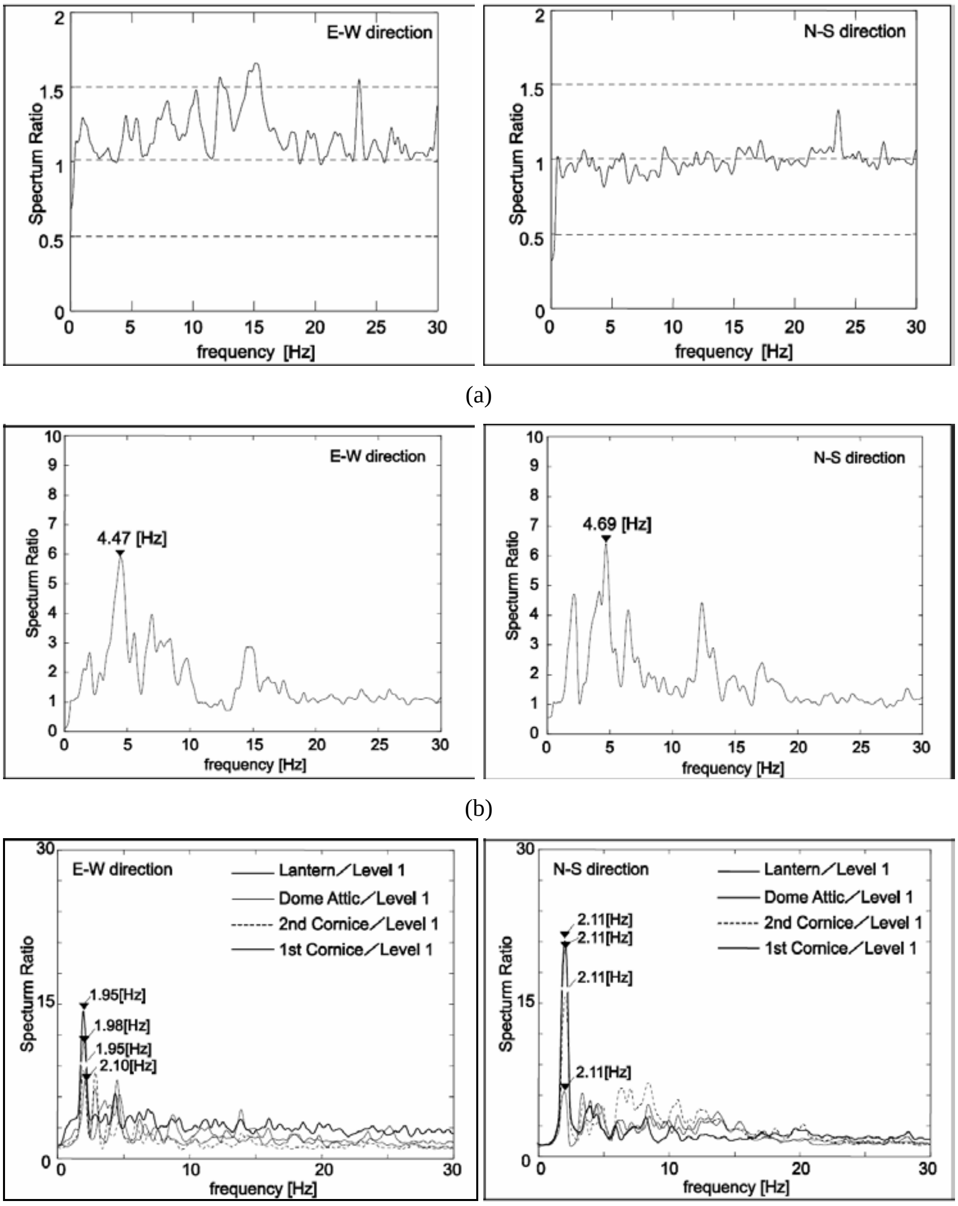
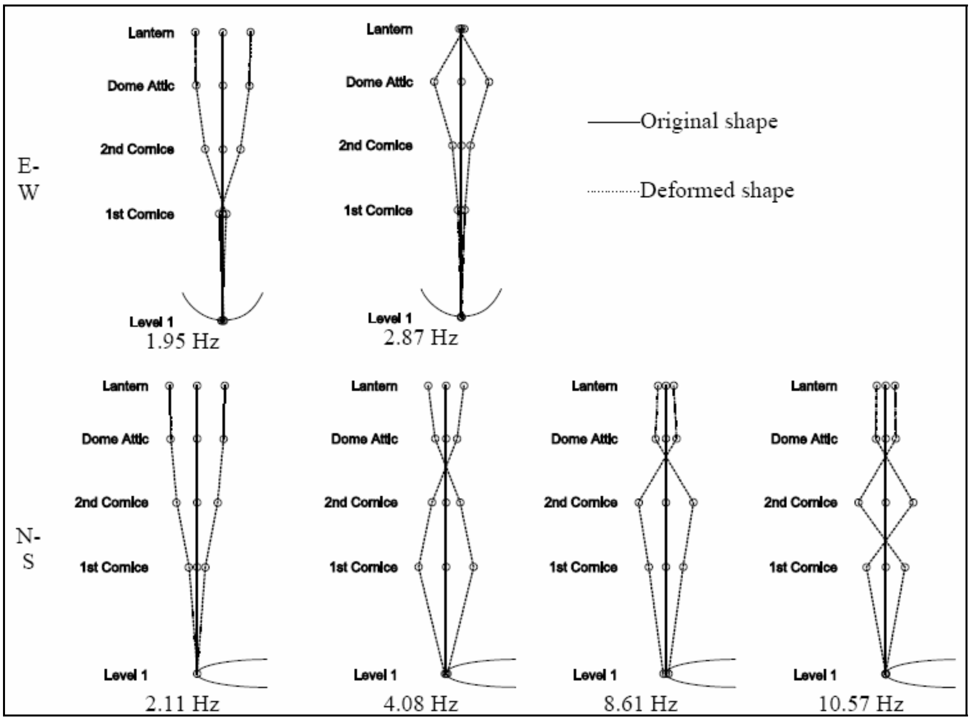


Figure 15 Mode shapes (vertical plane)



4.3 Evaluation of natural frequencies, damping factors and mode shapes by stochastic subspace identification

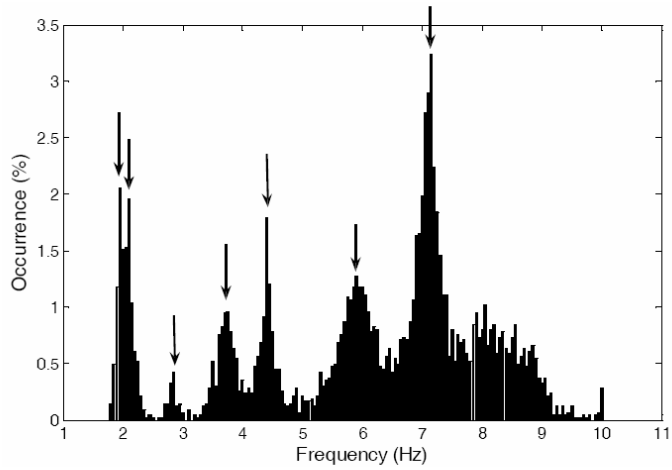
Assuming the signals to be locally stationary (Hammond and White, 1996), by subdividing the signals into partly overlapping segments it becomes possible to work out time histories that satisfy the stationary requirement, as well as to obtain a greater quantity of measurements on which to perform averaging operations on the results obtained. In this section, the obtained time history data were divided into time windows of duration 20 seconds with 16 seconds overlap.

The dynamic identification of such a complex structure requires the use of more sophisticated techniques; in this case the Subspace Identification method (Van Overschee and De Moor, 1993, 1994, 1996) was applied. Only the horizontal components of the signals acquired through 'Vico 2' and 'Vico 5' setups (Figure 11) were considered. This choice allows to consider in the identification process the component of motion which possibly affect much more the deformed shapes of the first modes of vibration (Figures 11 and 12). A distributed spatial characterisation of the mode shapes can be determined from the combination of the identified mode shapes separately obtained from the two setups.

The identification was carried out by determining the state-space representation matrices with the aid of the N4SID identification algorithm (Van Overschee and De Moor, 1994; Ljiung, 1999, 2009) which implements the subspace stochastic identification method. The stochastic subspace identification algorithm requires the order of the state representation to be satisfied, i.e., the number of states necessary to approximate the vibration measured. Based on all the available acquisitions, the optimal order for state-space representation was determined to be 14 here.

The distribution of the natural frequencies of the Sanctuary of Vicoforte relating to vibration modes with damping factor <15% is shown in Figure 16; here frequency range is between 0 and 10 Hz. This histogram makes it possible to identify some natural frequency values which on account of their being characterised by a higher occurrence level indicated by arrows in this figure. They are regarded as the most probable values of the natural frequencies of the structure.

Figure 16 Distribution of identified natural frequencies



The second step consisted of evaluating the vibration modes identified on the basis of the frequency values associated with each one. The identified vibration modes were regarded as possible structural vibration modes if their frequencies came close to one of the most probable values identified at the previous stage. The most probable frequency values were defined on the basis of the histogram shown in Figure 16 and are given in Table 2.

Table 2 Limit values of the probable structural natural frequencies

Mode	f_{min} *(Hz)*	f_{max} *(Hz)*
1	1.88	1.98
2	2.03	2.13
3	2.75	2.90
4	3.45	3.90
5	4.40	4.75
6	5.70	6.30
7	6.90	7.50

Groups of possible vibration modes of the structure, having a damping value <15% and a frequency in the around of the respective most probable value, were determined from the set of modes identified. The frequency and modal damping values of the structure were determined as the mean of the values corresponding to vibration modes characterised by mutually similar mode shapes. The mode shapes of the *i*th and *j*th modes are deemed similar if their modal assurance criterion (MAC) coefficient is greater than a predetermined threshold which in this case is assumed to be 0.90.

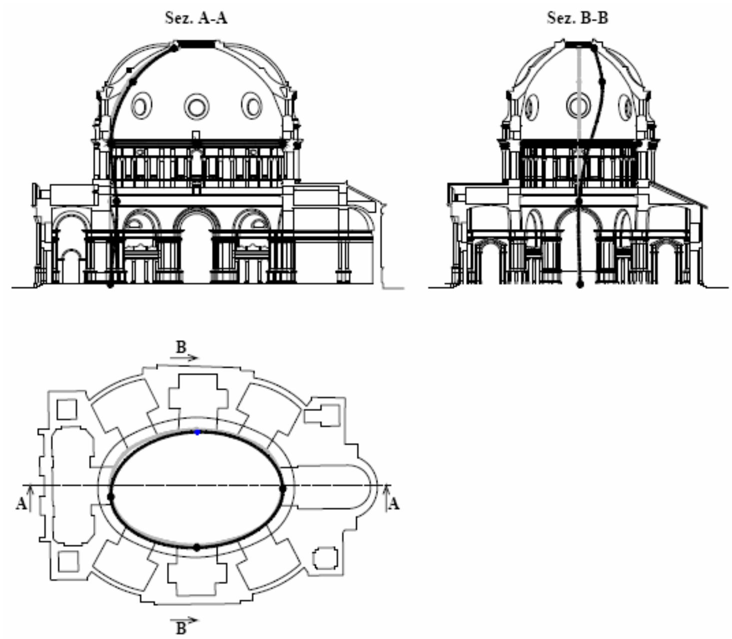
At the end of the selection process, the vibration modes identified are grouped not only as a function of frequency but also as a function of the corresponding mode shape. The natural frequencies and damping values and the components of the mode shapes of the structure are determined as the mean of the values of all the modes belonging to a given group.

Finally, a description of mode shapes in space was obtained by correlating the mode shapes relating to the 'Vico 2' and 'Vico 5' configurations on the basis of common channels. Table 3 gives the natural frequencies and damping values of the vibration modes of the structure and their corresponding mode shapes are shown in Figure 17.

Table 3 Natural frequencies and damping factors

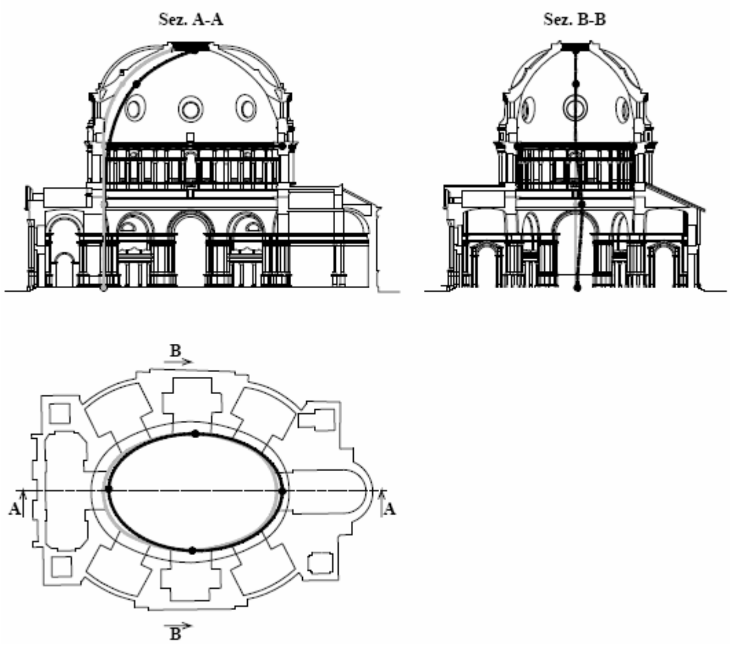
Mode	*f (Hz)*	*ξ (%)*	*Type*
1	1.93	4.89	1st flexural, direction E-W
2	2.07	3.45	1st flexural, direction N-S
3	2.84	0.61	1st torsion
4	3.60	2.51	1st ovalisation
5	4.56	1.06	2nd flexural, direction E-W
6	5.70	6.30	3rd flexural, direction E-W
7	6.90	7.50	2nd ovalisation (skew)

Figure 17 Mode shapes identified by stochastic subspace identification, (a) Mode 1, 1st bending E-W direction (b) Mode 2, 1st bending N-S direction (c) Mode 3, 1st torsion (d) Mode 7, 2nd ovalisation (skew)

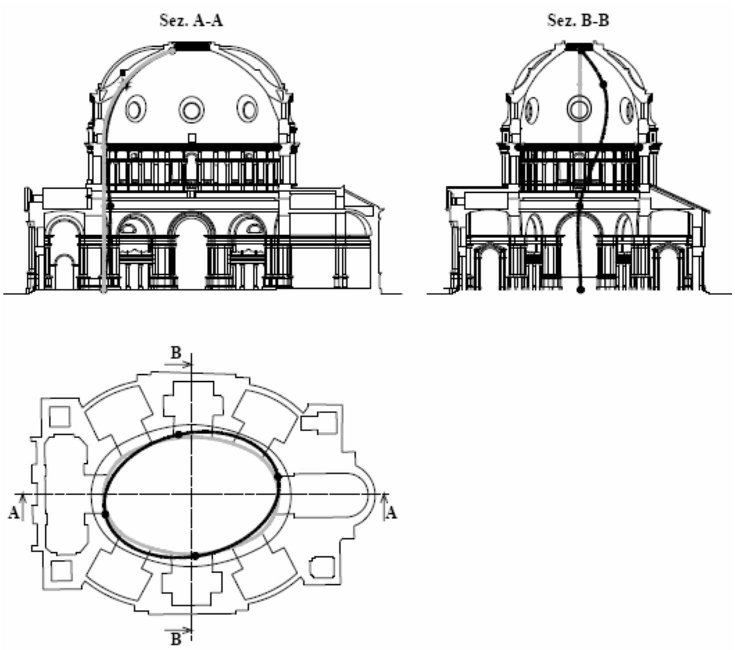


(a)

Figure 17 Mode shapes identified by stochastic subspace identification, (a) Mode 1, 1st bending E-W direction (b) Mode 2, 1st bending N-S direction (c) Mode 3, 1st torsion (d) Mode 7, 2nd ovalisation (skew) (continued)

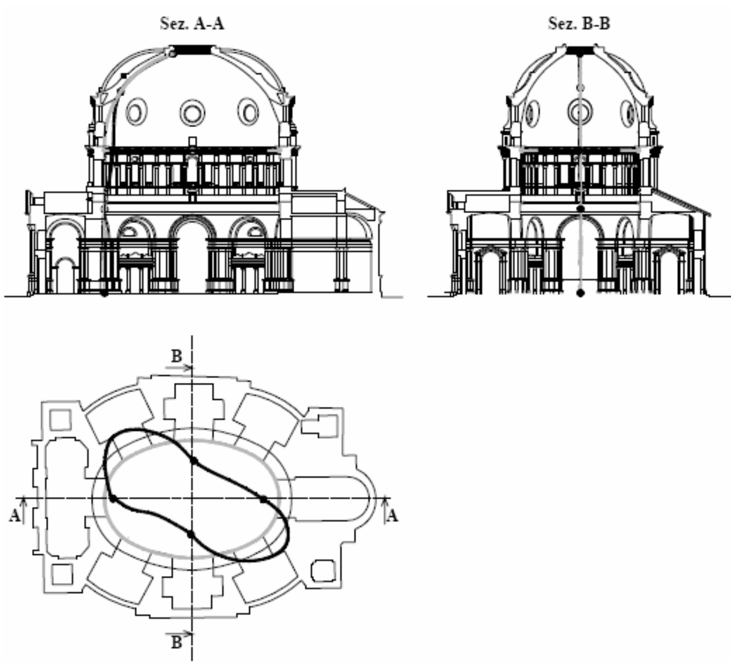


(b)



(c)

Figure 17 Mode shapes identified by stochastic subspace identification, (a) Mode 1, 1st bending E-W direction (b) Mode 2, 1st bending N-S direction (c) Mode 3, 1st torsion (d) Mode 7, 2nd ovalisation (skew) (continued)



(d)

5 Concluding remarks

This paper describes the non-destructive static and dynamic tests performed on the Sanctuary of Vicoforte. The following concluding remarks were obtained.

1. The state of delamination of stone finishing has been very dangerous when the infrared thermography investigation was applied and a repair work was done. A lot of delaminations of fresco painting were detected at the dome cornice level and at chapels. From the view point of safety assessment related to non-structural members, some measures should be taken against delamination.
2. There is a little difference between the measured values and those measured by Eng. Garro from 1935 to 1945. Substantial increases of subsidence were not observed.
3. From the elastic wave transmitted through the circular ring at every measurement point, the first set of iron ties is continuous. The second and third sets of iron ties are continuous in the south side of the main dome.
4. From the results of material tests of the brick, there is a good correlation among compressive strength and the scratched width and the penetration resistance.

5 The two fundamental modes of vibration determined through a preliminary analysis are consistent with the corresponding modes identified by the stochastic subspace identification algorithm. This result denotes the good quality of the acquired experimental data and points out the significance of the measurement positions. In fact these positions have proven to be able to catch the dynamics of the sanctuary and allow for a spatial description of the mode shapes on an exclusively experimental basis. The static expansion through a finite element model gives a further confirmation of the identified mode shape feasibility.

6 The statistic distribution of the frequencies identified through the stochastic subspace method leads to an unequivocal detection of the structural natural frequencies as being characterised by sharp peaks in Figure 16.

The positive outcome of the identification allows for further steps in the dynamic characterisation of the Sanctuary of Vicoforte, as model updating, damage detection and localisation. The seismic assessment is particularly important since the first two natural frequencies fall into the maximum earthquake acceleration frequency range characteristic of the Italian seismicity.

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