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NON-DESTRUCTIVE TESTING OF THE SANCTUARY OF VICOFORTE

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Abstract

A series of non-destructive tests such as Radiation Thermometer, Electromagnetic Radar, Impact Echo Scanner, Concrete Test Hammer, Scratch Tester, Windsor Pin System, and Electromagnetic Induction Scanner are carried out for diagnostic inspection of deterioration on the Sanctuary of Vicoforte. In this paper, 1) Delamination of stone finishing and fresco painting, 2) Thickness of main dome and vaults above chapels, 3) Detection of reinforcement, 4) Continuity of iron ties, 5) Subsidence of ground level, 6) Fundamental frequency of the dome, and 7) Estimation of compressive strength and Young's modulus of the brick are discussed.

Key Words

Non-destructive test, Diagnostic inspection, Deterioration, Sanctuary of Vicoforte

1 Introduction

The elliptical masonry dome of the Sanctuary of Vicoforte near Mondovì in northwest Italy was built in 1731 as religious monument, and it became one of the most important buildings representing the period, city, style, and culture of those days (Figure 1). The major and minor axes of the dome are 37.15 m and 24.80 m, respectively; and the height of the sanctuary is about 84 m. It is the largest of its kind, and the monument is technologically advanced space structures characterized particularly by its inner spans. 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 load and ambient actions, differential settlement of foundations, yielding and delayed rupture of original reinforcements, etc. The repair and

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maintenance of the sanctuary require a reliable evaluation of its structural behavior and current fundamental mechanical characteristics of their materials. However, the higher the historical value of a structure is, the more prohibitive core and other partially destructive tests become. Non-destructive tests, therefore, are useful for this reason.

(a) External view

(b) Internal view

Figure 1 The Sanctuary of Vicoforte

The project relating to monitoring, rehabilitation and structural strengthening was started in 1976 and a) structural and geotechnical investigations of foundations and foundation layers, b) rehabilitation of the drainage system of clay-silt layers, c) structural strengthening of the dome through the formation of a post-tensioning ring at the base of the drum (Figure 7), and d) monitoring of the principal parameters characterizing the structural disorder and of the response of the monument after strengthening were carried out (Pizzetti and Fea 1988, Chiorino et al 1993). The new five-year project named “Vicoforte 2002-2006” has 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 of the investigation relating to Hagia Sophia (Tanigawa et al 1996, Aoki et al 1992, 1994, 1997, 1998a, 1998b, 2000, 2001), seven objectives have been set as following in order to contribute to the joint research program:

1) Diagnostic inspection of deterioration by means of non-destructive tests (Komiyama et al 2002, Ohashi et al 2003)
2) Investigation of the mechanical continuity of the three sets of annular iron ties embedded at the base of the main dome by Eng. Gallo in 1734 (Komiyama et al 2002)
3) Measurements of natural frequencies and modes by ambient vibrations (Aoki et al 2003)
4) Estimation of compressive strength and Young’s modulus of the brick and the mortar (Aoki et al 2003, Komiyama et al 2003)
5) Interpretation of the static and dynamic behaviors of the dome and of the monuments by means of finite element three-dimensional elastic-plastic analyses considering the information of its foundations layers (Aoki et al 2003, 2004)
6) Model updating by taking into account the experimental measures
7) Proposals for structural conservation and restoration

The above 1), 2), 3) and 4) are discussed in this paper.

2 Results of non-destructive tests

2.1 Non-destructive tests

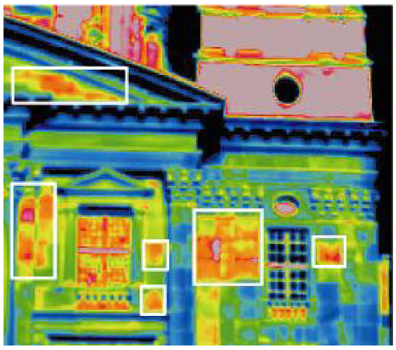
As a structural surveying project of the Japanese group, a series of non-destructive tests such as Radiation Thermometer, Electromagnetic Radar, Impact Echo Scanner, Concrete Test Hammer, Scratch Tester, Windsor Pin System, Ultra Sonic Tester, Electromagnetic Induction Scanner, and Micro tremors measurement for the Sanctuary of Vicoforte were carried out. The period of the first, the second and the third stages of investigation are February 12 to 25, 2002, September 17 to 24, 2002, and November 23 to 27, 2003, respectively.

2.1.1 Delamination of stone finishing and fresco painting

In order to detect defects such as delamination and water leakage, Radiation Thermometer is applied (Komiyama el al 2002). Delamination of stone finishing at both south and west sides are seen in the rectangular areas in Figure 2. The state of delamination of stone finishing is very dangerous, and this means that some measures should be taken against it.

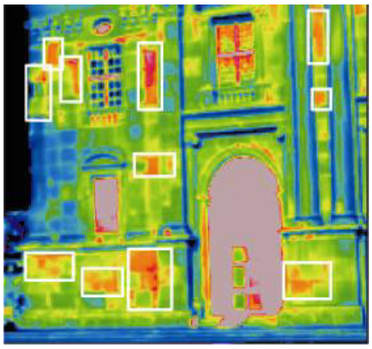
As for the detection of delamination and/or water leakage of fresco painting, active heart source are used. Figure 3 shows delamination of fresco painting in the northwest chapel. Delaminations of fresco painting of the main dome at both north and west sides are shown in Figure 4.

(a) Visual image at south side



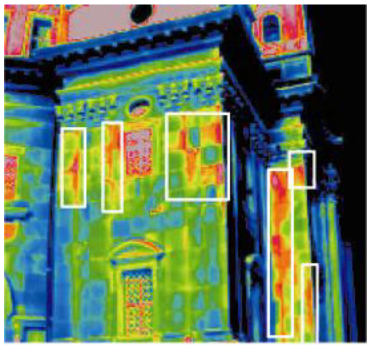
(b) Thermal image at south side

(a) Visual image at south side



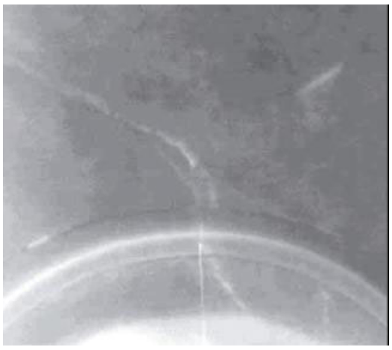
(b) Thermal image at south side

(a) Visual image at west side

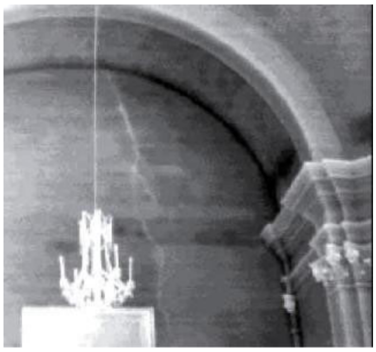


(b) Thermal image at west side

Figure 2 Delamination of stone finishing

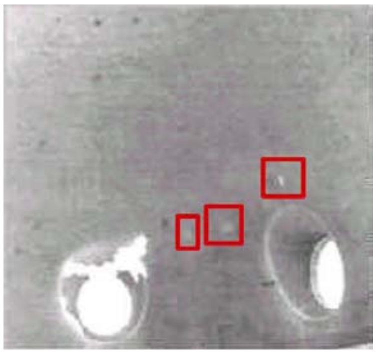


(a) Visual image (b) Thermal image

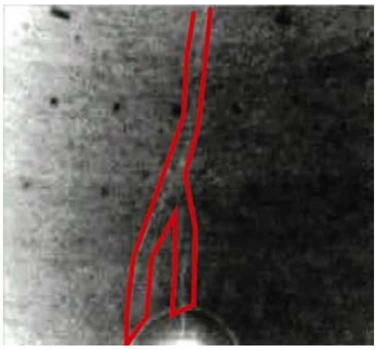


(a) Visual image (b) Thermal image

Figure 3 Delamination of fresco painting in the northwest chapel



(a) Visual image at north side *(b) Thermal image at north side*

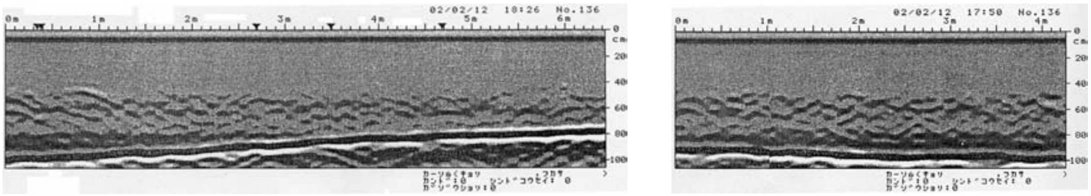


(a) Visual image at west side *(b) Thermal image at west side*

Figure 4 Delamination of fresco painting of the main dome

2.1.2 Thickness of main dome and vaults over chapels

Electromagnetic Radar is applied in order to estimate the thickness of the main dome and vaults over chapels (Komiyama et al 2002). Because of the difference of dielectric constant between concrete and masonry, a provable test of masonry wall over apse is carried out; and the correction factor of 1.33 is obtained by the fact that thickness of the wall which is measured 60 cm by Radar turns out to be 80 cm. As shown in Figure 5, the thickness of the main dome in south and east directions are measured from 110 cm to 133 cm and from 120 cm to 133 cm, respectively. These results correspond well to those measured by Eng. Bernasconi in 1976 (Bernasconi 1979). The minimum thickness of the vault over chapel is measured about 30 cm (Figure 6).



Base *Lantern* *Lantern* *Base*

(a) Long axis in south direction *(b) Short axis in east direction*

Figure 5 Thickness of the main dome

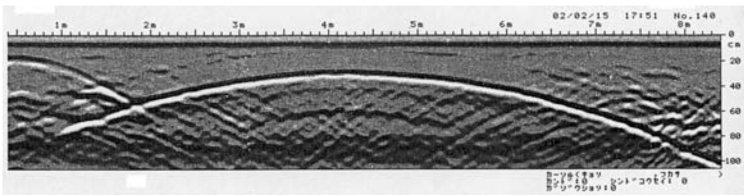


Figure 6 Thickness of the vault over chapel

2.1.3 Detection of reinforcement

In order to detect the presence of iron reinforcement, Electromagnetic Radar, and Electromagnetic Induction Scanner are applied (Komiyama et al 2002). Three sets of iron rings embedded at the base of the main dome by Eng. Gallo in 1734 are observed (Figure 7). No other annular reinforcements, however, are detected in the dome with the exception of the post-tensioning steel ties inserted at the base of the drum in 1987 (Figure 7). This confirms that the additional reinforcement by iron rings proposed by Eng. Garro in 1961 has not been actuated (Garro 1962).

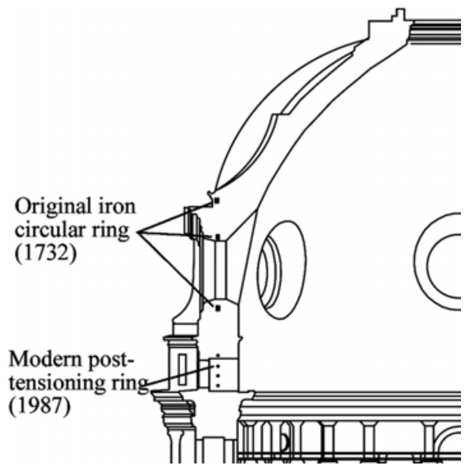


Figure 7 Position of reinforcement

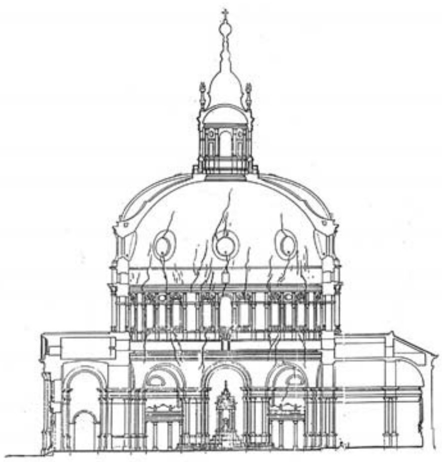
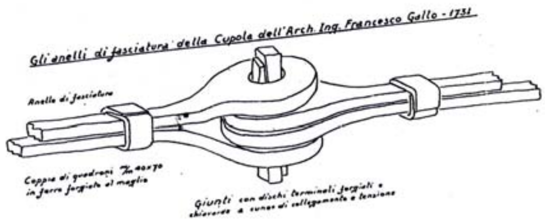


Figure 8 Cracks at west side

2.1.4 Continuity of iron ties

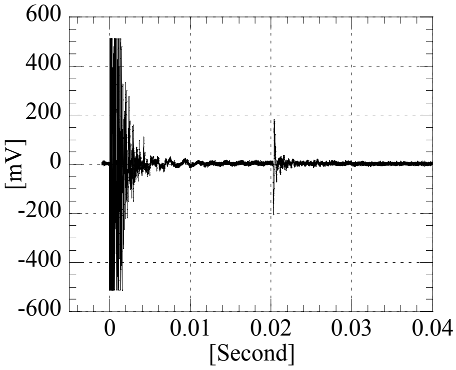
There are three sets of iron ties embedded at the base of the main dome by Eng. Gallo in 1734 (Figure 9). During and after construction, plastic deformation of the dome occurs, the materials separate into blocks, slippage begins, fractures develop, and the discontinuous deformation begins due to many reasons including dead load, differential settlement, temperature stress, and also chemical degradation (Figure 8). In order to estimate the continuity of these iron ties, Impact Echo Scanner is applied (Komiyama et al 2002). A sensor of longitudinal wave type is used here. The total length of the iron ties is around 104 m. As the sound velocity of iron is about 5,000 m/sec, one circuit time should be around 0.0208 second. As shown in Figure 10, these iron ties are probably continuous. As to the iron reinforcements, it is interesting to note that those embedded at the base of the dome of San Pietro have been broken.

(a) Original iron tie

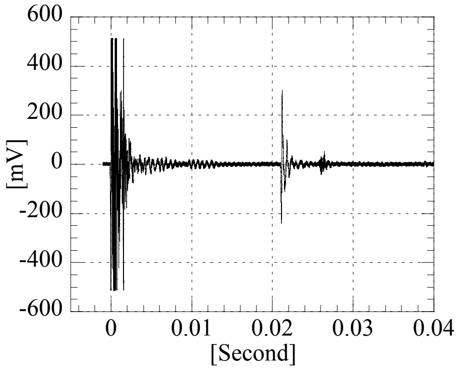


(b) Detail of iron tie

Figure 9 Iron ties embedded at the base of the main dome by Eng. Gallo

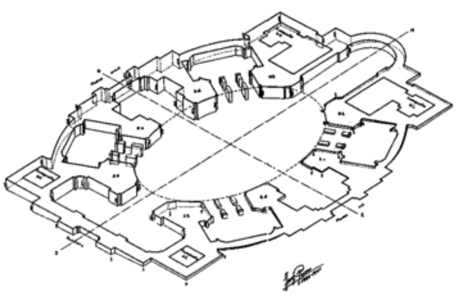


(a) First ring of iron ties

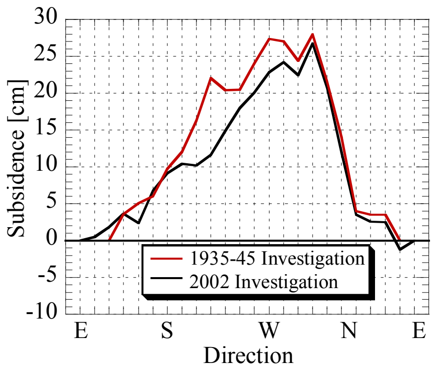


(b) Second ring of iron ties

Figure 10 Wave profile of received elastic wave



(a) Subsidence by Garro



(b) Ground level (outside)

Figure 11 Level survey

2.1.5 Subsidence of ground level and dome cornice level

Our 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 11) (Garro 1962, Ohashi et al 2003). The subsidence is bigger in the northwestern 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 8).

2.1.6 Fundamental frequency of the dome

For the purpose of obtaining the data concerning dynamic structural properties of the Sanctuary of Vicoforte, microtremor by ambient vibrations are measured at different positions of the dome, inside and outside the Sanctuary, as a first phase of dynamic test (Figure 12) (Aoki et al 2003). Smoothed spectra by Parzen's spectral window of 0.5 Hz are given in Figure 13. In Figure 13, bold solid line, bold dotted line and fine solid line show the spectra of north-south, east-west and vertical directions, respectively. According to the observation of microtremor by ambient vibrations, fundamental frequencies in north-south and east-west directions are estimated to be 2.12 and 1.95 Hz, respectively (Figure 13). The fundamental frequency of the dome of the Sanctuary of Vicoforte is close to that of ground motions when earthquake occurs. The dome of the Sanctuary of Vicoforte, therefore, seems to be most vulnerable to the kind of strong earthquakes such as we experienced in recent years.

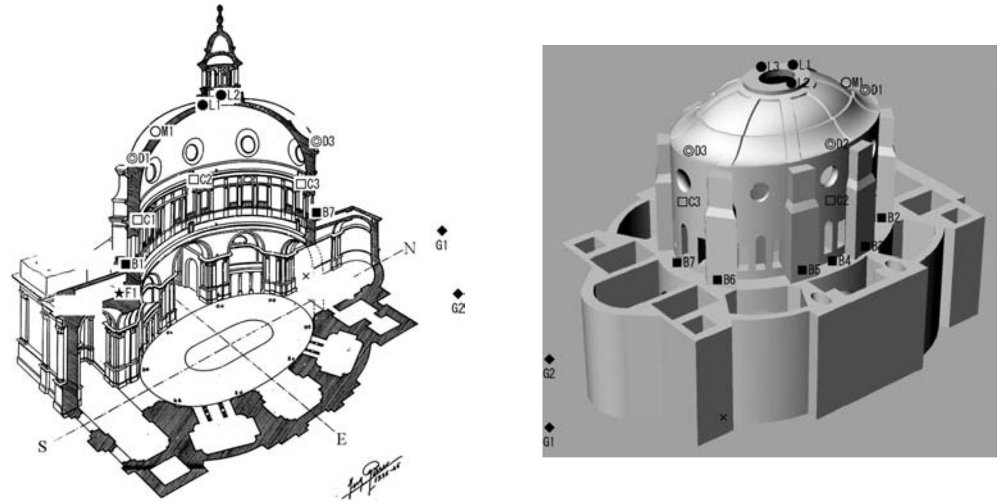
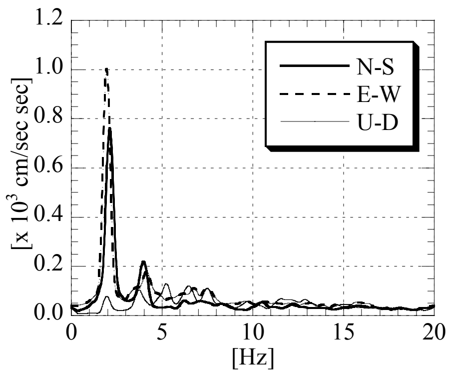
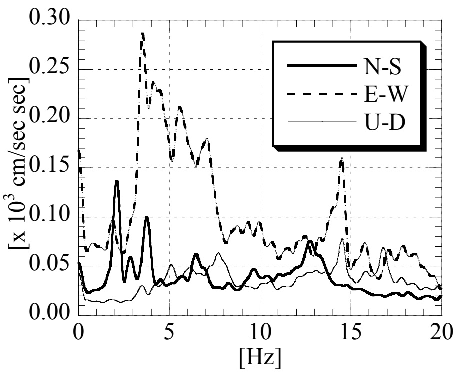


Figure 12 Measuring points of ambient vibrations



(a) Lantern cornice level L2



(b) Balcony level B2

Figure 13 Fourier spectra observed in micro tremors

3 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 (width of scratch) and Windsor Pin System (penetration resistance, defined as micrometer reading, in other words 1 inch minus penetration depth (inch)) are applied (Yuasa et al 2003, Ohashi et al 2003, Aoki et al 2003, Komiyama et al 2003, Rodio 1983).

Compression test of small sample for the brick and the mortar is necessary to estimate of their compressive strength. The brick specimen is a cylinder measuring ϕ33 mm x 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 Figures 14 to 17. Figure 14 shows the relationship between width of scratch and penetration resistance. Judging from these Figures, it is verified that there is a good correlation among the outcomes of the tests. Figures 15 and 16 show the relationship between compressive strength and width of scratch and 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 17. As the compressive strength becomes higher, Young's modulus also increases proportionally.

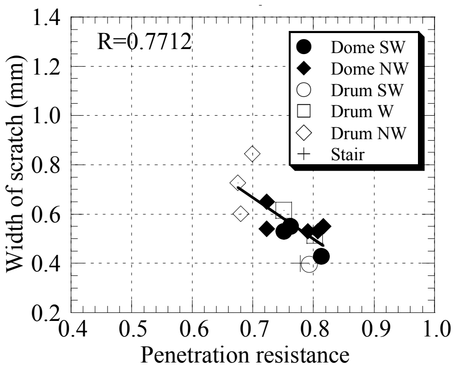


Figure 14 Relationship between width of scratch and penetration resistance

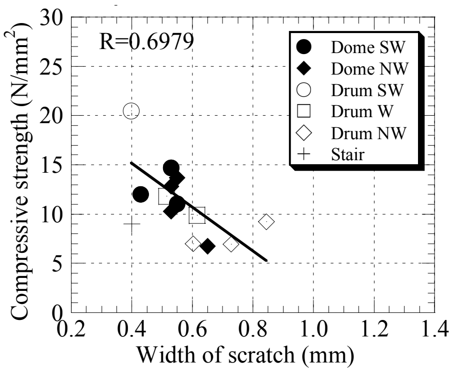


Figure 15Relationship between compressive strength and width of scratch

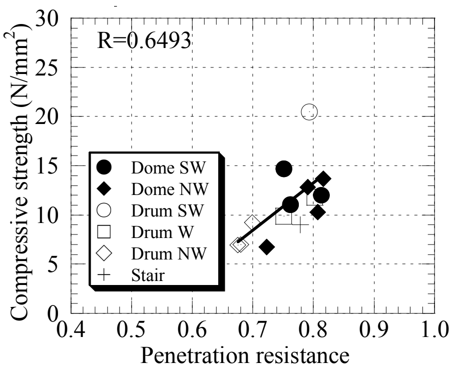


Figure 16Relationship between compressive strength and penetration resistance

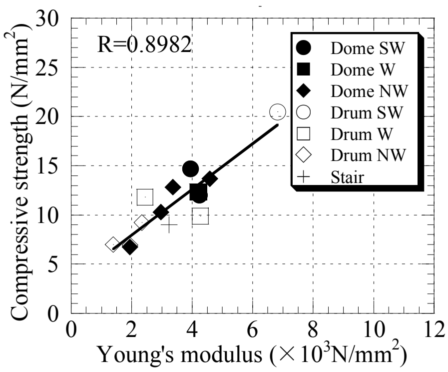


Figure 17 Relationship between compressive strength and Young's modulus

4 Concluding remarks

The following concluding remarks were obtained:

- Delamination of stone finishing and fresco painting by means of Radiation Thermometer: The state of delamination of stone finishing is very dangerous, hence some measures should be taken against delamination. A lot of delaminations of fresco painting are detected at the dome cornice level and at chapels.

- Thickness of main dome and vaults over chapels by means of Electromagnetic Radar: The results obtained from our research correspond well to those measured by Eng. Bernasconi in 1976.
- Detection of reinforcement by means of Electromagnetic Radar, and Electromagnetic Induction Scanner: No other annular reinforcements are detected in the dome with the exception of the system of prestressing steel ties inserted in 1985.
- Continuity of iron ties embedded at the base of the dome by Eng. Gallo by means of Impact Echo Scanner: First set of iron ties is continuous in the west side of the dome. Therefore these iron ties are probably continuous.
- Measurement of subsidence of ground level and dome cornice level: There is a little difference between our measured values and those measured by Eng. Garro from 1935 to 1945.
- Observation of natural frequencies by ambient vibrations: Fundamental frequency is around 2 Hz in both north-south and east-west directions. The dome of the Sanctuary of Vicoforte seems to be vulnerable to severe earthquakes.
- Estimation of compressive strength for the brick and the mortar by means of Scratch Tester and Windsor Pin System: There is a good correlation among compressive strength and scratched width and penetration resistance.

Acknowledgements

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