GPR Applications for NDT Investigations on the Cultural Heritage Monumental Buildings of Florence (Italy)

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Abstract: Florence (Italy) is a worldwide well-known cultural historical city, with many outstanding monumental buildings visited every year by about 20M people, since 1982 the historical city center is under the UNESCO Patronage. Conservation of monumental buildings is subject to the principles of integrity and authenticity, in Italy recalled by the Ministry for Cultural Heritage 2011 rule, which defines the procedure for their seismic vulnerability evaluation. For that, the knowledge of the masonry structure is in need, and in lack of historical documentation on the design, only non destructive tests (NDT), or very low destructive tests, can be run on the masonry for acquiring this knowledge on its structure and consistence. For this purpose, we are largely using specific ground penetrating radar (GPR) technology, which is resulting highly performing in defining masonry structure and consistence. This paper summarizes selected case histories regarding the main Florentine historical monumental buildings: Palazzo Vecchio, Brunelleschi's Cupola, Giotto's Bell-Tower, and San Giovanni Baptistery. The correct interpretation of the GPR data requires knowledge about the masonry techniques of the age of construction, and local verification with micro drill-holes with video inspections, sonic and ultrasonic tests, in defining historical monumental buildings masonry structure and competence, static and dynamic behavior parameters and seismic vulnerability.

Key words: GPR, cultural heritage, historical masonries, monumental building, Florence, seismic vulnerability.

1. Introduction

Survey on masonry of historical monumental buildings is performed for scientific purpose regarding the recovery of the ancient building techniques and materials, but also for public need in defining the seismic vulnerability of outstanding monumental buildings visited every day by thousands of people. Florence (Italy) is a paradigm for that, with its historical centre, under the UNESCO patronage since 1982, and about 20M people visiting its monumental building every year.

In the last decade, new rules ask for studies defining the seismic vulnerability of monumental

cultural heritage buildings in order to verify their level of seismic risk and promote reinforcing actions for reducing it. Florence is in a seismic classified area in needs for a seismic vulnerability evaluation of its monumental buildings.

In 2011, the Italian Ministry for Cultural Heritage (MIBAC) emitted compulsory rule for acquiring the knowledge of the structure of the monumental historical building masonry, which is basically in need in order to define the seismic vulnerability of the building. According to the international principles of integrity and authenticity, the national rule for cultural heritage protection, and in lack of historical documentation on the design, only non destructive tests (NDT), or very low destructive tests, can be run on the masonry for acquiring knowledge on its structure and consistence.

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For this purpose, ground penetrating radar (GPR) technology is resulting highly performing in defining masonry structure and consistence. The correct interpretation of the GPR data asks for knowledge about the masonry techniques of the age of construction and to be matched with other NDT data and weakly destructive inspections. The integration of all these multidisciplinary survey allows obtaining expendable results in defining historical monumental buildings masonry structure and competence to be used for assessing masonry static and dynamic behavior and parameters for monumental buildings seismic vulnerability evaluation.

In this paper, we present selected case histories regarding the main Florentine historical monumental buildings: Palazzo Vecchio, Brunelleschi's Dome, Giotto's Bell-Tower, and San Giovanni Baptistery.

2. Rules in Force in Italy

According to the international directive on the matter, in Italy the rules in force defining the regulation for seismic vulnerability evaluation of cultural monumental buildings and the performable in situ tests are:

- Legislative Decree 22 January 2004, n. 42 Code of Cultural Heritage and Landscape, issued pursuant to Article 10 of Law 6 July 2002, No. 137, as primary sector regulation.
- Art. 29 of Legislative Decree 42/2004 providing an organic reference framework for conservation interventions on cultural heritage.
- Guidelines for the evaluation and reduction of seismic risk for cultural heritage with reference to the technical standards for construction referred to in the decree of the Ministry of Infrastructures and Transport of 14 January 2008, issued by MIBAC on 19/01/2011.

MIBAC guidelines pay particular attention to the path for acquiring knowledge on the masonry (§ 4.1), and provide a guideline on the steps to be followed for acquiring all the preliminary knowledge that allows the development of a reliable model. MIBAC

Guidelines specifically ask for acquiring historical documentation about the building construction and masonry assemblages, and provide the execution of on-site tests for defining the type of masonry, its characteristics and assemblage, also through:

- Indirect NDT: GPR, thermography, sonic, ultrasonic;
- Weakly destructive direct inspections (WDI): micro controlled drill-holes with cutters analysis (DAC-test), endoscopies, peeling of plasters, small-scale essays.

3. GPR Principles

The GPR technique was developed for investigating subsoil objects [1], subsequently it was used for defining lithological contacts [2-4], faults [5], and fractures in rock-mass [6-9] and for defining soil units [10-15] and the water table level, too [12, 16, 17]. GPR has been also applying for investigating the competence of the concrete in bridges and tunnels and for the binder durability [18, 19]. Recently GPR has been used for investigation on masonry structure and assemblage [20, 21, 22].

The GPR principle uses the two-way travel time between a high-frequency electromagnetic input in the radar range 100 MHz-100 GHz and its return (Fig. 1).

The radar input travels in the material at a velocity mainly related to the magnetic conductivity and permeability of the medium [23-25].

The boundary between materials with different electromagnetic properties partially backscatters the signal to the antenna. The entity of penetration of the signal into the material is a function of the material properties and the signal frequency: lower the frequency higher the penetration but less the details of the investigation because they are function of the wavelength.

The knowledge of the wave velocity in the medium or that of a distance of a sure signal is compulsory for fixing the scale of the investigation and therefore for correctly placed in the surveyed body the material

Fig. 1 GPR operating inside the Brunelleschi's Cupola, and principle: an antenna inputs a radar signal in the medium, the boundary between materials with different electromagnetic properties backscatters the signal to the receiver determining the two-way travel-time of the signal.

interfaces, voids included.

In investigating masonry, a good practice is measuring the thickness of the wall plus placing a still/iron plate as reference to the opposite side of investigation for having a sure end-signal of the masonry, in order to fix the scale of the resulting radargram.

4. Masonry Knowledge

Masonry is the object to analyze and study by NDT in order to define the structure, assemblage and materials; masonry basic knowledge must include the various types of building that can be found to analyze, on a specific building, also in relations with its age.

HISTORIC	Tipologia di muratura	Categoria
	muratura in pietrame disordinata (ciottoli, pietre erratiche ed irregolari)	I
	muratura a conci sbazzati con paramento di limitato spessore e nucleo interno	II
	muratura in pietre a spacco con buona tessitura	III
	muratura a conci di pietra tenera (tufo, calcarenite, ecc.)	IV
	muratura in blocchi lapidei squadrati	V
MODERN	muratura in mattoni pieni e malta di calce	VI
	muratura in mattoni semipieni con malta cementizia (doppio UNI foratura $\leq 40\%$)	VII
	muratura in blocchi laterizi semipieni (percentuale foratura $< 45\%$)	VIII
	muratura in blocchi laterizi semipieni con giunti verticali a secco (percentuale foratura $< 45\%$)	IX
	muratura in blocchi di calcestruzzo o argilla espansa (percentuale foratura tra 45% e 65%)	X
	muratura in blocchi di calcestruzzo semipieni (percentuale foratura $< 45\%$)	XI

Fig. 2 Table C8A.2.1 C.M. Min. for Infrastructure and Transport No. 617 on 02/02/2009 grouping masonries into 11 types, 6 as historical and 5 as modern.

Basic knowledge must also include how masonry apparatuses can “appear” in a GPR spectrum depending both on the transmissivity properties of the signal by the materials and the material assemblage.

Moreover, the Ministry for Infrastructure and Transport circular 2/2/2009 No. 617 C.S.LL.PP., ex NTC2008, in Table C8A.2 of Appendix C8A gives a first form for masonry types’ classification (Fig. 2) recognizing 11 types of masonries, 6 as historical and 5 as modern.

The same circular at the point C8.5.3 states that regional authority can define, as integration, specific abacus for regional common for local masonry buildings types; the Tuscan Region emitted, by the way of the Florence University, an abacus for regional situations (Fig. 3); Sardinia Region [27] and ICCD [28] let be available others manuals.

The knowledge of the structure of masonry cannot avoid its internal structural assemblage, for that reason the SSRT (Seismic Service of the Regione Toscana) abacus provides explicative forms for each masonry type reporting its external and internal setting (Fig. 4).

Performing this knowledge requires a strict interdisciplinary cooperation with architects and art historians and knowledge about the modes of use of the construction materials through times.

Many manuals and textbooks are available for defining structure and assemblages of historical masonries, see as example Refs. [29-32].

Obviously, previous experiences and site-specific knowledge jointing with historical documentation can largely help in defining masonry types of historical monumental buildings.

5. Case Histories from Florence

The present day strong sensibility for people protection in the event of an earthquake and the need for cultural heritage conservation, moved administrations to start with multidisciplinary project addressed to seismic risk prevention.

At Florence, the Municipality and the Opera del Duomo engaged with the University for defining seismic vulnerability of the main outstanding Florentine cultural heritage monumental buildings: Palazzo Vecchio, Brunelleschi’s Cupola, Giotto’s Bell-Tower and San Giovanni Baptistery.

For acquiring knowledge on the masonry structure and assemblage of these buildings by means on NDT, GPR investigations had been largely performing on their walls.

5.1 Palazzo Vecchio

Arnolfo di Cambio erected Palazzo Vecchio in 1296 as City Hall; the first building was greatly enlarged during centuries and now it occupies the hull insulate. Therefore, the history of its building is complex [33] and the masonry types are very different from site to site according to the age and purpose of construction.

In order to have a first subdivision of the masonry in different groups, a GPR systematic survey of the walls had been performed (Fig. 5).

The best performing antenna was a 2 GHz; results well outline the difference among the master walls up to 1.5 m thick and built up by facing stone ashlar and internal mortared stone blocks, and the inner walls made by regular bricks and mortar rows or by a chaotic mortared assemblage of stone pieces and bricks.

5.2 Brunelleschi’s Cupola

Brunelleschi vaulted the Cupola in the years 1420-1436, no historical documentation is available on its structural assemblage and masonry, only indirect observations [35] and some cores with video inspection in the drill-holes [36].

In order to have preliminary data on the applicability of GPR investigation on the Cupola’ masonry an experimental survey was run [21].

The results point in favor for the antenna at 900 MHz

C.M. n. 617 del 02/02/2009 Tabella C8A.2.1	Regione Toscana Abaco delle Tipologie di Muratura
I muratura in pietrame disordinata (ciottoli, pietre erratiche ed irregolari)	C (I) muratura di pietra sbazzata in presenza di irregolarità
	D (I-3) muratura di pietra sbazzata con spigoli, mazzette e/o ricorsi in mattoni pieni e/o pietra squadrata
	E (I) muratura di pietra arrotondata o ciottoli di fiume di pezzatura varia senza spigoli, mazzette e/o ricorsi in mattoni pieni e/o pietra squadrata
	F (I-3) muratura di pietra arrotondata o ciottoli di fiume di pezzatura varia con spigoli, mazzette e/o ricorsi in mattoni pieni e/o pietra squadrata
II muratura a conci sbazzati con paramento di limitato spessore e nucleo interno	A (II) muratura a sacco formata da pietre di pezzature molto varie male intessute e prive di collegamento tra i due paramenti
III muratura in pietre a spacco con buona tessitura	B (III-4 oppure III-3) muratura a sacco formata da pietre di pezzatura più regolare bene intessute e con collegamento tra i due paramenti oppure con spigoli, mazzette e/o ricorsi in mattoni pieni e/o pietra squadrata
IV muratura a conci di pietra tenera (tufo, calcarenite, ecc.)	Ga (IV) muratura ad un paramento in blocchetti di tufo o pietra da taglio di dimensioni costanti
V muratura in blocchi lapidei squadrati	Gb (V) muratura ad un paramento in blocchetti di tufo o pietra da taglio di dimensioni costanti
VI muratura in mattoni pieni e malta di calce	La (VI) muratura in laterizio pieno e semipieno (percentuale foratura $\leq 45\%$)
VII muratura in mattoni semipieni con malta cementizia (doppio UNI foratura $\leq 40\%$)	Lb (VII) muratura in laterizio pieno e semipieno (percentuale foratura $\leq 45\%$)
VIII muratura in blocchi laterizi semipieni (percentuale foratura $< 45\%$)	Lc (VIII) muratura in laterizio pieno e semipieno (percentuale foratura $\leq 45\%$)
IX muratura in blocchi laterizi semipieni con giunti verticali a secco (percentuale foratura $< 45\%$)	Ld (IX) muratura in laterizio pieno e semipieno (percentuale foratura $\leq 45\%$)
X muratura in blocchi di calcestruzzo o argilla espansa (percentuale foratura tra 45% e 65%)	(H-I)a (X) muratura in blocchetti di calcestruzzo prefabbricati con inerti ordinari o leggeri (argilla espansa) omogenei in tutta la sua estensione
XI muratura in blocchi di calcestruzzo semipieni (percentuale foratura $< 45\%$)	(H-I)b (XI) muratura in blocchetti di calcestruzzo prefabbricati con inerti ordinari o leggeri (argilla espansa) omogenei in tutta la sua estensione
-	M muratura in blocchi di laterizio con foratura $> 45\%$
Tabella C8A.2.2	Z (6 e 7) muratura consolidata

Fig. 3 SSRT [26] abacus for classifying masonry structures (right column) related to the ministry classification (left column).

Fig. 4 SSRT [26] abacus for classifying masonry structures: B type, wall-sack masonry made by stone blocks well assembled and with transversal connection of the two wall facings; 3D setting and external appearance.

Fig. 5 Palazzo Vecchio. East wall of the Salone dei 500, with masonry made in different modes (from Ref. [34]).

Fig. 6 Brunelleschi's Cupola. Anomaly of about $50\text{-}60 \times 50\text{-}60$ cm referable to a putlog hole not well buffered at its bottom.

Fig. 7 Brunelleschi's Cupola. Platform substratum is dipping towards the rib; GPR survey well outlines screed and insole, too.

as the best performing in investigating the Cupola's 2.20 m masonry, which appears to be homogeneous and compact, the changing from the lower portion made by stone blocks to the upper portion made by bricks was well identifiable (Fig. 6).

The survey also outlined diffuse small voids in the masonry and the presence of putlog holes not well buffered; the survey also revealed the platform material stratigraphy and that the laying plans of the floors dip towards the corner ribs (Fig. 7).

5.3 Giotto's Bell-Tower

Arnolfo di Cambio was the first architect in charge of bell-tower; he designed the tower and executed the foundations in the year 1298, but construction works began in 1334 under the direction of Giotto. After his death Andrea Pisano directed the works until 1348, he increased the thickness of the walls of the first floor up to the present thickness of 3.9 m, and built the second floor with a wall thickness of 3.1 m. Later on, Francesco Talenti built the third, fourth and the fifth floors, with a high bell-cell, by erecting at the corner four massive pillars, connected by large windows; the bell-tower was finished in 1359.

Each designer changed the design, but, despite these changes, the masonry appears to be homogeneous and very well done; a few boreholes

testify the bell-tower masonry is made by stone and mortar; on all the visible inner outsides, stone quoins are accurately placed at "facciavista".

GPS survey, systematically executed by means of a 2 GHz antenna on walls and pillars of the bell-tower for verifying that, confirms this masonry structure and compactness.

Inner facing quoins are of about 30 cm thick and followed by a more chaotic response due to a competent masonry made by stone and mortar, externally the about 7 cm marble revetment gives a strong homogeneous response (Fig. 8).

5.4 San Giovanni Baptistery

The San Giovanni Baptistery was finished in the XI century, the walls have a thickness of about 1.7 m and are covered on both sides by marble slabs thick 7 cm, masonry is made of mortar and stone elements, as visible in putlog holes and in photos of the 1939 when many revetment slabs were renewed.

Preliminary GPS investigations were made for verifying masonry structure; the 900 MHz antenna investigated all the 170 cm of the masonry (Fig. 9).

The GPR survey highlights a solid and compact masonry with local reflections attributable to small voids in the masonry and in one segment also a very large unknown void: a secret?

Fig. 8 Giotto's Bell-Tower. Radargram along the staircase between the 4th and 5th floor on the external wall.

Fig. 9 San Giovanni Baptistery. Side SW, GPR slices showing the structure of the masonry and the presence of a secret void inside the wall.

6. Conclusions

As conclusions of our experience with the GPR on historical masonry of the main monumental buildings of Florence, we can assess GPR is a very powerful, versatile and useful tool for exploring the structure of a historical masonry.

Before planning a GPR survey on historical masonry it is compulsory acquiring the thickness of the wall to be investigated because this determines the type of antenna and the signal sampling time.

GPR output is radar-grams to be interpreted based on experience and specific knowledge about the masonry age and modes of construction at those times; missing in this can lead to gross errors in interpretation.

In parallel, it is appropriate to acquire other technical data on the masonry to be investigated through other NDTs like thermography, sonic, ultrasonic survey, and, where possible, WDI as DAC-test, endoscopies, peeling of plasters, small-scale

essays.

Only the convergence from historical documentation, knowledge on the historical masonry, NDTs and WDIs and, of course, experience can lead to a confident definition of the masonry structure, materials and assemblage for a cultural heritage historical monumental building, as done for the Florence main ones: Palazzo Vecchio, Brunelleschi's Cupola, Giotto's Bell-Tower and San Giovanni Baptistery.

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