MACMILLAN Advanced Research Series

3

STRUCTURAL ANALYSIS OF HISTORICAL CONSTRUCTIONS

Possibilities of numerical and experimental techniques

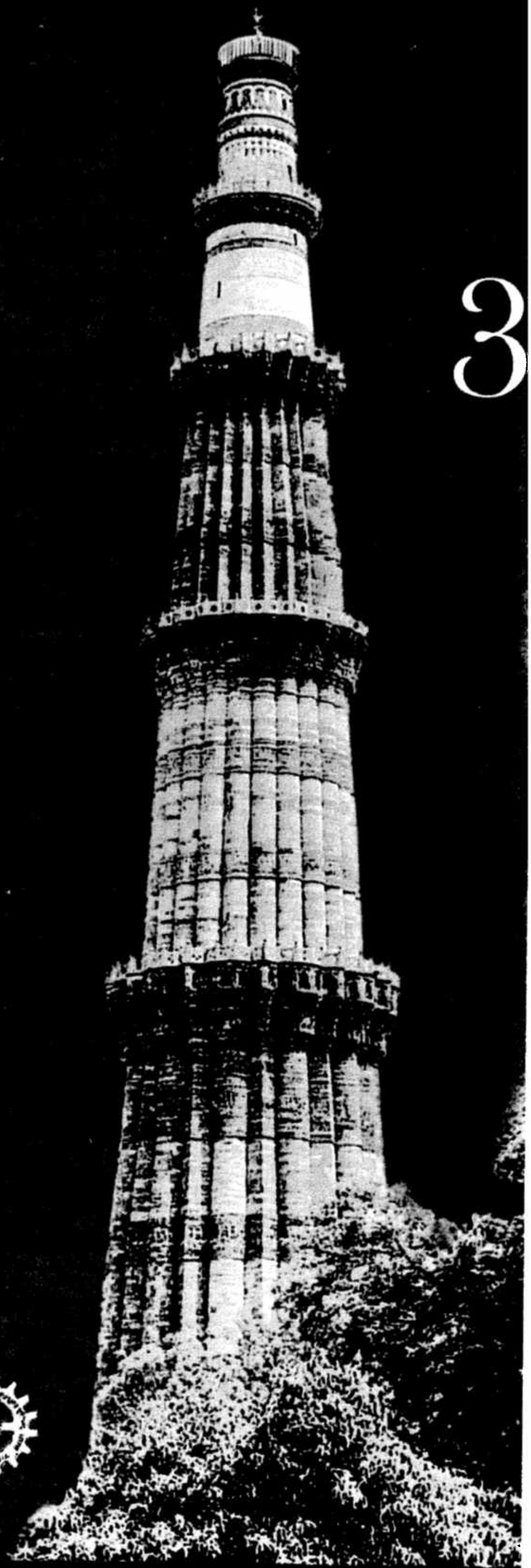
Edited by

Paulo B. Lourenço

Pere Roca

Claudio Modena

Shailesh Agrawal



UPC

First published, 2007

MACMILLAN INDIA LTD.
Delhi Bangalore Chennai Kolkata Mumbai
Bhopal Chandigarh Coimbatore Cuttack Guwahati
Hubli Hyderabad Jaipur Lucknow Madurai Nagpur
Patna Pune Raipur Thiruvananthapuram Visakhapatnam

Companies and representatives throughout the world

ISBN 10: 1403-93157-7
ISBN 13: 978-1403-93157-3

Published by Rajiv Beri for Macmillan India Ltd.
2/10, Ansari Road, Daryaganj, New Delhi 110 002

Printed at Rajkamal Electric Press
B-35/9, G.T. Karnal Road, Delhi 110 033

Proceedings
of the
5th International Conference

Structural Analysis of Historical Constructions

Possibilities of Numerical and Experimental Techniques

VOLUME 3

6-8 November 2006

New Delhi, India

Edited by:

Paulo B. Lourenço
University of Minho, Portugal

Pere Roca
Technical University of Catalonia, Spain

Claudio Modena
University of Padua, Italy

Shailesh Agrawal
Central Building Research Institute, India

MACMILLAN

Organization

University of Minho

Technical University of Catalonia

University of Padua

Central Building Research Institute

Sponsors

European Commission
EU-India Economic Cross Cultural Programme

Fundação Oriente

The papers are published in the form submitted by the authors, after revision by the Scientific Committee. The Editors cannot accept any responsibility for possible errors or discrepancies.

Published by: Macmillan India Ltd

Structural Analysis of Historical Constructions, New Delhi 2006
P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.)

The Façade and the Rose-Window of Troia Cathedral (Apulia, Italy)

Domenico Liberatore, Giuseppe Spera and Marco Mucciarelli
University of Basilicata, Department of Structural Engineering, Geotechnics, Applied Geology, Potenza, Italy

Nicola Masini, Angela Calia, Alessandro Capriuoli and Vito Racina
CNR, IBAM, Potenza, Italy

Luigia Nuzzo
University of Lecce, Department of Materials Science, Lecce

Enzo Rizzo
CNR, IMAA, Potenza, Italy

Luigia Binda and Lorenzo Cantini
Polytechnic of Milan, Milan, Italy

ABSTRACT: The façade of Troia Cathedral is tilted around a horizontal hinge, of seismic origin and passing through the rose-window. As a consequence, the rose-window is heavily damaged and deformed out-of-plane. In this paper, cognitive and diagnostic investigations are presented on the materials and the elements of the rose-window (GPR, thermography, sonic and ultrasonic tests, ambient vibration survey), together with a structural diagnosis.

1 INTRODUCTION

According to historical tradition, Troia Cathedral (Apulia, Italy) was founded in 1093 and consecrated in 1120. It is the masterpiece of the Romanesque architecture of the region of Capitanata, blending Byzantine and Muslim reminiscences with oriental elements.

The plan has the shape of Latin cross. The three naves are separated by 12 columns, divided in two rows of 6. A 13th column is located at the side of the first column on the right.

The façade (Fig. 1) is 18.28 m wide and 19.90 m high. It has a basement whose height ranges from 1.48 m to 2.08 m. Over the basement, there is a sequence of seven blind arches, placed on pilaster strips, which frame rhombs and oeil-de-boeufs. The central arch has diameter 3.20 m and the lateral arches 1.70 m. The central arch surmounts the portal, consisting of two smooth posts in “Proconnesio”, ending with two capitals bearing an architrave, richly adorned in bas-relief representing the theme of conversion, bearing in turn a lunette consisting of a smooth arch with moulded cornice, in “Proconnesio” as well. The blind arches and the rhombs are characterized by chiaroscuro effects obtained using the clear stone of Castelluccio and the sandstone of Roseto. A moulded cornice, resting on corbels decorated with zoomorphous, phytomorphous and geometric shapes, separates the lower part from the upper part of the façade.

The upper part is in turn divided in three parts: the central part, consisting of the tympanum and corresponding to the section of the nave, and the lateral parts, with single pitch, recalling the section of the side aisles.

The central tympanum consists of a round arch, resting on two couples of columns in reused marble, each resting in turn on a stylophorus lion. Inside the arch of the tympanum, there is another arch with plastic elements, in tondo or bas-relief with anthropomorphous, zoomorphous and floral figures. Inside this arch, there is the rose-window. Over the imposts of the outer arch, there are two other lions keeping the head of a calf and a human head.

The rose-window has diameter 6 m and consists of 11 twin columns, outer and inner, in stone and reused marble, connected to a central oeil-de-boeuf and to a ring consisting of prefabricated elements, whose surface is decorated by arched ribworks forming ogives. There are 11 transennae between the twin columns, embroidered to openwork, each with a different and strongly symbolic pattern: the square, the rhomb, the cross, the circle.

Some inner columns are in white marble with grey bands. These marbles could be “Proconnesio” or “Pentelico”, but other origins cannot be excluded. The outer columns are in white marble, sandstone, limestone, breccia with elements of marble or limestone.

The rose-window presents a wide set of constructive solutions aimed at providing equilibrium, not only in the final configuration, but also during the assemblage. Besides a particular care to stereotomy, the contact between the different elements is integrated by iron bolts and melted lead, especially between the columns and the capitals, and between the capitals and the arched ribworks, as detected by thermography and Ground Probing Radar (GPR).

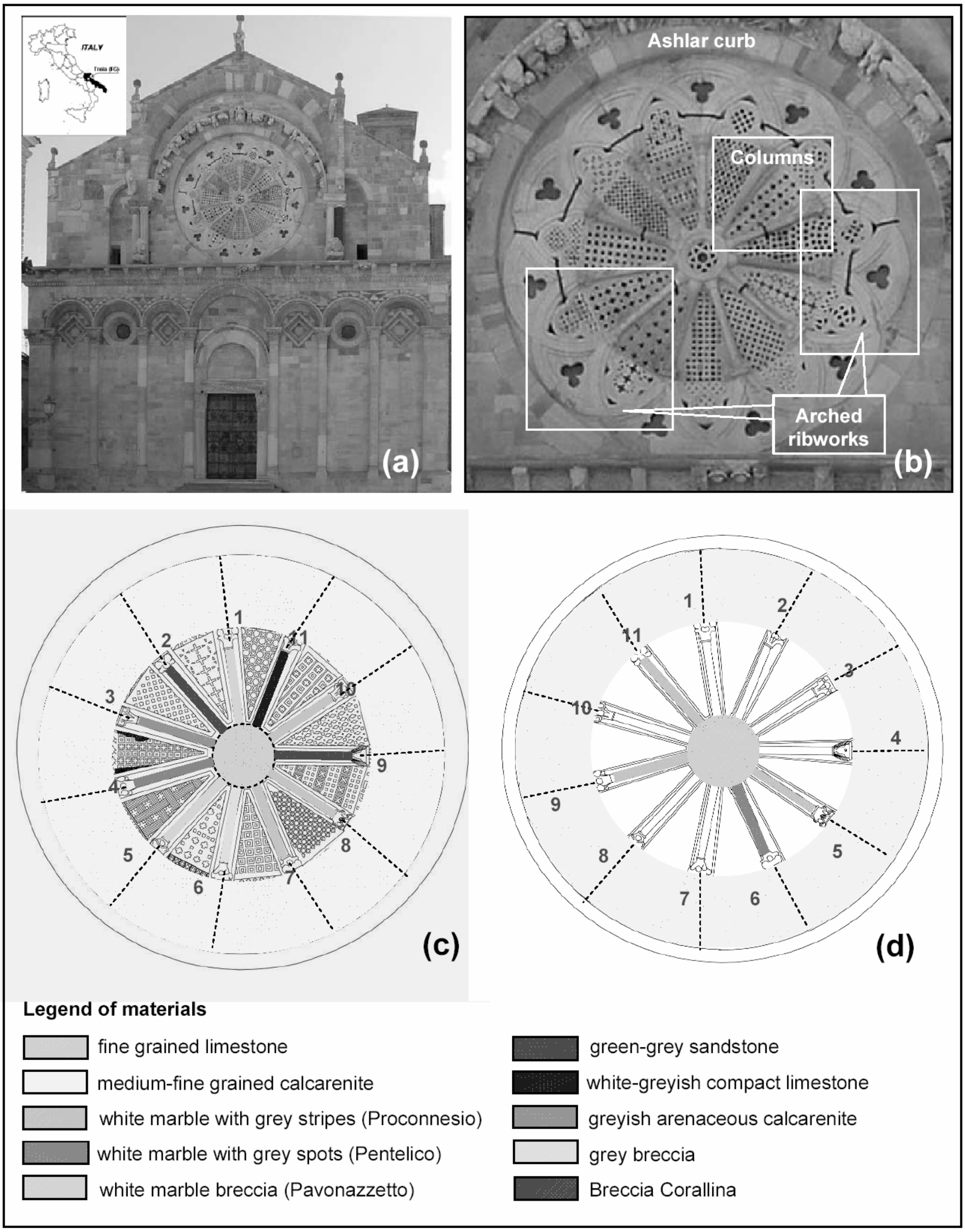


Figure 1 : Façade and rose-window of Troia Cathedral

2 COGNITIVE AND DIAGNOSTIC INVESTIGATIONS

2.1 Building materials

A mineralogical and petrographic study, based on the observation of thin section at microscope with polarized light and X-rays diffractometry, put in evidence different materials. In particular, the carved triangular panels are composed of medium-fine grained calcarenites, in turn divided in three different lithological types. Two are characterized by diagenetic crystallization processes of calcarenites with Apennine origin. The third shows characteristics which induce to hypothesize an origin from the Gargano territory (in the North Apulia).

Moreover, the oeil-de-boeuf is a fine grained limestone whereas the elements decorated by intersecting arches are coarse grained calcarenites which show the characteristics of carbonate rocks of the Gargano territory.

As regards the ashlar curb, it consists of two main kinds of materials, light-coloured calcarenites and greenish sandstones.

Finally, the columns of the rose-window are mostly reused marbles coming from the ancient *Aecae*, a Roman site located near Troia. In particular on the external side, one can see reused white marbles with grey stripes (the so-called “Proconnesio” marble, in columns 7, 8, 10), white marble with grey spots (“Pentelico” in column 4), white-marble breccia (“Pavonazzetto” in columns 1 and 5), green-grey sandstone (column 9), white-greyish compact limestone (column 11), calcareous breccia with a reddish ferruginous-clayey matrix (“Breccia Corallina” in column 2), greyish arenaceous calcarenite (column 3), and calcareous breccia with brown-greyish matrix (column 6). Because of their heterogeneous composition, different responses to the electromagnetic and sonic investigation are therefore expected. On the inner side of the rose-window the columns are more homogeneous. They are made mainly of marble, of the types “Proconnesio” (such as for columns 9, 11 and 5) and “Pentelico” (column 6). Most of them are covered with a thin layer of plastering preventing a certain identification of the supposed marble constitution.

The hypotheses about the origin of the materials have to be verified through the comparison with materials from the supposed origins. This study has been started, sampling the materials coming from the quarries of limestone and sandstone located in the territories of the two neighbouring communes of Castelluccio Valmaggiore and Roseto Valfortore.

At the same way, the identification of the marbles needs more accurate laboratory tests in order to discover their provenance.

2.2 GPR investigations

The design of the most effective restoration procedure requires a correct diagnosis of the problems and an accurate knowledge of building characteristics and of all parameters defining the structural model, such as internal and external constraints. For this reason the GPR survey (Nuzzo *et al.*, 2005) was aimed to:

- determine thickness and internal structure of the circular curb;
- detect cracks in the columns and calcarenite elements with intersecting arches;
- find iron bolts in joints between columns and capitals, and between columns and the central oeil-de-boeuf;
- delineate the boundaries between the restored parts and the original stone materials.

The complex geometry of the rose-window and the large elevation from the ground surface (about 15 m) required the use of a twin mast-climber and specific geophysical acquisition techniques. The GPR measurements were performed on different architectural elements of the wheel window, along the external and internal façade. SIR2000 instrument (GSSI) with 900 and 1500 MHz antennas in continuous mode was used. On the external side, due to the large diameter of the rose window (about 6 m), several adjacent profiles were carried out along the circular ashlar curb for a total length of about 20 m. Moreover, 11 radargrams were acquired along the intersecting arched ribworks and 11 radargrams along the columns. On the internal side, because of the presence of fixed scaffolding and two metallic tie-beams on the inner façade, only the upper part of the circular ashlar curb (about 6 m) and some columns were investigated.

Standard processing was applied to the data. It includes horizontal scale normalization to a constant trace density, gain removal, time-zero correction, 1D and 2D filtering, background removal to enhance very shallow discontinuities, and Kirchhoff migration using a constant value of the electromagnetic wave velocity for each profile. The velocity was estimated either by fitting diffractions to theoretical hyperbolas or using the reflection time from interfaces at known distance (typically the air interface beyond each architectural element).

In this paper we discuss the results obtained on the most significant architectural elements. Fig. 2 shows the unmigrated (top) and migrated radargrams (bottom) relating to column 6, for which a velocity of 0.108 m/ns was estimated. Three reflections at 2, 3.4 and 5.4 ns are referable to interfaces between the different materials. In particular, a 3 to 5 cm thick layer of inhomogeneous material separates internal and external columns. In this space the carved panels are joined together by rubble and mortar. Thus, the total thickness of the three-layers medium (external column - inhomogeneous material - internal column) is about 26 cm.

Moreover, two semi-hyperbolas with apex at 0.05 m and 1.2 ns, on the two ends of the external column, could be associated to the edge of an iron anchor bolt linking the column with the capital. The anchor bolt penetrates in the column for about 5 cm, as marked in the migrated section.

Fig. 3 is relating to the intersecting arched ribworks between columns 5 and 3. The radargram shows two different responses to the electromagnetic wave: the former between the abscissas 0-1.84 m, the latter between 1.84-3.68 m. This fact denotes the presence of two different materials. Moreover, diffraction hyperbolas at both ends reveal the presence of anchor bolts of about 10 cm linking the intersecting arched ribworks with the capital.

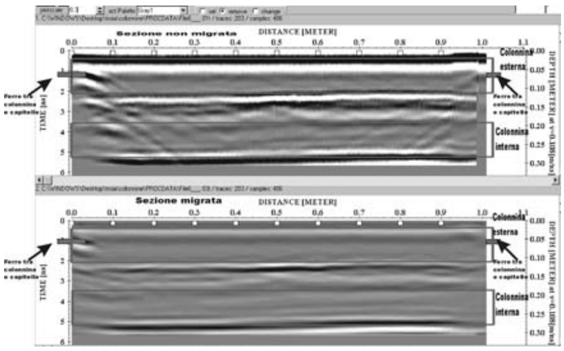


Figure 2 : Top: unmigrated radargram of column n. 6. Bottom: migrated radargram with estimated velocity of em waves 0.108 m/ns.

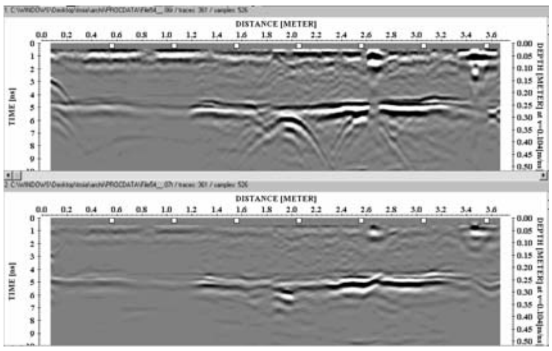


Figure 3 : Top: unmigrated radargram of the arched ribwork between columns n. 5 and n. 3. Bottom: migrated radargram with estimated velocity of em waves 0.104 m/ns.

Finally, in order to understand how the wheel window is linked to the façade masonry, GPR analysis was carried out on the ashlar curb. The radargrams highlight alternation of zones characterized by different propagation properties and reflection/diffraction patterns. The processing of radargrams shows threee reflections. The first could be observed at 4-5 ns (corresponding to a deepth of 20-25 cm) followed by chaotic diffraction patterns revealing an heterogeneous material. The second reflection is at 10-11,5 ns (deepth of 40-45 cm) and the final reflection is observable at about 14 ns (deepth of 65 cm).

In some cases only the final reflection is recorded, perhaps due to the presence of monolithic ashlars, the so-called “diatons”, inserted athwart in the masonry with the function of connection between the internal and the external rows of the curb. In other parts no reflection is recorded because of the high absorption of the electromagnetic energy of some ashlars.

Fig. 4 shows the interpreted curb structure superimposed on the composite radargram obtained merging the topmost halves of the migrated sections from the external and the internal side.

In summary, the curb structure is a sandwich composed by two external rows of ashlars and an heterogeneous intermediate layer in the masonry core, probably composed by rubble. The two external rows are joined by a large number of diatons, especially in the lower part of the rose-window.

Finally, as regards the iron elements, they have been detected at both ends of the lower columns, and at one end of the upper columns. This permitted to discover the construction phases of the rose-window. In the first phase, the lower columns were positioned, and the oeil-de-boeuf was centred. Subsequently, the upper columns were inserted for some centimetres in the cups of the oeil-de-boeuf and joined with the capitals by means of metal bolts. This permitted to optimize the tolerance during the positioning of the columns.

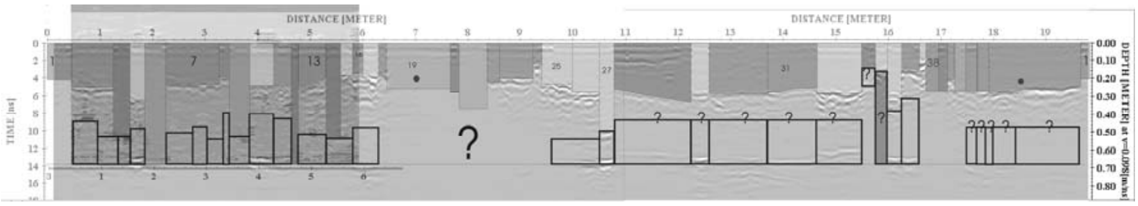


Figure 4 : GPR results on the circular ashlar curb: interpreted curb structure superimposed on the composite migrated section from both sides, outlining the ashlars geometry and materials, and highlighting a more heterogeneous masonry core.

2.3 *Thermography*

In order to integrate the information obtained by GPR survey, Infrared Thermography (IRT) has been performed. IRT is a non-contact sensing method concerned with the measurement of radiated electromagnetic energy (the so called spectral radiance defined by a law derived by Planck), emitted by a surface at a given temperature.

In the field of the inspection and diagnosis of historic buildings, IRT is an efficient investigative non-destructive tool, used for more than 30 years, which allows to detect subsurface voids and defects (Inagaki *et al.*, 1999), to map moisture (Grinzato *et al.*, 2002) and to evaluate conservation treatments (Avdewlidis and Moropolou, 2004) as well.

IRT has been perfomed on the external side in qualitative way with a passive approach. The thermographic system used is an IR detector TVS-600 that gives a spectrum response between 8 and 10 μm.

The aims of the application were to detect damage, old conservation treatments and the presence of iron elements joints. In order to obtain the best resolution of the pictures, the exposure to solar irradiation of the rose-window (WNW) has been observed and analyzed by means of IR camera, continuous from late afternoon to evening for three successive days. At the end, for each element a picture with the best resolution has been selected, by observing the cracks and the interface between marble (or stone) and mortar on the columns.

In this way IR survey has allowed to detect:

- cracks on the columns;
- surface cracks not visible;
- conservation treatments composed by mortar near the joints between the columns and the oeil-de-boeuf;
- superficial iron elements which join capitals to intersecting arched shape ribworks or to columns (Fig. 5).

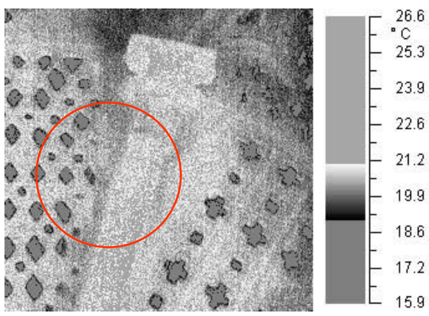


Figure 5 : Thermal variation induced by a metal element connecting column and capital.

2.4 *Sonic and ultrasonic tests*

Ultrasonic tests have been carried out on the columns of the rose-window and sonic tests on the arched ribworks. The test has been made both from outside and inside.

For each column, 6 points have been chosen, spaced by 20 cm and numbered from the oeil-de-boeuf to the capitals, where the ultrasonic tests have been carried out at the frequency 50 kHz. The tests highlight a good propagation velocity, generally ranging from 4000 and 5000 m/s, with some "falls", corresponding to small values, indicating localized damage.

The tests on the inner columns have been disturbed by a thin layer of mortar, so that it cannot be excluded that some small values of the velocity have been induced by the defect of adhesion between the instrumentation and the stone surface. The test results are reported in Tables 1 and 2.

Transparency sonic tests have been carried out on the arched ribworks, with results similar to the outer columns, even though with smaller propagation velocity.

Table 1 : Ultrasonic tests on the inner columns of the rose-window.

Col.	Point 1 (m/s)	Point 2 (m/s)	Point 3 (m/s)	Point 4 (m/s)	Point 5 (m/s)	Point 6 (m/s)	Min (m/s)	Max (m/s)	Mean (m/s)	Std dev (m/s)
1	1335.0	2169.0	1905.0	1443.0	1530.0	596.0	596.0	2169.0	1496.3	540.4
2	2865.0	2933.0	3077.0	2801.0	2571.0	1291.0	1291.0	3077.0	2589.7	657.7
3	2028.0	1307.0	2740.0	1698.0	2288.0	2740.0	1307.0	2740.0	2133.5	573.3
4	2571.0	4219.0	4082.0	4219.0	1770.0	3077.0	1770.0	4219.0	3323.0	1021.7
5	2570.0	3717.0	3953.0	3717.0	4219.0	2054.0	2054.0	4219.0	3371.7	857.1
6	2862.0	3717.0	3077.0	3413.0	3831.0	3610.0	2862.0	3831.0	3418.3	380.1
7	2280.0	3400.0	3610.0	3155.0	4082.0	2173.0	2173.0	4082.0	3116.7	754.7
8	1350.0	2625.0	477.0	491.0	1721.0	1380.0	477.0	2625.0	1340.7	807.9
9	1585.0	4219.0	4082.0	3831.0	4367.0	3077.0	1585.0	4367.0	3526.8	1054.4
10	2740.0	3155.0	3831.0	3953.0	2801.0	3077.0	2740.0	3953.0	3259.5	516.1
11	3226.0	3831.0	3155.0	3509.0	3610.0	3155.0	3155.0	3831.0	3414.3	279.6

Table 2 : Synthesis on the materials, decay and ultrasonic tests on the inner columns

Col.	Material	Decay	Ultrasonic tests
1	Bricks		Very low values of the velocity
2	Calcareous stone		Low value at column-capital joint
3	Calcareous stone	Relative rotation at column-capital joint	Low value at point 2 (40 cm from the oeil-de-boeuf)
4	Marble	Relative rotation at column-capital joint	
5	Calcareous stone	Fracture at mid-length	
6	Marble	Relative rotation at column-capital joint	
7	Marble	Compressive failure at column-capital joint	Low value at column-capital joint caused by the longitudinal crack
8	Grey to green sandstone	Strong decay at mid-length	Low values on the average, very low at mid-length
9	Calcareous stone	Fracture near the oil-de-boeuf	Very high values for a calcareous stone, very low value near the oeil-de-boeuf
10	Calcareous stone	Relative rotation at column-capital joint, fracture near the oeil-de-boeuf	High values for a calcareous stone, the lowest value is measured near the oeil-de-boeuf
11	Marble		Satisfactory values for a marble, the low std dev highlights homogeneous conditions

2.5 *Ambient vibration survey*

The Horizontal to Vertical Spectral Ratio (HVSR) is used to estimate the fundamental frequency of soils and buildings (see Mucciarelli and Gallipoli, 2002 for more details). For buildings, the precision is greater because the hypothesis of absence of amplification on the vertical component is better fulfilled.

The measurements on the façade and the rose-window were performed with a digital tromometer (Micromed Tromino), that hosts in a single, small case 3 seismometers, a 24-bit digitizer and the data storage unit. For all the measurement points, 6 recording were acquired, lasting 1 min each. The sampling frequency was 512 Hz. The signals were detrended and filtered in the range 0.1-256 Hz. After the transform in the frequency domain, the ratio between the horizontal and the vertical component was calculated in order to estimate the fundamental frequencies. The HVRS analysis identified separate fundamental frequency for the two orthogonal directions (in-plane and out-of-plane). On the façade, two frequencies were identified, at 3.2 and 8.0 Hz, with amplitude increasing with height, as expected for the fundamental mode (Fig. 6).

The measurements carried out on the rose-window (oeil-de-boeuf, arched ribworks and connection with the façade) show a different eigenfrequency (Fig. 7). While the façade frequencies are still visible, a separate frequency emerges at 22 Hz. This mode has greater amplitude at the center of the rose-window and decreases towards the connection with the façade, as expected for a 2D plate fundamental mode.

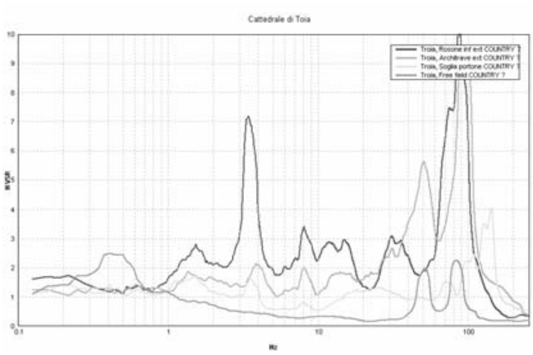


Figure 6 : HVSR of the façade at different heights.

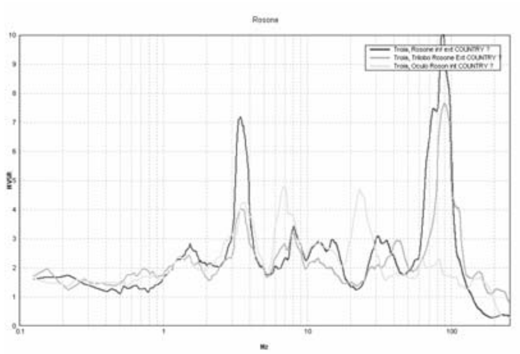


Figure 7 : HVSR of the rose-window.

3 STRUCTURAL DIAGNOSIS

The main damage of the façade consists of a rotation around a horizontal “hinge”, approximately 9.50 m above the base. The top of the façade is nearly 30 cm out of plomb. The origin of the rotation is clearly seismic, even though it was not possible to determine the date and the intensity of the event.

The rotation is also confirmed by the displacement of the inner surface of the façade, with reference to the corbel which was originally located on the top of the longitudinal wall on the left of the central nave, with the aim to bear the first roof truss. That corbel was originally in contiguity with the inner surface of the façade wall, whilst now it is displaced of nearly 25 cm. The opening created by the rotation of the façade was closed in the past. It is also interesting to note that the longitudinal walls were superelevated, with the aim to position the new roof trusses, preventing the interaction of the tie with the rose-window. The new corbel, which presently bears the first roof truss, is in contiguity with the façade, and is offset nearly 25 cm with reference to the original corbel below.

The damage of the façade is also confirmed by the damage of two couples of columns at the sides of the rose-window. The columns on the right appear splintered, with damage especially pronounced for the column in *Red Porphyry*, which has also conchoid fractures in the upper part and in the capital. Both columns are slightly tilted towards the right and inwards. The couple of columns on the left are tilted outwards and splintered at the base and at the top. Vertical cracks, indicating compression failure, can also be observed in their capitals.

The rotation of the façade is the presumable cause of a set of slidings and damages of the façade. The upper arch appears strongly ovalized, its keystone presents vertical fractures, and is displaced outwards and downwards. The lower arch presents a vertical fracture at the key, and some voussoirs are displaced outwards and downwards.

The rotation of the façade induced heavy deformations and damages in the rose-window, which is displaced outwards in the upper part, and inwards at the centre. Disconnections and rotations of the capitals, as well as compression failures of the columns may be observed. Relative displacements, up to 1 cm, may also be observed at the joints between the arched ribworks. An out-of-plane restraint was set up, presumably in the nineteenth century, consisting of two horizontal tubes, anchored to the ashlar and connected to some columns and arched ribworks through metal elements.

4 CONCLUSIONS

The façade and the rose-window of Troia Cathedral present a set of damages and deformations of seismic origin which can be ascribed to a rotation of the façade itself around a horizontal hinge passing through the centre of the rose-window.

With the aim to set up an intervention of restoration and seismic "improvement", a set of investigations have been carried out: identification of the materials, GPR investigations, termography, sonic and ultrasonic tests, ambient vibration survey.

The identification of the materials highlights the large use of reused marbles.

GPR investigations confirm the arrangement of the voussoirs surveyed on the surface and permit to estimate their extension on the wall thickness. They also highlight the presence of metal elements aimed at connecting the columns of the rose-window to the corresponding capitals. The presence of metal elements is confirmed by thermographic investigation.

The ultrasonic and sonic tests on the columns and arched ribworks, respectively, generally yield a good propagation velocity, with some exceptions corresponding to localized damage.

Finally, the ambient vibration survey yield the eigenfrequencies of the first in-plane and out-of-plane modes of the façade. They also permit to identify the first out-of-plane mode of the rose-window.

ACKNOWLEDGEMENTS

This study has been funded by Comune di Troia and Ente Diocesi di Lucera-Troia. The authors are also grateful to Edoardo Beccia, Stefano Cibelli, Piero Guadagno and Giulio Tricarico for their help.

REFERENCES

Avdewlidis, N.P. and Moropolou, A. 2004. Applications of infrared thermography for the investigation of historical structures, *Journal of Cultural Heritage* 5, p. 119-127.

Belli D'Elia, P. 1998. Per la storia di Troia: dalla chiesa di S. Maria alla cattedrale. *Vetera Christianorum* 25, p. 605-620.

Grinzato, E., Bison, P.G. and Marinetti, S. 2002. Monitoring of ancient buildings by the thermal method, *Journal of Cultural Heritage* 3, p. 21–29

Inagaki, T., Ishii, T. and Iwamoto, T. 1999. On the NDT and E for the diagnosis of defects using Infrared thermography, *NDT&E International* 32, p. 247-257.

Muccarielli, M. and Gallipoli, M.R. 2002. A critical review of ten years of HVSR technique. *Bollettino di Geofisica Teorica e Applicata* 42, p. 255-266.

Nuzzo, L., Rizzo, E. and Masini, N. 2005. Georadar investigations for the diagnosis of the rose window of the cathedral of Troia (Southern Italy): preliminary results, in Proceedings of Art'05 - 8th International Conference on "Non Destructive Investigations and Micronalysis for the Diagnostics and Conservation of the Cultural and Environmental Heritage." Lecce (Italy), May 15th - 19th, 2005.

Ranalli, D., Scozzafava, M. and Tallini, M. 2004. Ground penetrating radar investigations for the restoration of historic buildings: the case study of the Collemaggio Basilica (L'Aquila, Italy). *Journal of Cultural Heritage* 5, p. 91–99.

Sandmeier, K.J., 2004. REFLEXW, Version 3.0.8 Windows™ 9x/ NT- program for the processing of seismic, acoustic or electromagnetic reflection, refraction and transmission data. Copyright 1998-2004 by K. J. Sandmeier, Zipser Straße 1, D- 76227 Karlsruhe, Germany. www.sandmeier-geo.de