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From causes to effects. Integration of heterogeneous data from non-invasive imaging for the diagnosis and restoration of monuments. The case of the Church of S. Francesco della Scarpa in Lecce (Southern Italy)

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***Abstract* –The church of San Francesco della Scarpa is a church in the historic center of Lecce (Southern Italy), so called in the 16th century when the minor friars who lived in the destroyed convent of Santa Maria del Tempio were divided into conventual and observant: the former wore shoes unlike the seconds. The church has had static stability problems in recent years. In order to understand the causes, a series of findings have been undertaken with the use of integrated non-destructive methodologies. Ground Penetrating Radar (GPR), seismic tomography (ST), passive seismic (PS) and laser scanning survey were used. Results reveals the structural problems of the church.**

I. INTRODUCTION

Restoration is a multidisciplinary method aimed at preserving works of human creativity of recognized cultural value, including historical and aesthetic one, so as to extend its life and assure its posterity. It must be rooted as much in historical research as in traditional maintenance practices, and consequently based on complete fusion of historical and technical-scientific expertise [1]. , In order to produce an accurate preventive diagnosis of static problems of architectural and built heritage so as to suggest reinforcement interventions, the restoration cannot be separated from the knowledge and conservation of the structural components.. These interventions must be designed to act on the causes of the problem and not only on the effects. Moreover, they must be not only effective but also compatible and, 'quite' reversible. To this aim, multidisciplinary approaches need to be adopted by means of the integration and fusion of diverse, complementary and non-invasive methods of diagnostics able to fully characterize the issues of static nature by understanding the cause-effect mechanisms. With particular reference to the need to image cracks, deformations and structural failures, there are several applications and approaches published mostly by European scientists. We cite, for the sake of brevity only [2], who integrated microwave tomography, GPR and seismic tomography with some direct data, provided by coring and endoscopic inspection, to detect, map and interpret cracks affecting the pillars of a church; [3] studied a medieval rose window threatened by an out of plane instability phenomenon, detecting by GPR cracks and metallic connecting elements of the rose window construction elements; the integration of seismic tomography and GPR for the analysis of structural behavior of the Cathedral of Mallorca by [4].

Despite the rich literature on non-invasive investigation methods applied to the study of static problems, there are few contributions aimed at characterizing these problems with an investigation strategy designed at identifying the cause-effect mechanisms. This is the case of the baroque Church of S. Francesco della Scarpa in Lecce, affected by widespread cracking phenomena, not serious, but difficult to understand from the point of view of the causes due to the lack of strongly connoted degradation patterns that generally help to identify the type of structural failure (crushing, push failure, foundation subsidence).

Therefore, an integrated multi-imaging approach including seismic tomography, GPR, and Laser scanning survey has been adopted with the twofold aim: i) to characterize the structural alteration and degradation; ii) and to identify the cause-effect relationship.

II. STUDY AREA

The church, located in the historical centre of Lecce (Southern Italy, Fig. 1), was founded in the 12th century on the site of a noble palace, as attested by some epigraphs. It was rebuilt assuming the current Greek cross plan between the end of the 17th century and the first two decades of the 18th century. In the 19th century some works made in the colonnade of an adjacent building incorporated the main facade of the church into the new structures.

Figure 1. Location and architectural details of The San Francesco della Scarpa church

The Greek cross plant (probably originally was a Latin cross) is oriented along the NE-SW (main entrance axis) and NO-SE directions. The four arms of the cross (NE. SO, NO, SE) are characterized and embellished by two orders of Corinthian and Tuscan style pilasters and by four altars. Originally there were six other altars, then removed and placed in another church.

Between the years 2000 and 2005, the church underwent restoration interventions on both structural and historical-artistic aspects. After a few years some problems of structural degradation have arisen, consisting of a widespread crack pattern on a load-bearing element placed at the intersection of the SO and SE arms of the Greek cross. The cracks that are found are 0.5-3.5 mm wide, mainly vertical and sub-vertical direction and 10-30 cm long which affect the base and the stone cladding of the pillar (Fig. 2).

The aim of the investigations was to make a diagnosis by identifying the causes of this failure and providing any indications on the methods of restorative intervention.

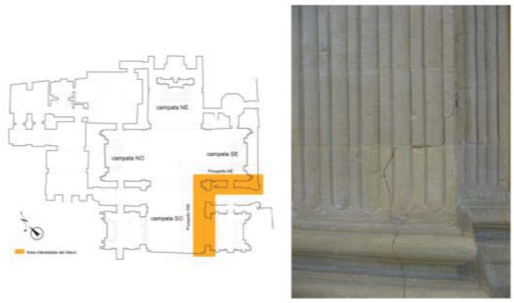

Figure 2. The area interested by structural problems

II. METHODOLOGICAL APPROACH

The objectives which the investigation methodology was based on, have been the following:

a) to detect, map and analyze deformations and cracks, in order to characterize and quantify the effects of the failure;

b) to perform multitemporal monitoring of the cracks aimed at understanding if the failure was still active and to what extent or whether it tended to achieve a balanced condition

c) to carry out the geophysical exploration of the shallow subsoil and foundations to identify the possible presence of subsidence of foundations as the cause of the failure.

To achieve these objectives, the following investigations were conducted :

1) 3d laser scanning survey aimed at obtaining the deformation framework of the structures of the church, performed with the Leica HDS ScanStation2 scanner (max speed. of 50,000 points per second, with a maximum range of 300 m, accuracy of about 0.3 cm, in flight time);

b) georadar prospections performed with IDS pulsed GPR equipped with low frequency (200-600 MHz) and high frequency (900 MHz - 2 antennas) GHz) to detect inner cracks and to identifythe building characteristics of the right side of the former church affected by the structural instability;

c) ultrasonic speed measurements using multi-channel instrument for sonic and ultrasonic measurements "TDAS" (frequency used 55 KHz) to analyze the stiffness characteristics and the state of degradation, and detect the inhomogeneity and internal cracks in one of the pillars affected by fracturing phenomena;;

d) environmental micro-tremor measurements (HVSR spectral ratio technique), performed with a compact portable instrument housing three geophones (velocimeters), a 24-bit digitizer and the power supply unit (Tromino) in a single rigid metal container (as regards microtremor measurements applications to historical buildings monitoring see [5]) to characterize the dynamic behavior of the building;

e) the installation of centesimal electronic crack meter to perform multitemporal monitoring of cracks and deformations.

III RESULTS AND DISCUSSION

Integrated non-invasive in situ investigations and a laser scanner survey have been performed in order to characterize and identify the causes of a crack picture that mainly affects the southeast of the church and in particular a pillar located at the intersection of the South East and South West spans adjacent to a rampant staircase.

The laser scanner survey revealed some constructional defects and out of plane deformations with a maximum value of 4.5 cm / 8 m (fig. 3).

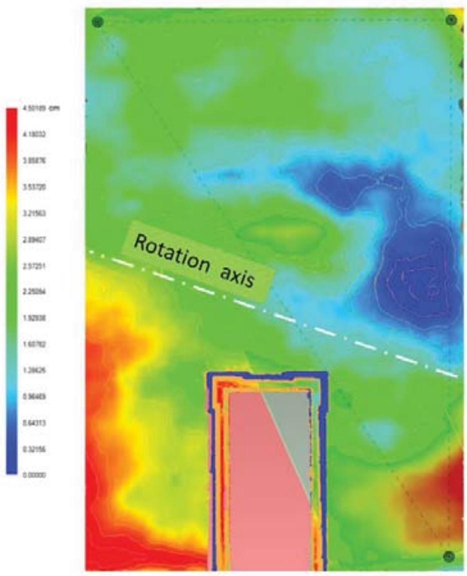

Figure 3. Deformation map obtained by laser scanner

Starting from this basic knowledge, the geophysical prospections have been aimed at exploring and investigating 1 to 2 m of the subsoil order to detect the causes of the static instability. The radar profiles showed in the first meter the presence of significant disturbances to be related, probably, to structures of anthropogenic origin and linked to the renovation of the pavement. The distribution of the propagation speed of the electromagnetic wave was estimated on all the georadar profiles created inside the former church and, subsequently, through the use of the empirical relationship, the distribution of the volumetric content was estimated in water (Fig. 4).

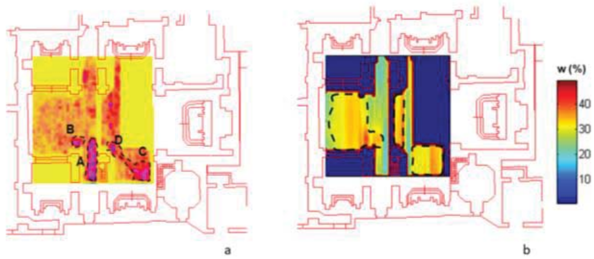

Figure 4 a) depth slice; b) volumetric water content map

From about 1.4m to over 2m radar profiles and time slices image the presence of cavities (fig. 4a), some of them close to the structure affected by instability phenomena. In correspondence with these cavities, the distribution of the volumetric content in water variable from 30 to 40% in the subsoil was estimated (fig. 4b). Seismic tomography prospections, applied to the structures revealed the distribution of the seismic velocity and allow to evidence the presence of weakened points. In the same structures, vertical seismic refraction tomography (fig. 5) detects very low speed values (800 <Vp <950 m /) for thicknesses ranging from 25 to 40 cm. This suggests that the lesions, although characterized by small amplitudes, are not superficial but affect the entire coating and probably the interface between the coating and the bearing core of the pillar.

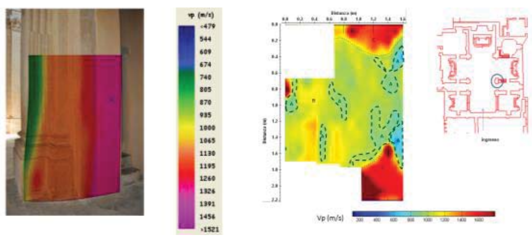

Figure 5. Seismic tomography results

Microtremor measurements and 3D seismic measurements provided additional information on the overall mechanical behavior of structures.

In particular, the analysis of the microtremor measurements (fig. 6) in the structure under investigation (NE facade of the SE arm) shows an inverse dynamic behavior compared to what is typically found on a wall. In particular, the mid-basal part oscillates more than the high part and with lower frequencies as well as having strongly different behaviors both in terms of frequencies and in terms of the extent of the oscillations if we consider the direction in the plane of the wall in comparison with the direction orthogonal to the plan.

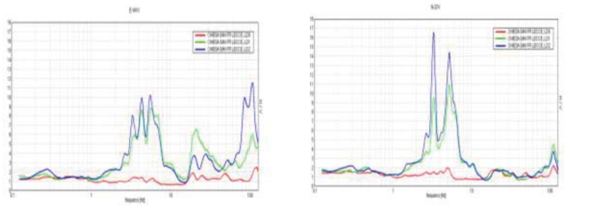

Figure 5 - Northwest span: value of H / V in the two directions at the various altitudes (direction orthogonal to the plane of the masonry, also called direction E-W, at the top, and in the plane (N-S) in the plane, or direction E-W, at the bottom)

The anomaly in the dynamic behavior detected in the wall of the south east arm can be due to two possible causes: i) one is the presence of the rampart staircase which causes a drastic decrease in stiffness in the middle-basal part of the wall, ii) the second is a non-uniform soil-structure interaction, as is observed by 3d seismic tomography (fig. 7) which highlights a non-homogeneous distribution of the propagation velocities of the P waves.

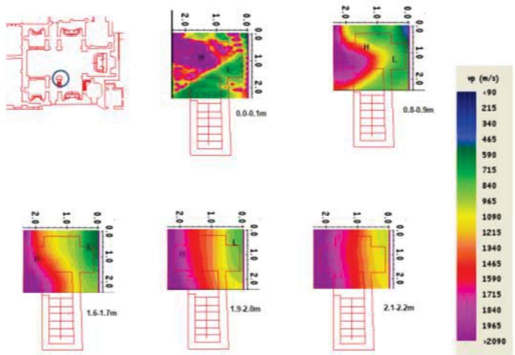

Figure 7. Seismic wave velocity distribution at several depths

IV CONCLUSIONS

In relation to the results of the relevant campaigns carried out, it is possible to establish that the crack pattern mainly affects the pillar coating but also begins to extend towards the bearing core.

Microtremor measurements and 3D seismic activity added more information on the overall mechanical behavior of structures. In particular, the analysis of micro-tremor measurements in the structure under investigation (NE facade of the SE arm) shows an inverse dynamic behavior compared to what is typically found on a wall. In particular, the mid-basal part oscillates more than the high part and with lower frequencies as well as having strongly different behaviors both in terms of frequencies and in terms of the extent of the oscillations if we consider the direction in the plane of the wall in comparison with the direction orthogonal to the plan.

In the current state of knowledge, the anomaly in the dynamic behavior detected in the wall of the SE arm can be traced back to two possible causes: one is the presence of the climbing ladder which causes a drastic decrease in stiffness in the middle-basal part of the wall, the second is uneven soil-structure interaction.

The presence near the pillar of cavities, of which a small part was known and in the remaining part was detected by the georadar (figure 4, in particular see anomalies A and D) may have played a decisive role in: i) reversing the behavior dynamic of the masonry structure, ii) and determining the anomalous distribution of the P waves in the foundation. Both i) and ii) caused the instability phenomenon which manifested with the above described cracking pictures of the pillar, placed at the intersection between the SE and SO arms of the Greek cross plant. As a whole, the integrated and multi sensor approach (see fig. 8) proved to be effective in characterizing the effects and determining the causes of the instability phenomenon of the church.

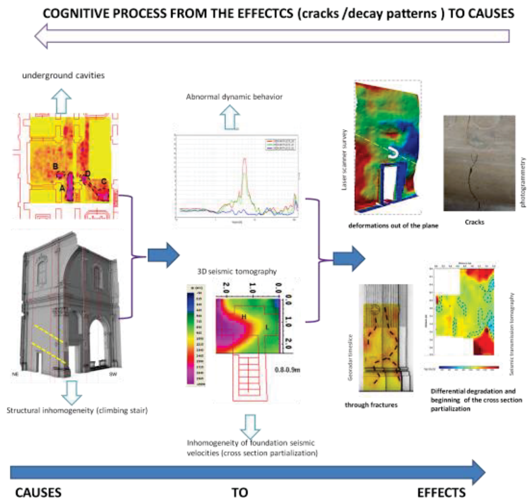

Figure 8. Schematic reconstruction of the results

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