Innovative Methodologies for Structural Control of Masonry Building under Preservation or Reconstruction Using Geomatic and Topographic Techniques.

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1 ABSTRACT

Operating a deformation analysis on masonry and ancient monumental buildings is not a simple operation. This type of extremely complicated structures present great irregularities and a variety of construction techniques that not always are visible. Thus, the measurement's network has to be wisely projected in order both to reveal all possible kinematic mechanisms, displacements, eventual deformations and to guarantee an elevated reliability of the whole surveying network. For this reason a preliminary deformation analysis is crucial to identify representative points on the structure that will manifest its dynamic characteristics. In our case, an L-shaped monumental masonry building, seriously damaged by the earthquake that hit L'Aquila almost three years ago was chosen to curry out this experiment. The survey methodology was indeed based on the use of 30 mini-reflectors installed on the building's facades and observed by a robotic fully-motorized total station Leica TS30. Extra mini prisms that are also installed on stable surrounding structures are used to orientate the instrument before any set of measurements. All the stable points and especially the base where the total station is positioned for each survey are periodically monitored by a GNSS triangulation in order to guarantee their stability over time. After an immediate estimation of all coordinates made automatically by the instrument a detailed statistical adjustment of the whole network is performed to enhance both the network's reliability and accuracy. With periodic repeatability of all measurements the final position of each point is calculated, adjusted and integrated to the final database. In this way a complete knowledge for the structure's dynamics also considering the seasonal changes is gathered in order to evaluate possible final deformations of the whole structure.

2 INTRODUCTION

Three years ago, on April 6, 2009, a devastating earthquake hits the central Italy. The city of L'Aquila, capital of the Abruzzi region and one of the 12 most important art cities of Italy suffers huge damages. Only a couple of days after the main shock the number of the victims raises to 300, the city center and all of the surrounding villages are being evacuated leaving temporally homeless more than 70.000 residents. About 10.000 structures are totally or partially collapsed. Among them, at least 400 historical and monumental buildings of considerable architectonical merit, born during the renaissance and baroque periods, are also suffering serious damages. The magnitude of the earthquake, according to the INGV, was estimated between the 5.8 and 6.3 degrees of the Richter scale while a swarm of aftershocks raises a long-lasting seismic sequence that included more than 30 earthquakes with magnitude $3.5<Ml<5.0$ [1] All these events created a very difficult environment for the whole management of the post emergency period as not only the access to the affected areas was very dangerous but also the need to immediately intervene with surveys, shoring and stabilization interventions for thousands of buildings was eminent. The fact that most of the structures where made of masonry that could ulteriorly worsen by the strong winder of L'Aquila waiting to arrive only some months after the quake created ulterior pressure and need for fast and accurate solutions. For these reasons, teams of firefighters and civil protection arrived from all over Italy to immediately face the catastrophe by creating provisory shoring for all damaged buildings. In fact, only some months after the quake more than 2500 buildings are preliminary stabilized by provisory shoring made of wood and steel. (Figure 1) But the disaster has not passed, the financial resources needed to face such an enormous disaster are difficult to gather and the reconstruction delays, hundreds of buildings will have to remain under the provisory shoring for many more months. Certainly, due to the fact that indeed this shoring is provisory, a structural control of these building is necessary. To do so, a detailed documentation of all damaged buildings begins immediately also revealing the first problems.

The long history of these constructions, that sometimes includes many changes on their principal plan like expansions, use destination changes and reconstructions, makes this type of buildings extremely complicated. Thinking that most of these reconstructions were curried in different periods of times, so using different materials and most importantly by applying incorrect building methodologies, raised the need of a good knowledge for their particularities in order to wisely plan any kind of surveying methodology for their control. Thus, the need of an accurate set of surveys and tests on each structure in order to understand their deformation status, their particularities and all mechanical characteristics of their materials, immediately emerged. To do this, a preliminary deformation analysis was needed for each structure in order to decide the points that could manifest the first symptoms of kinematic mechanisms that could create ulterior problems like overturning of the facades, deformations and collapses of the whole building. These points were surveyed by geomatic and topographical instruments to obtain models able to describe the dynamics of each structure. After a statistical adjustment of all measurements and within accurate elaboration and interpretation of all data, considerations for the actual state of each structure could be made. The results of this methodology, applied on a monumental building of the 16th century situated in the old city center of L’Aquila, will be presented and discussed in this paper. This building, named Palazzo Camponeschi, represents an important site both for the whole city and especially for the University of L’Aquila as has been the seat on an Archbishop and the headquarter of the Humanities and Philosophy faculty for many years until the earthquake.

Figure 1: L’Aquila destroed by the earthquake. On the left, two of the 99 monumental curchess of the city. on the right, the whole city under provisory shoring.

3 THE CASE OF STUDY - PALAZZO CAMPONESCHI

Palazzo Camponeschi is a monumental masonry building constructed during the first half of the 16th century. It is situated in piazza Riviera among other monumental buildings like the old Jesuits’ Church and Palazzo Carli (headquarter of the University). The building was originally created to be a boarding school of the ancient Jesuit church, during the 17th century changed use many times to finally host the philosophy and literature faculties of the University of L’Aquila till April 2009. Part of the buildings’ plan probably dates before the 16th century, even if several modifications were introduced during the following centuries. Building geometry is currently characterized by an L-shaped plan consisting of two arms of equal length (along the SE-NW and NE-SW directions respectively) delimiting an internal courtyard. An architecturally important feature of this building is represented by a staircase of appreciable value. The fact that this building is established upon a rather sloping site gave to its structure an even more chaotic plan where two semi basements are covered by two floors creating a total four story building partially set below the sloping ground level. A typically Italian gable wooden roof also made by planking and bricktiles covers the building on top. The free arm of this L-shaped plan presents a regular vertical and horizontal distribution of two orders of rectangular windows and an arched portal on the right side while repeated regular arcs supported by masonry columns characterize the whole internal fronts facing the internal courtyard. From a structural viewpoint, Palazzo Camponeschi’s original resistant system consists of vertical masonry walls composed of irregular stone units and poor lime-clay mortar. Large inclusions of bricks or other low- quality materials are found in the masonry volume, so that a chaotic masonry texture is generally recognized in the building. Although a number of local reinforcements (tie rods and concrete riddles) have been inserted over the years to fortify single parts of the complex building structure, the overall poor connection among orthogonal walls and the inhomogeneous masonry in the walls thickness were causes for heavy structural damages during the April 2009 earthquake. Majority of barrel and coved vaults covering most of the buildings rooms suffered partial collapse; outside layers of composed masonry walls failed; diagonal crakes due to in plane action resulted in extended portions of the resisting walls; out of plane displacement have been recognized in few front sides of the building.

4 TESTS CURRIED TO THE STRUCTURE

To plan the surveying methodology for this building, the individuation of numerous representative points that would be able to manifest all the dynamic characteristics of the structure was needed. To do so, a preliminary visual damage analysis of the structure was curried immediately to evidence the building's actual state. Unfortunately, studding all visible creeps and local collapses proved not enough mainly because of the chaotic complexity and irregularities of this structure. While the reason of same visible damages was evident, other collapses seemed really strange as their origin was not immediate. A further research on the buildings' history in order to understand the way that the original plan was evolved, worsen the situation, evidencing that this building had reconstructed several times in the past, not always under wealthy periods that could permit engineeringly valid interventions. Finally, the following tests were curried to the structure helping to better understand all it particularities and thus project the surveying network.

4.1 Geometric documentation.

First of all, a detailed geometric documentation was needed in order to understand the structures' real dimensions, its constructive elements (walls, arcs, roofs and attics) and their spatial distribution. Thus, a laser scanning surveying network was planned in order to gather as much geometric information as possible creating both three-dimensional and navigable models of the whole structure and ulterior considerations for the building's characteristics. (Figure 2). Ulterior plotting of the buildings prospects and sections was possible using the laser scanning elaboration software.

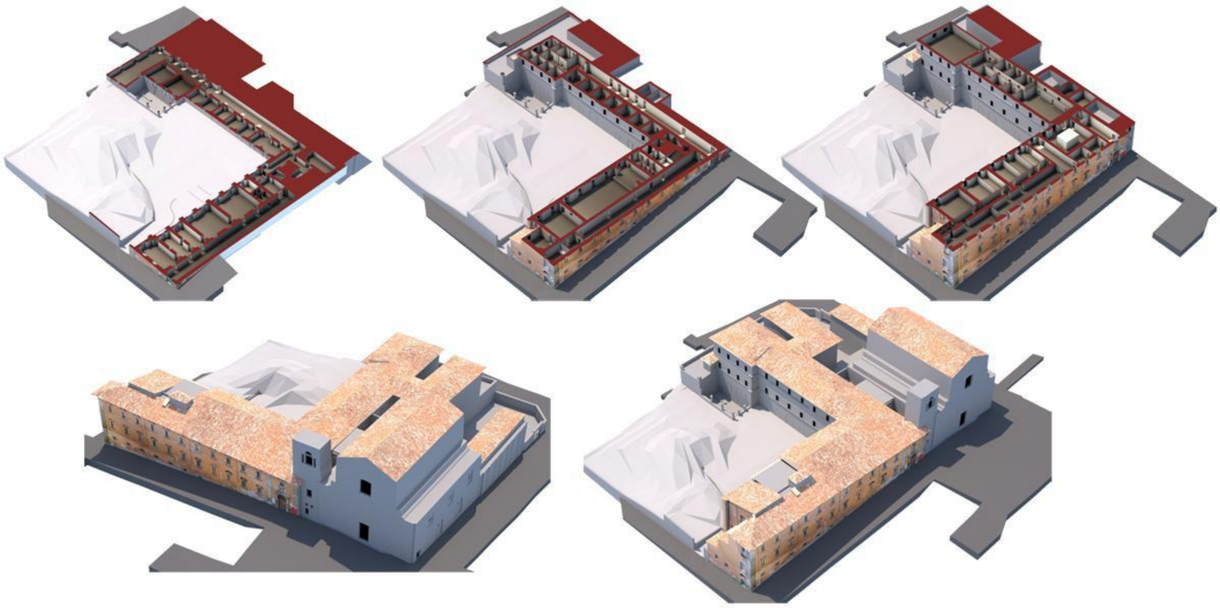

Figure 2: Tree-dimensional models of the structures – results of the geometric documentation also totally covering the building's interior.

The extensive analysis of both all the internal and external spaces permitted a better damage analysis evidencing all visible creeps and collapses of the structure. Especially regarding the visual damage analysis, this valuable set of information was crucial to understand the deformation mechanisms of the whole structure. From a research point of view, this survey gave the possibility to experiment new methods to survey ulterior visible parameters like humidity infiltration and displacement monitoring.

4.2 Thermal Cameras.

The long history of these buildings, as mentioned above, can contain numerous interventions that can seriously change its original plan and with it, many of its structural characteristics. In fact, typical examples of interventions found using thermography in old palaces are the evidence of different wall construction techniques that can alternate the buildings' stability, the use of different materials under the same wall creating a non-optimal continuity of the wall itself and the closure of openings that initially had important reasons of existence. Even in cases that these particularities do not apply, a correct individuation of the masonry's type and many of its characteristics can be obtained by thermal cameras with interesting results. Thus, digital models that present the different materials used and the construction techniques can be created. Figure 3 shows some interesting information found with thermal cameras in Palazzo Camponeschi:

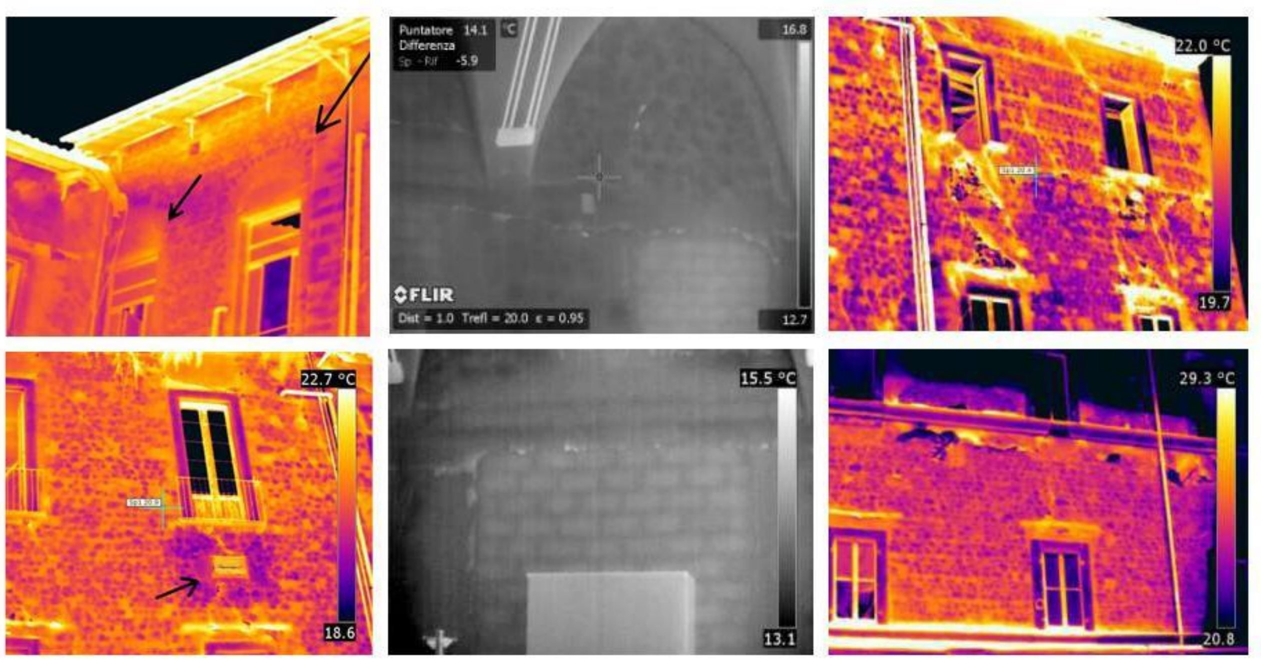

Figure 3: Construction particularities in Palazzo Camponeschi, in particular: partially closed arched windows and air conditioning frames (left), Closed openings (middle), different materials and especially different construction techniques used under the same masonry wall (right).

4.3 Non Destructive Pulse Tests (NDPT) and Endoscopic Surveys.

Qualitative information regarding the construction techniques and the type of the materials used are certainly important. However, there are many cases where an even more detailed information regarding the specific mechanical characteristics of each material are needed. In these cases, non-destructive tests using sonic frequencies (20 Hz – 20 kHz) can help to study parameters like the material's density and indirectly its mechanic qualities and homogeneity only by evaluating the sound's speed throughout the material.

Figure 4: NDPT at Palazzo Camponeschi curried in Direct mode (left) and indirect angled mode (middle).

Endoscopic inspection of a masonry wall to study the wall's homogeneity. (right)

In Palazzo Camponeschi sonic tests where operated to many masonry walls to provide information regarding their consistence. Figure 4 shows some of the tests made both in direct mode and in semi direct - angulated modality. An integration of these techniques with endoscopic tests also permitted a visual inspection of the materials found in parts not easily accessible can be interesting as present both numeric and qualitative information regarding the studied elements. Thus, the overall and detailed investigation of the structure permitted both a good knowledge of the structure itself and for its particular characteristics. All tests were finally integrated among them to create models of the damage analysis and final plots of the building with all gathered information. Figure 5 shows the final damage analysis and the types of masonry found in all over the structure.

Figure 5: Different masonry types and their distribution on the structure (left).
The final damage analysis of the structure (right).

5 EQUIPMENT AND SURVEYING METOOLOGY

Structural monitoring at Palazzo Camponeschi was carried out performing automatic topographical measurements repeated at different time for several months. In particular, kinematic collapse mechanisms of the fronts such as overturning of the facades and other forms of either local or even global structural collapse were monitored observing a number of strategically selected points of the structure. To make this choice, a series of considerations were made mostly using the good knowledge of the structure obtained by the tests made. In particular, evaluating the damage analysis, crucial points that could immediately manifest eventual movements were individuated in both extremities of the facades. Also, the two central arcs upon the main entrances of the structure were chosen as points that would display movements. As many of the damages found near the windows, the grid's columns were made of vertical alignments to correspond with them while the grid's rows to correspond with the internal building's floors respectively. Finally the surveying network was chosen of 27 control points plus three orientation points found in surrounding steady structures and used to orientate the total station. Figure 6 shows the network's final distribution: note the grid spacing corresponding at the NW part of the structure was reduced to better investigate the possible overturning of the middle facade.

Figure 6: The Final Surveying Network.

In Addition to these 27 points, three more were selected independently from the structure to assume their position invariant and to serve as reference for the local coordinate system orientation. Then, a total number of 30 points finally constituted the designed surveying network. To observe these points, a motorized robotic total station was established in a particular pillar made of reinforced concrete with notable dimensions. To guarantee its perfect repositioning and orientation of the total station over time, the sustaining concrete pillar's coordinates were repeatedly checked by GNSS means. For the structural monitoring of the building, a 6 layer reading procedure was curried with angle and distance measurements: this made possible the statistical adjustment of all data, the elimination of the systematic errors and the achievement of the final desired precision. Before each set of measurements, the instrument is being positioned in the pillar to clear the orientation operation. During this phase, the instrument surveys three known and stable points positioned in surrounding structures in order to orientate itself in this local three dimensional referencing system. When correctly orientated is ready to clear a set of measurements.

5.1 Surveying Methodology.

Survey methodology was based on the use of mini-reflectors by Leica, installed on the above mentioned 30 selected positions, to be observed by an advanced motorized total station. High precision angle and distance measurements feature the total station TS30, also characterized by a piezoelectric motor that guarantees a stable rotation of a few milliseconds and a very accurate repositioning. This type of motorization uses direct drives based on the piezo-principle, which directly transforms electric power into mechanical movements. With this technology, a fully controllable and stable motion of the instrument can be performed by simply changing the power's intensity, also, the movement of all non-stable parts is performed at a maximum speed and acceleration. Horizontal and vertical angle measurements are performed with LED technology combining very precise and accurate angle measurement with the high speed of the direct drives. Summing up, this instrument integrates extreme precisions and notable accuracies needed for this surveying network. The detailed technical characteristics, functionalities and qualities of the chosen instrumentation was extensively presented in [Ref.3 pages 2-4]

5.2 Data Elaboration

In order to verify whether or not a structural movement represents an evidence of a wider deformation mechanism further analytical examinations are needed. In fact, there is a wide range of factors resulting in temporal, no permanent displacements which has nothing to do with a real deformation pattern of the structure: thermal expansions, local surface vibrations or atmospheric conditions represent emblematic examples. Data elaboration procedure that includes data conversions, statistical corrections and other verifications required to finally obtain correct coordinates of the 30 monitored points of the structure in the local three-dimensional reference space have been discussed in [Ref 3, pages 4-5.] Analyzing the results obtained, no evidence of movement resulted from experimental measurements, with the considered points remaining steady over time. A first explanation for such a static result may consist on real effectiveness of scaffolding and the stabilization shoring mounted to the building after the main shock to stabilize the structures against future minor earthquakes.

5.3 GNSS Surveys.

A vital part for the whole survey network was the accurate and continuous monitoring of the pillar's position. As described above, Camponeschi palace is situated in a dense area of the old city center where narrow streets among relatively tall buildings cover great part of the sky. Thus, a well-defined and planed surveying campaign made by a geomatic triangulation of at least three permanent stations with good distribution and equal distanced baselines was needed in order to achieve an elevated accuracy of the materialized vertexes' positions. To ensure the accuracy of the final results, a second triangulation was also selected adopting the ItalPos network created by Leica in national scale. With this methodology precision of both the selected networks (each one made of three permanent stations) was found to be lower than 1.5 millimeter, while deviation errors and an error eclipses did not exceed the limit of 1.5 millimeters proving both the stability of the pillar over time and the correctness of the whole campaign. This GNSS methodology and the whole data elaboration were extensively described in [Ref 4, pages 6-7].

6 CONCLUSIONS

Operating a structural control in such complicated buildings was a complex operation especially due to the great number of irregularities presented in this type of artifacts. The variety of techniques used on Palazzo Camponeschi was proven very efficient in order to understand all building's particularities; moreover, the experience of this case evidenced the importance of the preliminary documentation prior to the networks design. Overally, this methodology was proven very accurate for the structural control of monumental masonry buildings both under preservation and during reconstruction or other constructive interventions. During the next months all surveys will continue also experimenting an extension of the actual network in order to enhance redundancy and to allow a further statistical adjustment whole surveying network. The same methodology is currently applied to other structures that have to be controlled over time in the L'Aquila old city center.

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