Using New Techniques of Geomatics and Structural Control in the Old City Center of L'Aquila after the June 6, 2009 Earthquake

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ABSTRACT:

The old city center of L'Aquila is a place rich in historical buildings of considerable merit. The earthquake of April 6th caused significant structural damages, affecting especially historical and monumental masonry buildings. Thus, was immediately emerged the need of intervening with a variety of techniques, combining both structural controls and the modern methods of geomatic surveys. In this paper we present the results of a survey carried out on a monumental building of the XVI century, headquarter of the Humanities Faculty of the University of L'Aquila, situated in the heart of the old city center seriously hit by the earthquake. In particular, after identifying representative points on the structure that can describe, with their motion in time, the evolution of any kinematic collapse mechanism (such as overturning of the facade or other forms of either local or even global structural collapse) all the results and the information obtained by the structural monitoring, performed by repeated partially automated topographical measurements, were analyzed and discussed. The survey methodology was indeed based on the use of 30 mini-reflectors set on the building's structures and observed by a motorized total station TS30. The instrument is equipped with a piezoelectric motor that guarantees a stable repositioning of a few milliseconds. After clearing a three-dimensional angle and distance compensation made automatically by the instrument, the estimation of structural deformation respect to the fixed points was concluded –in real time- with the accuracy of the mm. The results confirm the extreme accuracy and the interesting possibilities offered by modern techniques of geomatic surveys in the monitoring of important buildings both during the immediate post-earthquake period and certainly during their total reconstruction and recovery.

1. RESEARCH SIGNIFICANCE AND OBJECTIVE

1.1 Introduction

April 6, 2009, a devastating earthquake struck the city of L'Aquila and surrounding villages in the Abruzzo Region (Italy) (Figure 1). The earthquake caused more than 300 fatalities, thousands of injuries, extensive and severe damage to buildings, structures and lifelines. From 10,000 to 15,000 buildings were completely or partially destroyed: about 80,000 residents must be evacuated and more than 25,000 remained homeless.

According to the geophysics Italian institute (INGV), the magnitude of the earthquake was estimated as high as MI = 5.8 (Mw = 6.2 respectively). Figure 1 also shows the long-lasting seismic sequence including the main shock and more than 30 minor earthquakes with magnitude 3.5<MI<5.0, and several thousand of others lower magnitude events. Three large aftershocks (MI =4.8, 4.7 and 5.3) occurred on April the 7th with epicentres in the south-eastern vicinity of L'Aquila, and fourth significant events occurred on April 9 (MI =5.1) with epicentres located in the northern vicinity of L'Aquila. Overall, the region affected by the seismic activity covers an ellipse-shaped area measuring about 15 km in length (parallel to the Apennines mountain chain) and 5 km in wideness.

Geologists stated this seismic activity to be the result of a normal fault movement on a NW-SE oriented structure which is part of the 800 km long segmented normal fault system running all along the Apennines mountain chain (Ameri, 2009; Chioccarelli, 2009a,b; INGV, 2009b). The same faults is also considered responsible for previous recent earthquakes, in Umbria-Marche (1997) and Molise (2002).

L'Aquila's earthquake was characterised from the main shock hypocenter being located at the depth of 9 km: hypocenter of other northern and southern aftershocks have instead been located at mean depth of about 12 km and 15 km respectively. According to CPTI04 catalog (Gasperini, 2004), several other times, back in the history, the same area was hit by similar power earthquakes than in April 2009: relevant events of magnitude Me =6.5, 6.4 and 6.7 date 1349, 1461 and 1703 respectively.

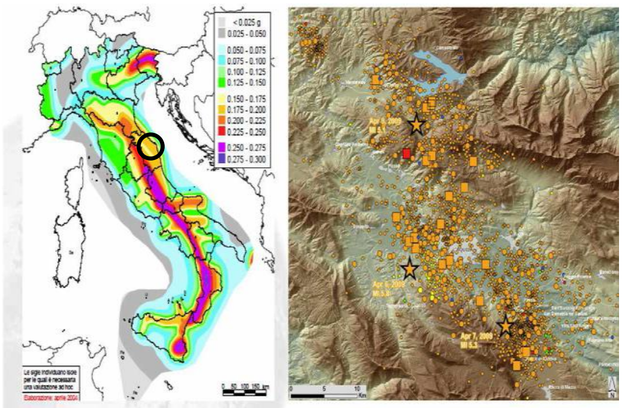

Figure 1.On the left: localization of L'Aquila on the Italy map of seismic hazard. On the right: map of instrumental seismicity around the city of L'Aquila (December 2008–September 2009).

The town of L'Aquila sits upon a hillside in the middle of the narrow valley of the Aterno River, at an altitude of 721 meters.The region hosts about 100,000 residents, many of them (about 70,000) living in L'Aquila itself, a medieval walled city dating from the 13th century, and recognized as the main historic and artistic site of Abruzzo, seat of an Archbishop and an ancient University. Within this urban setting, the seismic event caused serious damage to numerous important buildings, mainly including a valuable real estate heritage stemming from the Baroque and Renaissance periods, and also including eminent churches (St. Mary's church of Collemaggio, St. Bernardino), important palaces (Palazzo Centi, Palazzo Quinzi), and other monumental buildings and structures (Castello Cinquecentesco, Fontana delle 99 Cannelle, etc).

All the masonry buildings (including the traditional palaces and high-density residential quarters in the old city centre) suffered severe damage and many partial collapses. Many of these buildings survived anyhow, their general collapse being in most cases avoided by tie, rods, anchor plates and other simple but effective earthquake-resistant presidium schooled by the historical seismic nature of the land.

The new residential areas are mainly located in the western and eastern edges of the city respectively. Here, most of the buildings are made in reinforced concrete and they revealed a variety of different responses to the earthquake. In modern reinforced concrete buildings a diffuse scenario of non-structural damage was recognized, in combination with interesting cases of local structural failures as well. In aged reinforced concrete buildings (built in the '50-'60) few emblematic cases of global collapses were recorded. Although investigation are still running, a list of possible causes for such a devastating result includes cases of soft-story mechanisms, complicated interactions between adjacent buildings, lack of adequate confinement and transversal reinforcement in concrete buildings. On the other hand, poor connections among orthogonal masonry walls, reduced floors stiffness, wrong mass distribution and absence of restrains to out of plane wall rolling in masonry structures were recognized as causes for collapse of most masonry buildings. Scattered distribution of the heaviest damage revealed that also site-specific conditions played a crucial role in the amplification of the seismic action for both classes of reinforced concrete and masonry buildings.

Time for rehabilitation of the buildings has been estimated in several years, and restoring interventions have being first addressed to strategic buildings and greatest sights symbol of the town.

The research work presented in this paper concern the survey carried out on Palazzo Camponeschi, a monumental building of the XVI century, headquarter of the Humanities Faculty of the University of L'Aquila, situated in the heart of the old city center seriously damaged by the earthquake.

1.2 Motivation

University of L'Aquila represents an institution of great cultural, social and economic importance for the town of L'Aquila and whole Abruzzo region (Italy) as well. Its real estate consists of significant examples of different architecture typologies, including both historical masonry buildings and modern constructions. Since April 2009 earthquake, about 90 % of the University' strategic buildings remained out of service and plans for their rehabilitation are complex to be defined in a integrated view with the future of the town. Engineers and scientist are concentrating a number of investigation to the geological characterisation of the sites and the assessment of the buildings' damage evolution. The need for a variety of different techniques combining both structural controls and the modern methods of geomatic surveys raised. Preliminary results obtained during the just started monitoring of Palazzo Camponeschi (figure 2) represents the precursor of survey techniques possible to be extended to a numbers of other monumental buildings in the town.

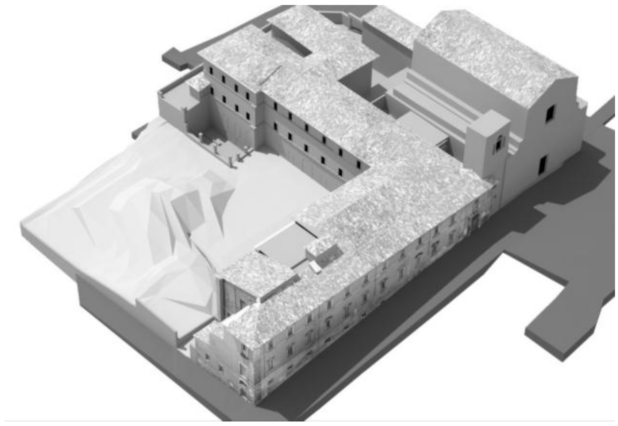

Figure 2. Rendering of Palazzo Camponeschi, L'Aquila (Italy)

1.3 Site and Building Description

Palazzo Camponeschi is a monumental masonry building standing in the old city center of L'Aquila, on Piazza Rivera, just in front of other historical buildings including the old Jesuits' Church and Palazzo Carli (headquarter of the University). It originally hosted an ancient Jesuit boarding school and the Faculty of Literature was set in it until the April 2009 earthquake. The original building plan probably dates before the 16th century, but several modifications to the original building' structure were introduced in the following centuries. Building geometry is currently characterized by an L-shaped plan, (Figure 3) consisting of two arms of equal length (along the SE-NW and NE-SW directions respectively delimiting an internal courtyard. The staircase is located at the L-corner and represents a structural element of appreciable architectural value.

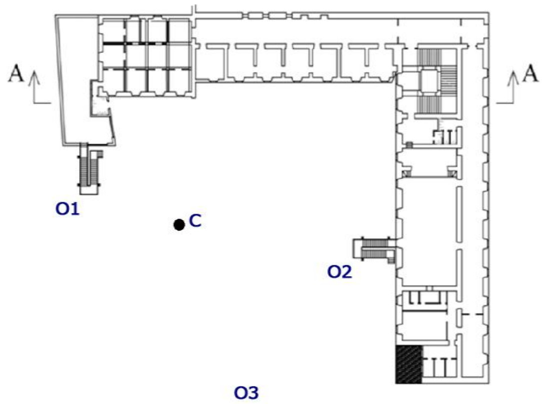

Figure 3. Palazzo Camponeschi plan: spot C represents the location of total station; spots O1, O2, O3 represent reference points.

The building sits on a sloping site and it consists of three stories, the first of which partially set below the sloping ground level, with the highest fronts measured at the end of the two arms respectively. A traditional gable roof in wood truss, secondary wood elements, planking and brick tiles covers the buildings on top. Along the public road, the building' south-east facade presents a regular vertical and horizontal distribution of two orders of rectangular windows and an arched portal on the right side (Figure 4). At the basement, the internal fronts facing the internal courtyard are characterized by regular arches supported by masonry columns (Figure 5).

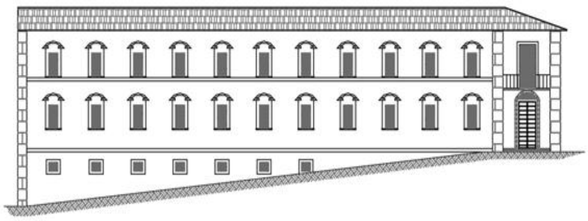

Figure 4. SE front of the building (facing the street)

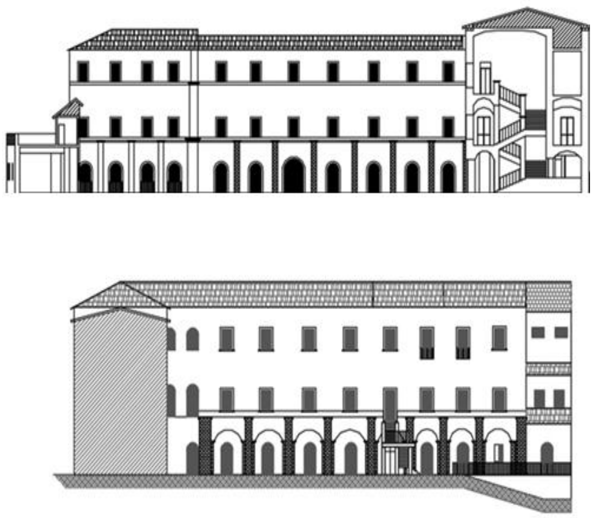

Figure 5. SW and NW internal fronts of the building (facing the courtyard)

From a structural viewpoint, Palazzo Camponeschi' 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.

The presented research work deals with the survey of damage suffered by the internal fronts of the building. Specific structural controls have been addressed to the collapse mechanism (overturning) of the SW-NW front, involving the geomatic techniques discussed in the following section.

2. EQUIPMENT AND SURVEYING METOOLOGY

Structural monitoring 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.

2.1 Design of the surveying network

In order to recognize the signs of ongoing kinematisms and possible collapse mechanisms, a visual inspection of the structure was first required. Evidence of structural damages was found at any level of both the internal fronts of the building, so that a grid of 27 points distributed along 9 vertical alignments and 3 rows was decided as monitoring network. In particular, grid's columns were made to correspond to selected vertical alignments of window along the buildings fronts, and the grid's rows to the internal building floors respectively. Figure 6 shows the distribution of the 27 control points: note the grid spacing was reduced to better investigate the possible overturning of the middle SW facade. In addition, three more points (O_1, O_2, and O_3 respectively) were selected independently from the structure to assume their position invariant and to serve as reference for the local coordinate system orientation (figure 3). Then, a total number of 30 control points finally constitute the designed surveying network.

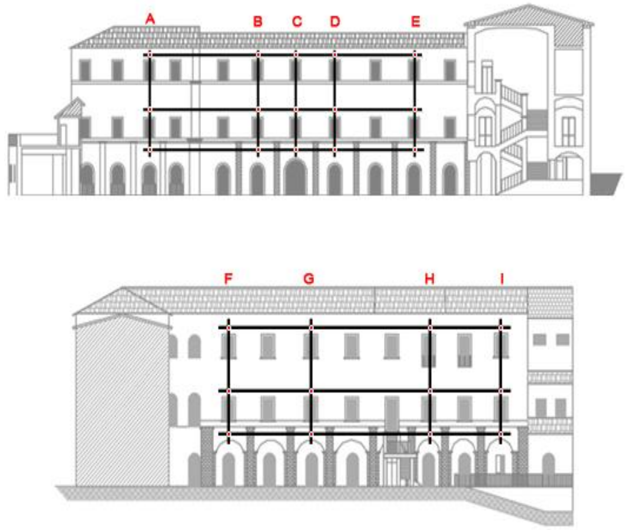

Figure 6. Grid of the monitored points on the SW and NW internal fronts.

2.2 Choosing the instruments

Survey methodology was based on the use of mini-reflectors, 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, also characterized by a piezoelectric motor that guarantees a stable rotation of a few milliseconds and a very accurate repositioning of the instrument. 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 can be performed by simply changing the power intensity and also movement of all non stable parts of the total station is performed at a maximum speed and acceleration.

2.2.1 Angle measurement system: Horizontal and vertical angles measurement are performed by the total station with LED technology, so combining very precise and accurate angle measurement with the high speed of the direct drives. The digital absolute angle information is obtained combining for each angle a great number of repeated measurements. In order to achieve a high accuracy, all data are being statistically processed to create the final observation which can reach up to 0.3 gon of precision. Angle measurement are also performed by total station at high frequency (up to 5000 angle measurements per second) and according to the quadruple angle detection system. In this way systematic and periodical errors are being eliminated, the measurement accuracy is increased and reliability of the angle measurement is enhanced. In addition, the periodic error due to the eccentricity of the glass is eliminated by using two encoders for the angle measurements, and two more encoders remove further minor π-periodic errors which are determined by the system. Finally, correction algorithms based on statistical observations filter all interior data so reducing at the minimum (if not eliminating) all types of other systematic errors as well.

2.2.2 Electro-optical distance measurements are performed by the total station with a visible laser beam coaxial to the optical axis and transmitted by the EDM system. The reflected light is detected by a sensitive photo receiver and converted into an electric signal. Using this technology the system analyzer properties are defined for each individual type of measurement for both the EDM laser beam and the target qualities. Finally, the distances are calculated with modern signal processing methods based on the principle of maximum-likelihood. The adopted total station was characterized by and improved EDM able to achieve up to 0.6mm + 1ppm in accuracy. In addition to this high measurement quality and reliability, the PinPoint EDM allows distance measurements under adverse atmospheric conditions including dust, smoke, mist, rain or snowfall, etc.

2.2.3 Reflectors: In order to maximize the measurement's accuracy and to minimize possible sources of errors (such as non optimal surveying conditions, atmospheric refraction, bad signal response quality) high accuracy mini reflectors were properly installed on the structure. This type of prisms are characterized from a special coating on the reflective surfaces named Anti-Reflex Coating, and a copper coating on the reverse side. With this construction the distance measuring range, ATR and power-search is increased to by up to 30% reaching a signal centring capacity up to 0.3mm while the durability of the copper coating and the outer allumin case gives a decisive background for a long life surveys. The glass dimensions, the position in the holder and with it the spatial orientation, are important for measuring accuracy (figure 7) . In this project both the position and the orientation of each reflector is steadily fixed to the surface of the contraction to guarantee minimum reflection constant by up to 17.5mm. To sum up, choosing to set a surveying network made with this instruments combines accuracy, precision, performance, and efficiency to master this complex project and enhance the art of achieving highest performance and accuracy on deformation surveys.

Figure 7. One of the reflectors installed on the Structure's surface.

2.3 The surveying methodology

Monitoring a number of 30 points within an under-millimetric precision is not a simple operation. The correct positioning and orientation of the total station, the high quality of all measurements and a careful data elaboration are all crucial parts for the final result. To guarantee perfect positioning and orientation of the instrument a concrete pillar with notable dimensions and a deep foundation was constructed, moreover three mini reflectors have been installed in stable constructions of the surrounding area to be used as orientation points. Before each set of measurements the total station is placed on its special steel base attached to the pillar (figure 8). An accurate orientation is obtained both by surveying the three auxiliary reflectors and by attributing the correct coordinates of two extra points of the surface decided by a separated survey. An even further stability control of the central pilaster's position is obtained by a geomatic triangulation using a GPS measurement. Three permanent GPS receivers, well distributed in the city's space to form a possibly isosceles triangle are used on a static GPS measurement to ensure that the hypothesized stable points remain steady over time. In this way the correct positioning of the three-dimensional reference system on which all coordinates will be placed is guaranteed.

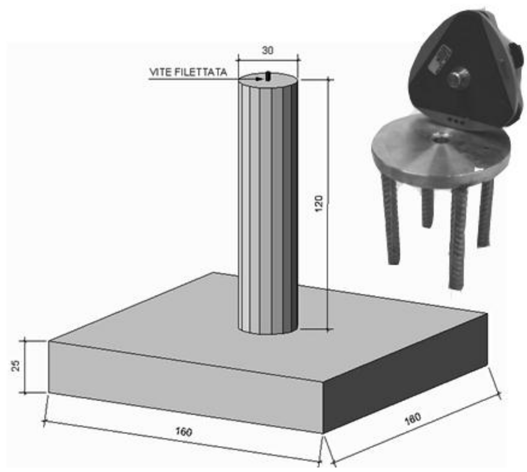

Figure 8. Reinforced concrete pillar layout and view of the still base.

All the preliminary operations are at this point cleared and the first measurement can be made. For this project a 6 layer survey method is decided in order to give enough material for further statistical correction, also, between other advantages in this way systematic error eliminations and measurement's precision are guaranteed too. A needed period of testing surveys was also set in order to ensure the stability of the whole network, thus the first data were taken for elaboration on June 2011.

3. RESULTS AND DISCUSSION

Each set of measurements is primarily made of angle and distance observations. This is only the first part of a longer elaboration procedure that includes data conversions, statistical corrections and other validity verifications necessary to arrive at the final correct coordinates of each point in the local three-dimensional reference space.

Firstly each angle or distance information is being compensated with a least squares statistical adjustment software. Even if a previous series of corrections are also applied automatically by the instrument's algorithms, these software still reveal errors that are being corrected. These data will be used as input to the Leica's TPS software that decides the final coordinates of each point. Monitoring the surface of this building consists on studding the value of each coordinate over time. A six layer periodic survey of all 30 points provides all the necessary input to create an information database able to describe the whole moving pattern of the structure. Each movement found is being studied to decide if it's a local temporal phenomenon or part of a wider deformation mechanism. Therefore, all data are being introduced to surface mapping software to study in a detailed manner the quality and the nature of each movement. A further deformation analysis is also projected with the GeoMos software that will combine observations obtained from both the total station and the geomatic surveys of the pillar position as well.

3.1 Preliminary results

When a movement is found a further analytical examination is needed as described in order to verify that this movement represents an evidence of a wider deformation mechanism. There is a wide range of factors that can reveal a temporal moment which has nothing to do with the deformation pattern of the structure like thermal expansions, local surface vibrations or atmospheric conditions. Due to these reasons every movement has to be examined, only when a movement remains over time and presents a qualitative relation with the global kinematic mechanisms can be accepted as a deformation.

In this project, the first correct position of each point is registered after the testing period of the whole surveying network. This set of measurements, called zero circle, is now used in order to estimate each movement. The first results already gives an idea on structures' dimensions and state during the hot months of this year. All these information are expected to be used in order to draw the whole situation after the seasonal change and the temperature reduction on near future. In this way a complete imagine of the whole structure is drown to permit a careful estimation of every possible future deformation. Graph in figure 9 represents the displacements recorded for the tree point aligned on vertical C of figure 6: no evidence of a specific trend was recognized, probably due to the short time period of observation and proving, so far, effectiveness of the scaffolding and prop mounted into the building to stabilise the structures against future minor earthquakes.

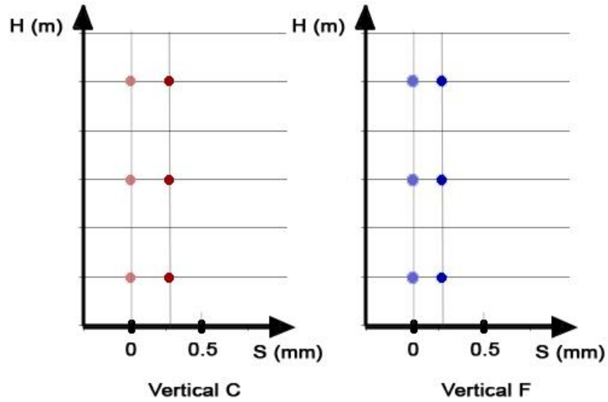

Figure 9.No evidence of displacement for monitoring points belonging to verticals C and F in Figure 6

3.2 Other investigation

To achieve a dipper knowledge of the building and to gain information about its structural characteristic and behaviour, results from the structural monitoring performed with topographic techniques were enriched with information obtained from other Non Destructive Test Methods (NDTM) performed on the structures and including tomography and Sonic Pulse Velocity Test (SPVT). Figures 10 shows examples of images captured with a thermo-camera: they allow to recognize the nature of masonry when hidden by the plaster and the change in masonry quality from part to part of the same wall.

Figure 10. Thermographs revealing masonry typology behind the plaster (above) and different masonry types in the same wall (below).

This information were useful in selecting the grid spacing when deciding the survey network, focusing on that part of the buildings front potentially less stable. On the other hand, measuring the sound pulses velocity in traversing the wall thickness allows to evaluate homogeneity of the masonry in its volume and quality of the walls in their thickness. Graphs in Figure 11 report the results obtained from SPVT performed on different representative portions of the SW front of the building, at the first wall elevation above the ground level. Different values of the pulse velocity are reported in the two pictures, and two representative average velocity values can be computed, so that two different masonry types are recognized (less dense and probably weaker the former, more dense and probably stronger the latter). Moreover, variability of the pulse velocity found in different points of the same picture highlight the inhomogeneous nature of the masonry in the wall thickness (in both the graphs).

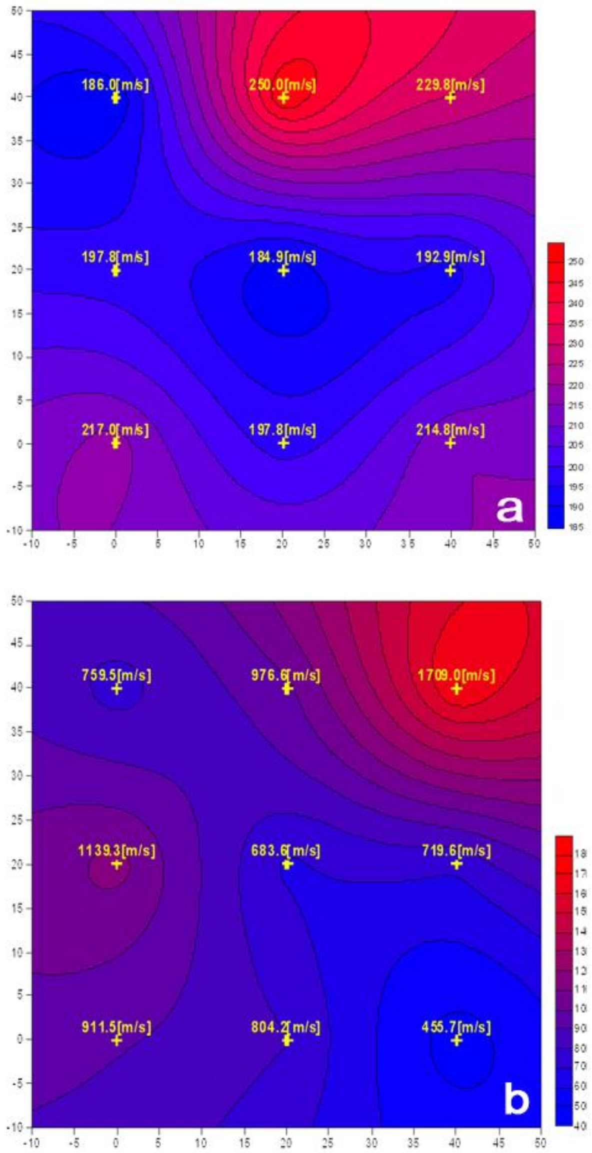

Figure 11. Sound Pulse Velocity Tests: lover velocity values in graph a) correspond to less dense and probably weaker masonry than in graph b). Values dispersion indicate masonry were inhomogeneous in both cases a) and b).

Such information are useful in predicting global and local response of structure to seismic actions, helping calibrating material properties when defining numerical models of the building. Once masonry quality is well known in all part of the building structure, elastic and dynamic analyses of the building are possible at the computer. Figure 12 shows the graphic results from elastic analysis carried out to evaluate stress concentration in the structures under vertical loads.

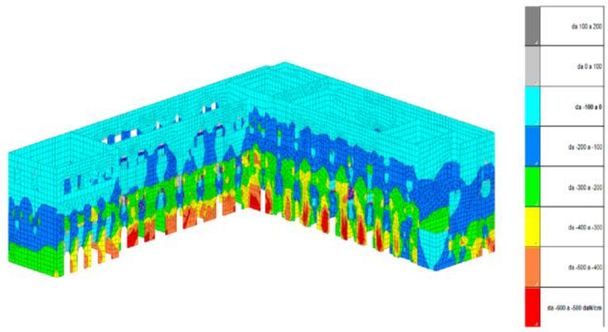

Figure 12. Stress concentration in structural elements resulting from an elastic analysis of the building.

Some hypothesis on global and local modal properties of the building are reported in figure 14: part of the structure characterised by a poor connections among orthogonal masonry walls, reduced floors stiffness, wrong mass distribution and absence of restrains to wall overturning were recognized as causes for possible local or global collapse in the building to be monitored.

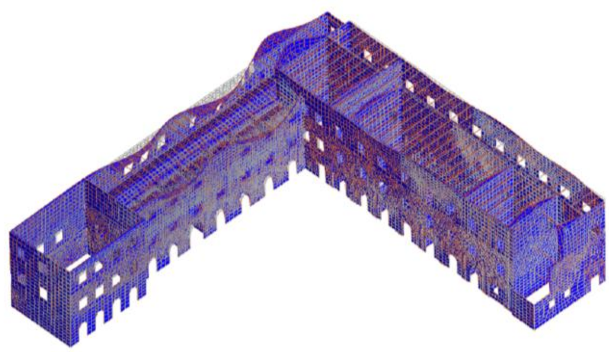

Figure 14. Global and local modal properties of the structure.

4. CONCLUSIONS

Creating a structural control on old historical and monumental structures revealed a complex operation mainly because of the great number of irregularities presented in this type of buildings. The variety of techniques used on Palazzo Camponeschi is proven very effective in order to understand the whole parameters of this structure and use this knowledge to refine the intervening methods. The structure's stability even if based on very preliminary results in this way is proven and all future operations can be improved in order to perfectly meet the structure's needs. During the next months all surveys will have to be continued in order to better examine all types of movements and better describe the structure's dynamics. In meanwhile this methodology is being applied on other monumental structures of the old city center.

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