MODERN INVESTIGATION TECHNIQUES FOR THE RESTORATION OF ANCIENT BUILDINGS OF STONE OR BRICK MASONRY

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ABSTRACT

Restoring a masonry building involves not only the physical rebuilding of its parts, but also involves the identification and the conservation of the peculiarities of each building as a first stage.

Therefore it becomes important the process leading to the identification of the main characters. The process itself becomes a chief part of the restoration design.

Three aspects of this process are important: 1) the perfect knowledge of building’s form and dimensions, 2) the dating of each part of the building, 3) the evaluation of the actual strength of building components.

Several investigation techniques are today disposable for the project manager in order to get an accurate mapping of the building and to test on site the behaviour of building components.

The paper also shows the problems incoming using several different diagnostic devices on ancient buildings.

INTRODUCTION

In Italy and in the whole Europe the number of restorations of historical buildings used for purposes different from their original ones is increasing and is expected to increase much more in the next future.

It is commonly accepted that restoring a building involves not only the physical rebuilding of its parts, but must also involve the identification and the conservation of the peculiarities of each building as a first stage. Therefore the process leading to the identification of the main characters becomes important.

The restoration design is a chief step of the process and it has a great role in the identification of the ways of the intervention and, consequently, of the costs level. This step may be taken to optimization by means of the preliminary acquisition of technical data on different items.

We mean to build up a design method based on the scientific analysis of the

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building employing several diagnostic devices in order to globally know in advance the building itself and its pathological situations, if any (1).

This process leads to a scientific knowledge of the possible pathologic situations using different techniques to-day disposable. Therefore design process must be integrated with acquisition of preliminary technical information. These information involve: 1) architectonic survey that includes metric and critical survey; 2) measurements of physical characteristics of chief parts of the building; 3) the identification of their way of standing.

ARCHITECTONIC METRIC SURVEY

It is to-days current experience that computer aided calculation is employed to evaluate stress distribution on the resistant parts of the buildings. But it is of clear evidence that the more exactly you can know masonry's dimensions and dislocation, the more exact calculations may result.

The problem is how to reach a fully exact survey in a cheap and quick way. The goal of such a survey is to obtain three-dimesional co-ordinates of all remarkable points of the building. For remarkable point we mean each point useful to get an exact representation of the parts. For instance room's edges, window's corners, the intersections of even or round surfaces are remarkable points.

The survey must be able to grant the possibility of:
- drawing up detailed plans for restoration, and/or new use of the building;
- overcoming the need of further measurements of details, each of them being included in the first survey;
- drawing maps at whichever level; drawing cross sections both on horizontal or vertical layers, thus leading to know the thickness of masonry in any point;
- changing the orientation of reference system in order to choose the best one for the representation of façades and sections.

The method employed in this paper is an integration of topographic and photogrammetric survey (2). It was used with great satisfaction in the case of a XVIII century building in Spoleto. Topographic survey is based on an external closed polygonal to which several branches, at the interior of the building, are related.

An especially built signal was positioned into each window. (Fig.1)

![Fig.1 Shows the signals positioned on each window for topographic measurements](image)

1 Braida, A. "La diagnosi non rompe" Costruire n.140, Italy, 1994

2 The method was conceived by prof. G. Fangi, of Ancona University, and developed by a private company in the case of this paper.
These signals were more than 200. From the external polygonal all the signals were measured with a precision better than 1 millimeter.

Each internal branch of polygonal was referred to the external one by means of the position of window's signals. From the internal branch of the polygonal the above said remarkable points were measured.

A dedicated computer program is used to calculate the coordinates of each point and to transfer them into a DXF file that any CAD system may import.

This method is able to guarantee a precision better than 1 centimeter in each of the three coordinates for any point, at the interior or outside of the building.

Architectural photogrammetry is used as an integration, whenever useful, in order to catch the images of decorations, paintings, affrescos etc.

Employing the above shown method to a 2,400 square meters wide XVIII century building led us to get a planimetric and elevation mapping with a precision better than 1 cm. in about two months.

Such a precision is of course of great interest both for architectural design and for numerical processing of mathematical algorithms used to know the stress distribution in each part of the building.

Figures 2 to 4 show the building position inside the town, the front elevation and an enlargement of the same that explains the level of information contained in the drawings.

Fig. 2 Nord façade as resulting from topographic survey

Fig 3(left) position of the building inside the town; Fig 4(right) an enlargement of the façade shows the level of information contained in the drawings.
ARCHITECTONIC CRITICAL SURVEY

This method is based on the determination of the characteristics of the building through the knowledge of the formation / transformation processes of the building itself. Commonly, such transformations may be subdivided into two main categories: transformations due to substitutions, entailing the destruction, either total or partial, of the existing physical structures, and transformations due to addition or superposition, in which the existing physical structures survive, but undergo even important interventions, such as superposition of plasters, enlargements, the making / closing of openings, etc.

Therefore, the critical survey method entails the identification and interpretation of transformation characteristics and traces in order to gather the fundamental data of buildings as well as the structural discontinuities and/or deficiencies determined during the formation-transformation process.

The information obtained from the various investigations was collected in cards and graphically represented in the plans. This research showed the substantially homogeneous character of the building technique in all the building bodies, independent of the time of construction. In short, the result was a masonry composed of boasted stones kept together by very poor mortar, sometimes powdery and with internal pockets of remarkable size. A rather widespread lack of efficient toothing was also observed.

Another important source of information is the historiographical analysis. The study of record office documents and of both drawings and paintings of the time provided us with information regarding the disposition of masses during the centuries.

Summing up the information led us to arrange the evolution tables illustrating, although schematically, the subsequent aggregation of the building bodies from the 15th century to the 18th-century restoration work (Fig. 5).

Fig. 5 Referred to 2° floor, "critical survey" method led us to define the above evolution

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3 AA.VV., Prontuario del restauro, in "Progetti e ricerche della città di Pesaro," n.7, Comune di Pesaro, Pesaro, 1980

4 Doglioni F Gabbianí B, - Metodologia per la conoscenza analitica del manufatto edilizio per il controllo tecnico culturale dell’intervento di restauro, IUAV, Venice, 1983

NON-DESTRUCTIVE DIAGNOSTIC TECHNIQUES

In spite of the widespread appreciation of the efficiency of the results, the critical survey is by some authors considered a "destructive" method in relation with the tests and the removal of plaster it entails.\(^7\)

In the case of the building of this paper the use of non intrusive diagnostic technologies aim to overcome the limits of critical survey method. Destructive effects were minimised by using endoscopic imaging for in-depth testing and the exfoliating scalpel removal technique for superficial tests aiming at the identification and restoration of pictorial decorations.

An innovative non-destructive diagnostic technology is now being developed at our University \(^8\) in order to investigate plasters, frescos, decorations etc. This method involves use of laser Doppler vibrometer to measure the vibrations of different layers of plasters and/or frescos.

The theory is that, if a layer of plaster is detached from the masonry, it has a range of vibration different from a well attached one and, if multiple layers are present, they have a vibration range different from the single one.

On this hypothesis it becomes sufficient to compare the test on site to values referred to well known situations. The problem is to achieve a data base, built up on well known examples, large enough to give a significative correlation with the values measured on site.

The method requires a mechanical excitation of the layer. Different types of tools may be employed for this item: hammer like tools, acoustic devices; electromechanical shakers. Each of them has, of course, its better field of application. In the case of ancient buildings, acoustic devices have proved to work better in the case of thin layers, such as multiple paintings, whilst electromechanical shaker fits better in the case of layers of plaster (thickness of 1 to 4 cm.)

During mechanical excitation, detached parts of plaster have a bigger movement than attached ones. This phenomenon becomes of clear evidence at resonance frequencies. Resonance frequencies are related to the extension of the detachment and to the thickness of the layer. The use of electromechanical shakers allows to test at different frequencies.

The displacements under vibration are very little and the may be affected by the use of traditional measuring devices.

The use of a Doppler laser vibrometer (Fig.6) requires no devices on the surface of the plaster. Therefore no interference is due to measuring system.

The instrument allows long distance measuring; thus investigation at great eight and/or at unreachable walls becomes possible.

As a first step the instrument measures the vibration speed of a stated number of points on a bi-dimensional grid. A software program builds up for each point a diagram of vibration speed related to excitation frequency (Fig.7).

Fig. n.8 shows the full instrumentation equipment referred to a calibrating panel.

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\(^7\)Feiffer C., Il Progetto di Conservazione, F. Angeli, Milan, 1990

\(^8\)Paone N., Castellini P., Tomasini E.P., Application of laser Doppler vibrometer to non intrusive diagnostic of fresco's damage -1° Int.Conference on vibration mesurements by laser techniques, Ancona 1994
As a second step the wall is excited at the frequencies that showed greater effect and a new measurement, extended at the whole surface, is taken.

For each frequency the program gives a mapping of vibration speed. The output may be presented as a coloured mapping or as a 3D diagram. Fig. 9 & 10 show the results on a calibrating panel.

Experience and a data-base comparison lead to evaluate which kind of detachment is involved and/or if any second layer is underneath. The thickness of the layer is also evaluated. No stress to the existing old surfaces is induced by this diagnostic method.
Fig. 9-10 Show two types of output for laser Doppler vibrometric diagnostics

DIRECT TESTING TECHNIQUES

With a view to the project operational choices, knowing the bearing capacities of the masonry structures in their original conditions is of utmost importance. In general, given their remarkable thickness, masonry work does not have great problems in terms of vertical loads, but tends to be more exposed to the effects of horizontal seismic strains.

In current practice, a good interpretation of their behaviour is possible with the use of a computerised calculation, in which shear values are taken from the literature according to the typology and the degree of preservation of the masonry being examined.
In the hypothesis of a perfect knowledge of both size and masonry quality, mathematical algorithms can be used to process numerical data with the precision desired. However, the problem arises precisely with the two aforesaid instances, i.e. the knowledge of the exact size and quality of the masonry. Normally, these data are only approximate in terms of topology, and referred to bibliographical information concerning the masonry bearing capacity.

The case of this paper is significant as the afore-mentioned issues have been solved by means of precision topological mapping, critical surveys and endoscopic surveys with the purpose of determining the time of the construction of the masonry, which enables the formation of homogeneous masonry groups, and the carrying out of direct testing in order to assess the masonry bearing capacity (particularly, with shear strain and flat jack tests).

Direct shear test on stone masonry

A direct test of main forces becomes of great interest whenever the designer supposes the possibility to find "better" values of the ones commonly used, and is always the best way to have full knowledge of the masonry.

In the case being treated in this article, we opted for a direct test in situ, measuring the value of the shear strain needed to take an ashlar to breaking point. Such test was conducted on two different ashlars of the building. Subsequently, the ashlars were consolidated by fluid mortar injection and, following the setting of the binder, they were taken once again to shear breaking point.

The purpose of these instrumental tests is to measure sure values referring to that particular masonry under examination. The comparison between the values obtained in present conditions and those regarding consolidated masonry are indicative of the degree of efficiency of the injection of a fluid mortar with a cement binder.

In other papers we referred in detail on this item. Here we only want to remember that test graphs showed that in the ashlars left undisturbed, the breaking load is a τ of about 6.6 Bar, during test A and 4.4 Bar during test B. obtained with a deformation in the order of 4.7 mm in test A and a deformation of 3.7 mm in test B.

The τ value corresponding to half the breaking load entails a deformation in the order of 1 mm in test A, and of 0.5 mm in test B, whereas 1.5 Bar - (the value generally given in the literature for similar masonry work) - corresponds to a deformation of only 0.2 mm in both test.

Brick masonry flat jack test

Flat jack test is used to evaluate the compression stress in an existing masonry. It consists in inserting a 1/2 inch thick jack into a 40 cm long cut made for the full thickness of the masonry by a sawing device.

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8 Montagna R. - "About building dating and the evaluation of masonry's strenght in Palazzo Pianciani, Spoleto, Italy" - proceedings of : Seventh Canadian Masonry Symposium - Hamilton, Canada ,1995 (pag.1184-1192)

9 R. Montagna, Stone and brick Masonries in historical buildings: tests to evaluate their real strenght - proceedings of: Seventh North American Masonry Conference, University of Notre Dame, Indiana USA, giu 1956
Measuring the force necessary to bring back to their previous position two stated points, make it possible to know the value of existing compression stress.

The use of two slim jacks positioned at a convenient distance (about 40 cm) make it possible to measure deformation of the masonry when it is free of load and when it is brought back to its previous stress.

This test can give a good idea of elasto-mechanical characteristics of the masonry (stone and mortar joints or brick and mortar joints).

This kind of test showed to be unfeasible in a masonry composed of stones with a powdery mortar. The cutting device induced such vibrations that the mortar slid away and the masonry locally collapsed before we could insert the jacks.

On the contrary this test was usefully carried out onto a bearing brick vault, at second floor of the building; We realized two different tests: first one (employing only one flat-jack) directed to measure the compressive stress level at the attach point of the vault; second one (employing two jacks) directed to investigate the quality of the masonry in its global condition of bricks and mortar joints. Stress value in its own status showed to be about 0,3 N/mm² with a global force of 45 kN per meter in the axe of the vault.

CONCLUSIONS

From our experience we may affirm that:
- a detailed topological mapping is a first necessary step for any restoration program. The integration of precision topographic survey and architectural photogrammetry proved to be top-level. Automatic CAD restitution enables the architect to work at a detailed scale whenever he wants.
- the faults attributed to "critical survey" method may be reduced with the use of non destructive investigation techniques, thus reaching a good level of historical and constructive knowledge;
- laser Doppler vibration measurements are able to identify plaster detachments and irregularities. The measurements involve no damage of the surfaces. This method is now being studied, but it looks to be very effective.
- direct masonry tests are destructive; but a very little number of them is enough to evaluate the real level of building "strength";
- values of shear and compression resistance of the masonry measured on site are usefully inserted into computerized calculations in order to optimize restoration design;
- generalised cement injection is not always needed to improve stone masonry's resistance;
- measured values explain why buildings of the type of the one tested may overcome several centuries of earthquakes of remarkable intensity.

Not all of the diagnostic test employed are totally damage free, but the damage is reduced to very low level. Only shear tests involve a higher level of damage but choosing ashlars of lower artistic importance makes it possible to execute them on great number of ancient buildings.

Of course an in depth diagnostic campaign has a relevant cost.

In this case of this paper, at 1995 prices, architectonic metric survey costed about 45.000 US $ for a building of about 7.000 mq of floor. Critical survey had a cost
of about 35,000 US $. The expenses for direct tests arose to 30,000 US $ (including two shear tests, one flat-jack test and about 40 endoscopic investigations).

But the only choice of not injecting stone masonry with cement mortar, coming out from direct shear test, lead to save more then 500,000 US $, on a global cost of restoration of about 6,000,000 US $.

In fact the costs of a diagnostic campaign preceding the design are always rewarding in the total costs of building restoration. It is common experience that in the absence of serious diagnostic campaign, design must be changed during works thus increasing final costs.

In addition a better level of knowledge of the building, is reached employing a full range of diagnostic techniques. This means a better level of safety and at the same time a better level of compatibility with the ancient "way of standing" for the structural design .

A lower level of intervention also permits, for historical buildings, a better level of safeguard of the ancient characters that the architects intend to protect

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