In-situ and laboratory investigations on materials and structures for the static improvement: “Torre Quadrata del Circo Romano” (Milan)

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ABSTRACT: The “Circo Romano” was built by the Emperor Massimiano in the last years of the 3rd century. It was erected with the attempt to give Milan a building capable to represent the city as a capital of the Empire. Nowadays the only witness of such an imposing group of buildings is the Tower of the “carceres”. The intervention planned for the “Torre quadrata del circo romano”, includes the project for static improvement and the more complex preservation project of the upper part of the building (the loggia).

In order to prepare the project it was necessary to carry out a diagnostic campaign to verify the effective conditions of the building. All the retrieved information were represented on drawings identifying geometrical survey, image rectification and stratigraphic readings referring to the historical-archival and the brickwork discontinuities. In addition, there was also representation of the readings of crack networks and of out-of-plumbs; structures and materials non-intrusive or light-intrusive diagnostics performed by means of sonic method; checking of the status of sleepers, tie beams and chains in order to verify their functioning; mortars and bricks sampling for the identification of the base elements; the results of petrographical and mineralogical analysis.

1 INTRODUCTION

The corpus of the survey conducted on the Torre Quadrata del Circo Romano in Milan made it possible to delineate the status of the structure as we find it today.

The analyses focus on two different subjects, albeit closely linked: the historical/evolutionary aspect of the structure and the static/dimensional aspect.

In view of this, and in agreement with the Lombardy Regional Department, the appropriate analyses that needed to be carried out on the structure were established for the purpose of developing a project to improve static functions and to re-utilize the Torre.

From the point of view of conserving materials as well as with reference to static aspects, the portion of the structure that presented the most critical situation is the summit, where even a simple observation with the naked eye shows the complexity of the situation.

It is here, in fact, that deterioration can be observed on the slim marble columns and on the wall structures that support the summit section of the loggia where, in recent years, a partial static consolidation attempt was made. Unfortunately it did not serve its purpose,
purpose of verifying the Torre’s geometrics, the status of the works already implemented and of providing indications on the conservation status of the stone materials and of the connecting grout in the wall section relating to the loggia.

Figure 2. The topographic polygon.

2 SURVEY, MAPPING OF CONSTRUCTION PHASES AND VERTICALITY CONTROL

In order to provide better support in interpreting the results obtained and, at the same time, to provide an additional way of looking at the situation, the stratigraphy survey carried out in the Nineties by the architect Gianfranco Pertot was re-examined. The stratigraphy, in fact, correlates quantitative and qualitative information, utilizing the chronological succession of the structure construction episodes as the guiding parameter.

The geometric findings, together with the photographic straightening, was the first operation undertaken, by which it traced accurate maps on which, subsequently, information acquired as a result of the other diagnostic surveys would be mapped.

A closed topographic polygon was realized (with laser total station) composed of seven stations in which more than seven hundred points required for tracing the structure geometrics were measured. Thereafter, a detailed profile was executed, performed with the help of direct measuring instruments such as laser distance meters, rigid meters and ribs to integrate the missing information and to study the level of detail of certain more significant portions of the structure. In addition, a self-leveling laser was used to determine

Figure 3. Drawings representing the entity of out-of-plumbs.
the difference in level between the stairwell landings in the internal staircase.

Seven different outlines were realized, each one corresponding to a landing, in addition to that for the ground floor and for the loggia, with five sections and four external prospects. The considerable amount of details determined made it possible to correctly highlight the entity of the out-of-lines, measured on the four corners of the structure, as well as the opportunity to coherently represent the deformations and the bulging of the walls.

In order to correctly restore the plumb lines, also taking into consideration the particular deterioration of the bricks with which the structure was realized, it was deemed advisable to execute the readings on the corners from very close up (approximately every 30–40 cm for the entire height of the Torre). Sufficient information thus became available to identify and isolate any mistakes in the reading or in collimation.

The topographic bearings, used for the geometric restitution, were also employed as references with real coordinates for the photographic straightening procedure for the four external fronts and for the four internal prospects on the loggia level.

In order to acquire the photographic material, a digital reflex camera equipped with standard optics (focal length 50 mm) was used and it was also equipped with tele-optics (210 mm) based on the camera station; wide angle optics (20 mm) were used for the loggia shots, and the relevant deformations were subsequently corrected by software.

The procedure for photo straightening and placing the single images in mosaic order was realized with dedicated software. The coordinates provided by the topographic shots were used, as specified.

The geometric tracing and the control of verticality made it clear that the front presenting the most displacement is that facing west, on the contrary to that facing east, which is nearly perfectly plumb.

The information determined on the external corners of the structure is also confirmed by the measurements carried out inside the loggia. These were effectuated by using a high accuracy laser plumb and once again it is the west wall that shows the most displacement from the vertical. In this case the values are more modest but, in fact, even the portion of the wall analyzed is considerably less extensive than on the external walls, where the out-of-plumb was calculated,
taking into consideration nearly the entire height of the building.

The analysis of the situation concerning crevices evidenced a modest presence of lesions and crevices, at the same time showing the existence of no-anchoring areas among the angles of the Torre and the loggia’s supporting fill walls.

It is believed that the origin of this phenomena is not attributable to structural settlement or to yielding, but rather to the particular genesis of the entire structure. It was constructed in many phases and over a very long period of time and presents construction stratifications at times not properly solved and generated by an urgent need rather than by a single project.

On the basis of the plans realized by the photographic straightening, a stratigraphic analysis of the structure was outlined for the four external façades. Thanks to a high definition photographic support, subject to verifying the stratigraphy unit readings, this analysis made it possible to restore the development and interpretation of the numerous construction activities that followed each other during the course of time.

In fact, the stratigraphy analysis tables describe the perimeter of the stratigraphy units (S.U.) and of the architectural elements (A.E.). Through appropriate background information, they communicate the construction activities in chronological sequence, highlighting wall irregularities and the architectural structure’s critical points.

With respect to the Torre, seven different construction phases were identified and eight different periods of interventions were classified, to which the three restoration phases, carried out from the second half of the 19th century, must be added.

3 DIAGNOSTIC ANALYSIS

In addition to providing priceless information as to the evolution dynamics of the structure, the stratigraphy readings also constitute a fundamental basis for the choice of homogeneous samples to analyze the characteristics of the materials. At the same time these surveys were carried out, an analysis campaign was organized that aimed at recognizing the stone materials present in the structure and at the characterization of the connecting grout used for the walls in the loggia.

This in-depth study is justified by the evident decay affecting the Torre’s stone elements, especially the loggia, where decorations can no longer be read and where entire sections of material have disappeared.

14 samples were taken from the four façades of the loggia to analyse the column, plinth and stone materials present in the masonry in the area below the loggia’s floor.

Samples were analysed in a laboratory with polarized light microscopy (MO-LP) using traditional methods of mineralogical analysis in “thin sections”
that entails the use of a very thin (about 0.03 mm) layer of stone glued between two slides. The material is observed through a polarizing microscope and the analysis is conducted under different types of polarized light in order to clearly observe all the characteristics of that particular sample. These characteristics, unique to each mineral, allow specialized technicians to recognize the materials on sight.

The results obtained confirm the visual analysis, in that they showed the great variety of the materials sampled, including: Pietra di Angera, Rosso di Verona, Trachite dei Colli Euganei, Pietra di Saltrio, Pietra Aurisina and Marmo Apuano.

The absence of consistent placement inside the building for each litote is moreover confirmed in the context of the elements themselves. The four columns analyzed are in fact one different from the other: the re-used stone materials originate from different urban “quarries”.

Laboratory analyses continued, as previously mentioned, with the characterization of the mortar beds used in the loggia and were conducted with X-rays diffraction (XRD).

Diffraction allows the crystalline planes present in the samples analyzed to be recognised and, if compared with appropriate reference tables, they identify the elementary components of the material. In brief, the procedure uses X-rays that are directed towards a rotating sample and then diffracted with varying angles according to the materials that make up the sample. At the same time, a detector measures the width of the diffraction angles and records them on file for
subsequent analysis. This method provides qualitative and in some cases semi-quantitative results.

The results highlighted a rather uniform situation both in terms of the composition (high concentrations of quartz and calcite with a significant presence of potsherds) and of the state of conservation that is not good no matter the location and morphological aspect of the sample under study. In particular, nearly all the mortars are poorly consistent with pulverization in some sporadic cases, though, on the average they show a uniform and compact structure.

It is thus difficult to identify deterioration problems with respect to the exposition of the interior fronts as well as with respect to other factors external to the material. The results show a general state of conservation that is slightly worse as regards the mortars used to build the loggia parapet and those used for the masonry located over the arches and in the normal parameters relative to angle irons.

Analyses on the stone materials continued with ultrasound tests to control the compactness of the elements.

Ultrasound tests are based on the relationships that link the propagation speed of elastic waves in a given material to the elastic properties of the material itself. The propagation speed of these waves can be directly linked to the physical and mechanical characteristics of that material and, more to the point, a reduction of the propagation speed indicates irregular (cracks, empty spaces, detachments) or deteriorated material.

Ultrasound tests can be carried out in three ways (by transparency, on the surface and by radial transmission) according to the position of the transmitter and receiver on the surfaces under study.

These tests were performed on the small stone columns in the loggia and on the huge columns in cipolin marble at the Torre entrance. They revealed that the loggia elements are in good condition, despite the external surface attacked by corrosive elements and sulphation, and that the material is compact. On the other hand, the columns at the entrance revealed low speed values and in some points the total absence of propagation of the ultrasound waves, indicating a situation that is worse than that seen by mere observation. The column on the left especially shows clear signs of chipping and lamination of the crystalline planes of the material with a progressive reduction of the resistant section.

The Torre has undergone a number of maintenance and restoration works over the past two centuries that implemented a series of measures aimed at improving the structure's static equilibrium.

The surveys conducted therefore focused on controlling the condition of these measures, and in particular the tension of the metal chains within the loggia that were not located inside the walls and the presence of steel strands within the masonry built (it is assumed) during the restoration works conducted in 1981.

The check on the chain tension was conducted through the dynamic analyses of free vibration. Only the north and south chains (only two of the four chains in the loggia) were assessed, inasmuch as they were the only ones detached from the masonry. In fact, this circumstance greatly compromises the reliability of the analysis that was consequently not been conducted on the metal elements facing east and west.

The analysis was conducted by disturbing the chain, applying an impulse and recording the accelerations produced with an accelerometer placed at the center of the chain. The results acquired through a personal computer showed the poor tension of the metal elements that will undergo a tension enhancement procedure or will be replaced during the restoration works.

The last analysis consisted in checking, (using a magnetometer), the presence of metal consolidation strands which according to the projects that we possess were installed in 1981.

The theory that the documentation on paper referred to was confirmed by the presence of markers on the building's façades that were painted with colored paint which according to the other documents, represents the actual position in which the building firm that carried out the consolidation work had placed the strands.

Six readings were made on the external façades (on the north and east fronts) and two on the internal fronts (west façade), in order to verify the presence.
The diagnostic analyses conducted (that constitute the necessary projects to know the static condition of the structure) were provided by the Regional Office of the Lombardy Region to the structural engineer who, on the basis of such data, will develop the security implementation plan for the Torre itself.

4 CONCLUSIONS

The survey of the “Torre quadrata del Circo Romano” has been based on the analysis of direct and indirect sources, useful tools for the comprehension of the building itself, taken within its historical evolution, as well as of its structure and materials’ consistency. Thanks to the archive research carried out, and to the method used for dating historical buildings (stratigraphy, mapping and identifying of the different wall construction techniques, chronotypology of apertures) we were able to understand the construction of the building in all its complexity.

Mapping of external and internal fronts led to the identification of walls’ continuity or discontinuity and to the recognition of tooting or non tooting of partitions, of dividing walls and of doors and windows. Besides this it was also useful for the identification of stratigraphic facts that suggested the “critical areas” in which the conservation project will have to focus on.

Material data and geometrical aspects that have been surveyed provide considerable information and attest the building’s past history, giving, at the same time, useful hints and indications on the methods to apply for a correct approach to the intervention project.

As a matter of fact, all the information resulting from this campaign, correlated with the direct measurements, with the monitoring of verticality and with the diagnostic analysis, let us achieve detailed and exhaustive answers to the complexity of the problems that affect the building. The clearness and completeness of the preventive diagnostic outline, further strengthened by petrographical, chemical and physical analysis of materials, has allowed for the correct development of a specific conservation and structure improvement project.

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Figure 10. Localization of the analysis carried out with magnetometer.