THE ANCIENT CITADEL OF DAMASCUS (SYRIA) AND THE HIDDEN WATER:
FROM HISTORICAL AND ENVIRONMENTAL ANALYSIS
TO STRUCTURAL CONSOLIDATION

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ABSTRACT

A project of conservation and rehabilitation of a monument can’t disregard the primary operation of analysis and diagnosis, essential to the knowledge. Therefore, the definition of the possible hazards for the buildings of the Damascus Citadel and the design of all the essential operations for their rehabilitation, are only a part of a greater scheme, which contemplates the preservation and revaluation of the entire Citadel as the heart of an ancient culture: the Syrian and Mediterranean one. Aim of this paper is to show the procedure and the results of the studies on three historical buildings inside the ancient Citadel of Damascus, Syria, lead by the research group of Parma University, together with Rteknos monitoring society and DECO Inc. Architectural society, coordinated by Prof. Carlo Blasi and Prof. Eva Coïsson - in strict cooperation with a group of Syrian experts of the DGAM of Damascus.

INTRODUCTION

The purpose of the work was the “Analysis and Diagnosis of the damaged structures of the Citadel of Damascus”, a cooperation project financed by the General Direction for Development Cooperation of the Italian Ministry of Foreign Affairs in the framework of the cultural project “Renovation and reorganization of the National Museum of Damascus and rehabilitation of the Citadel of Damascus”, signed in November 2004 by the Government of the Italian Republic and the Government of the Syrian Arab Republic. This project was launched to preserve and revalue the entire Citadel [1] as the heart of the ancient Syrian and Mediterranean culture, also looking forward to the fact that Damascus has assumed the mantle of Capital of Islamic Culture in 2008.

Figure 1: The ancient citadel of Damascus. General view of the East-northern corner (Ayyubbid Hall and Tower 8)
Object of this work are three buildings situated in the ancient Citadel of Damascus: a central vaulted hall (the Ayyubbid Hall) and two towers at the north-eastern (Tower 8) and north-western corners (Tower 12) of the Citadel (Fig. 2). These buildings belong to different historical periods, as the Citadel itself was built in several phases, starting from the 10th century and significantly modified during the centuries.

The primary goal of this work was the maximum understanding of the stability conditions and possible hazards of the structures interested by the project, in order to give the best results for their conservation and rehabilitation. Therefore, a critical analysis path has been conducted, in step with the most recent “Italian Guide Lines for consolidation of historical monuments” [6]. A reasoned program of tests on the buildings has been established, articulated in several mechanical and endoscopic analysis, together with chemical ones, and the installation of a digital monitoring system on the three structures.

A mixed procedure of empiric observation and advanced analysis methodology has represented the solution to the complex problem of ancient structure rehabilitation, which is always an interesting mixture between past and present. The aim of all this study was in fact to identify not only the structural damages themselves, but also the mechanisms which had produced these damages and, in consequence, theirs causes, by following “the empiric-experimental methodology”.

The instruments used for this analysis path have been several and different: starting from the exam of historical documents [4], together with the analysis of the historical structural alterations, carrying on with the investigations on soil and water, obtaining then the identification of the collapse mechanisms [2], ending with their calculations with numerical models and their control through the installed monitoring instruments.

Figure 2: Plan of the citadel of Damascus, with the identification of the studied buildings:
Ayyubid Hall, tower 8 and tower 12
HISTORY AND STRUCTURES

The present static conditions of a historical building always depend on several factors which have occurred somewhere during its long history: building materials and techniques, settlements, modifications, wars, earthquakes, collapses and reconstructions. Therefore, the assessment of the present hazard level should always start with a thorough analysis focused on all the possible structural alterations to which the building has been subjected to in the past.

This kind of analysis should include not only the study of historical documents, but also on site inspections of the monument. Indeed, we have to remind that the word “monument” comes from the latin word “monumentum”, which means memento, document. The monument is, therefore, the first document of itself and the traces and scars that we can “read” on it are important attestations of past events, of which often no written testimonies are left.

This type of analysis carried out on the three buildings of the Damascus citadel led to the identification of two main mechanisms which have caused most of the structural damages, and for which rehabilitation interventions may be needed:

- a differential settlement due to water-related subside phenomena,
- the seismic action (combined with the thrust of the vaults at each floor).

Indeed, the historical study also pointed out the main earthquakes that hit Damascus [2] since the citadel construction and that left traces on the walls that can still be seen today (Fig. 3).

Once the damage mechanisms of the analyzed structures have been identified, it is important to tell apart the ones that are still moving from the ones that are ancient and not active any more. To understand the current evolution of these mechanisms, a structural monitoring system was installed, measuring the opening of the main cracks and the variations of environmental conditions (temperature and humidity). After nearly two years of data analysis, it is possible to notice that the cracks on the east and west walls of the towers show a higher aperture velocity than the others, suggesting that the mechanism of overturning of the north walls is nowadays the most active one.

Figure 3: Past reconstruction phases and present damage mechanisms on tower 8
SOIL AND WATER

Having identified water (and its interaction with soil and structures) as a possible source of problems for the stability of the monuments, a deeper inspection have been made on the presence of water in and around the Citadel, and its evolution to the actual configuration.

Indeed, as shown in Figure 4, in the past the Citadel was closely surrounded by a moat full of water, which lapped directly the towers walls. More recently the moat was filled with earth, leaving a small basin south of tower 12 and keeping the Barada river to flow about 12 m away, north of the Citadel. Moreover, the hidden course of the old canals in this area has been identified, which go from the West to the East side, passing near the south side of tower 12.

The soil investigations carried out near the two towers, showed that the clay and sand strata are roughly parallel to the ground inclination and that the water table level is about 7-8 m deep, while the foundations start about 0,5 m lower (Fig. 5).

Moreover, two differences between tower 8 and 12 have given us interesting information. It could be noticed in both corings that layers of stones were found about 5 m deep, probably collapse residues, and that these are much more abundant under tower 12 than under tower 8. The coring near tower 8 also shows, beneath the stones layer, a stratum of organic clay from 6 m to 8 m: this is most probably the residue of the moat plants and mud, confirming that a moat actually passed at the foot of the wall in this area.

**Figure 4:** Relationships between the citadel and the water: the ancient course of the moat all around the Citadel

**Figure 5:** The water-structure relations in tower 12: the basin on the right, the Barada river on the left and the level of the ground water table
It is then possible to hypothesize that the moat slowly filled up with mud and plant residues, for about 2 m, when an earthquake probably caused a partial collapse of this part of the tower, whose remains can still be found under about 5 m of soil. All these facts can justify the subside phenomena and the differential settlement of the structures, which is shown mainly by the global capsizing movement of the two towers toward north.

THE EMPIRIC-EXPERIMENTAL METHODOLOGY

From this historical and environmental analysis, in a comparative process of past and present, it has been possible to identify some general causes for the damage mechanisms of the citadel and this is fundamental in calibrating the future intervention of structural consolidation. The two main problems have been analyzed through a double method, combining the equilibrium approach to the results of numerical models. Numerical models, can hardly describe the non linear mechanical behavior of the masonry [7], and they cannot describe, with simplified numerical parameters, the consequences of historical events as ruins, reconstructions, floods, soil movements (Fig. 6), and the degradations caused by age and weathering. So, it was necessary to identify the most probable collapse mechanism, and to solve the problem using the equilibrium approach, by reducing the structure to an iso-static scheme.

![Figure 6: Structural analysis with finite element method of the interactions between soil and Tower 8.](image)

The models used are tested to explore the relation between the different geometrical parameters and the possible equilibrium conditions. Collapse mechanism analyses are determined by combining kinematics and statics. Complex three-dimensional problems are analyzed using this methodology, by reducing the complex structure to a kinematic mechanism of collapse and then finding the equilibrium solutions to the hypothesized movement. Therefore, at the end of this comparative process we have checked the hypothesized collapse mechanisms with the ABAQUS models (finite element method), verifying the same results. The model realized with the f.e.m. code, in fact, has revealed the same mechanism, stressing the creation of natural hinges between the different elements, following the typical collapse mechanism of the arches, confirming, at the end, the followed analytical path.
The cracks pattern, together with the study of the possible causes of damage, has permitted, in fact, to formulate a kinematic hypothesis of movement on each building, which has been reduced to a simplified geometrical combination of the different constitutive structural elements, trying to identify the global mechanism of collapse. For each rigid block, the correspondent actions (dead weight and seismic action) have been applied; for each element, then, is possible to formulate the three equilibrium equations, composing a system of equations which can be solved through progressive iterations in the matrix of values.

So, checking the structure is possible to reduce the general static problem to the solution of a rotation movement of each external wall of the building, subject to (Fig. 7):

- the seismic action (applied as a static horizontal force), indicated with $S_i$;
- the self weight, which is $W_i$ for each $i$ element involved in the collapse mechanism;
- $H_d$ represents the traction force of the tie needed for the stability.

**Figure 7:** The equilibrium approach, used to reduce the complex structure to a kinematic mechanism of collapse.

The numerical models of the structures, as already said, has been performed by consecutive steps, in order to identify the causes underlying the observed static problems, which had emerged during the “in situ” investigation. The solid continuum mechanics, especially the finite element method, offers the most suitable and practical models for skeletal structures macro-modelling.

Then, a 3D model of the three buildings have been built, by using a simplified solid elaboration (Fig. 8). A precise geometrical survey restitution is very important for the construction of the model; however the correct simplification of the numerous data of the 3D survey (as the photogrammetric one) it is also of fundamental value. A solid model has been built, on survey base, for each structure, following the symmetry simplifications, which grows in height and follows the profiles of the real shape of the vaults, the walls and the pillars (or columns), as measured in the survey.

In normal applications, the finite element method is optimal for elasticity problems, not for evaluating the stability. In this case, instead the finite element method has been used as a discrete one: this simplification is particularly suitable for masonry structures because it allows the definition of individual blocks within the structure.

The constitutive properties of blocks have been defined from tests on materials, although in the kinematic approach the materials characteristics have a limited influence on the results. The problem of movements of these single blocks have been simulated, by following the lines of reconstruction and the cracks zones, identified by the previous analysis. Contact forces between
the blocks are assumed to be proportional to the loads on each blocks, and the behaviour between
them derives from the non-penetration and friction laws used to define the contact between the
blocks.

Traditional masonry structures have a very low tensile strength, which decreases with time. In
practice, the masonry can also be considered as an ideal no-tension material, especially in the case
of vaulted structures, in which the prevalence of compressive stresses is obvious.

This situation is more complex to be evaluated, in consideration of the nature of three leaves walls
which constitute the bearing structure of the three buildings. But the question has been simplified
reducing the problem to the identification of the kinematic collapse mechanism of a rigid structure.

Figure 8: A simplified 3D FEM model of a collapse mechanism

The results of the previously described ideal model of the three buildings have verified the
outcomes of the first empiric-experimental phase. Moreover, these findings have confirmed the
collapse mechanism hypothesis, based on the observation of the cracks. The tensile pattern
obtained by the model matches with the actual cracks, which really represent the main continuous
monitoring system of the structure. The cracked model has simulated the real behaviour of the
structure, even if it uses a linear-elastic constitutive law for the finite elements inside the blocks, as
the non-linearity of the material is concentrated in the cracks. After these analysis, we can say that
the elastic linear model, with the empiric insertion of the cracks, could represent a good
approximation of the reality, of easy application and control.

RESULTS & DISCUSSION

The use of interdisciplinary instruments and different competences has allowed to reach a
thorough knowledge of the three structures which were objective of the study. In particular, it was
possible to identify that the main mechanisms which have damaged the buildings in the past and
that can be considered as main hazards for the future were the differential soil settlements and the
walls overturning due to seismic actions.

The soil settlements, both horizontal and vertical, enhanced by the reduction of the ground water
table level, have caused in the past a northwards rotation of tower 8 and they are still the cause of
the opening of cracks in both the analysed towers, particularly towards the Barada River, due to
the inclination of the soil strata in this direction. The monitoring system has showed that these
differential movements between the different parts of the towers are still active and, though they should not be considered an immediate threat for public safety, should be blocked to ensure the long term conservation of these two buildings. The best solution to hinder this phenomenon has been identified in the insertion of ties at the foundations level, so that each tower will move as a whole and the cracks opening will be avoided. The Ayyubid Hall does not show any remarkable disorder connected with foundation settlements, as it rests over a solid layer of soil.

Earthquakes have also played an important role in the disorders suffered by the whole Citadel in the past [8]. On the two analysed towers there are clear traces of partial collapses and several reconstructions. The seismic risk is still present in all the studied buildings, indeed, in the towers it is worsened by the cracks that disconnect almost completely the north part from the rest. Moreover, the horizontal actions on the walls are increased by the thrusts of the large vaults. Therefore, a better connection among the external walls is needed, in order to make the whole structure to work together and to prevent overturning of single walls. For this purpose the least invasive and most respectful intervention is the insertion of ties at each floor and in the two directions (Fig. 9). In the Ayyubid Hall it is also advisable to reduce the thrust of the vaults by removing some of the filling strata added during centuries on the upper terrace.

**Figure 9:** The FEM model of the Ayyubid Hall with the insertion of ties for seismic rehabilitation

**CONCLUSIONS**

Ensuring the safe fruition of the buildings is an important but preliminary instrument for a more general path of renovation and revitalization of this ancient Syrian citadel [9], which is nowadays closed to the public. The studies on the damages and the stability calculations, following the empiric-experimental method, have represented only the final step of a deep knowledge process, which should always be followed when ancient buildings are concerned.

The results of these analysis gave some useful indications for the rehabilitation project. It was possible to demonstrate that the main identified hazards (walls overturning for seismic events and foundation differential movements due to soil settlements) can be prevented with the insertion of few (and cheap) ties, limiting the impact on the monuments and preserving their authenticity. Indeed, as a part of a complete restoration intervention, also the structural rehabilitation should always follow some fundamental laws: the minimum intervention, the reversibility, the physical and chemical compatibility, the respect of the authenticity, including the respect of the original structural behaviour.
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