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The antiseismic rehabilitation of Marchesale Castle at San Giuliano di Puglia

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ABSTRACT: After the earthquake (October 31st, 2002) which struck Molise Region (Italy), an ENEA team has been collaborating to the reconstruction of the town of San Giuliano di Puglia. Many buildings suffered severe damage or partial collapse, including important Masonry CUltural HEritage Structures (MCUHESs). This paper specifically deals with the rehabilitation of the notable Marchesale Castle, in the framework of the ENEA scientific advice given to the Office of the Public Works Ministry. ENEA reviewed in detail the rehabilitation project (entrusted, as other works, to private consultants), suggesting some remedial actions.

1 INTRODUCTION

1.1 A brief information on the October 31st, 2002 seismic event

A moderate earthquake struck Molise (Italy) on October 31st, 2002, 11:35 local time; the first shock (M 5.4) was followed by another (M 5.3) the day after. Spread damage was evident in San Giuliano di Puglia, a small town located 5 km far from the epicenter. The maximum seismic Intensity at the site was estimate to be VIII-IX MCS, observed both during the 1456 and 2002 events. Damage was not uniformly distributed inside the San Giuliano narrow area, characterized by different levels of seismic hazard and structural vulnerability (Indirli et al. 2004a, b). ENEA experts took part in all the activities following the seismic event: i) the emergency, under the coordination of the Civil Defense; ii) the post emergency phase, carrying out a detailed evaluation of damage, drafting the demolition plan, ensuring safe conditions to the buildings to be repaired, and operating for allowing residents to safely reenter their non-damaged houses; iii) the San Giuliano reconstruction planning, in the framework of a specific working team; iv) the technical-scientific advice to the Office of the Public Works Ministry for some important reconstruction and restoration projects, including Marchesale Castle.

1.2 Seismic input

Before the 2002 earthquake, San Giuliano was not classified as a seismic zone. After the earthquake, it has been included in zone 2 (maximum Peak Ground Acceleration PGA equal to 0.25g) in the seismic reclassification of Italy (Presidente del Consiglio dei Ministri 2003a) and the Civil Defense appointed a technical commission to provide the San Giuliano seismic microzoning. The study reflects zones with different geology, topography and seismic local amplification (Indirli et al. 2004a, b). A specific decree of Molise Region fixed the PGA value to be used for the San Giuliano territory equal to 0.21g. The 1456 earthquake (maximum values M 6.6, MCS XI) hit a large area of South-Central Italy for the first time on the December 5th's night. This event probably consisted in a long series of shocks, due to the simultaneous activation of several seismic sources, overlapping at least three areas encircling different epicenters.

1.3 Structural vulnerability of the San Giuliano historical center

The medieval center (Fig. 1), interesting from an historical and architectural point of view, was deeply investigated; in spite of the low local amplification, it presented partial collapses and a medium-severe damage; only a few houses were ready for reuse. Also the more notable MCUHESs (including Marchesale Castle, Fig. 2) suffered heavy damage. All the area was in general characterized by high vulnerability and the most usual collapse mechanisms were the wall failure with typical cross cracks, but also out-of-plane overturning (Indirli et al. 2004a, b).

Figure 1. View of the San Giuliano historical center.

Figure 2. Damage to Marchesale Castle.

1.4 Design codes and requirements

In several Italian scientific studies regarding the restoration of historical centers and MCUHESs located in seismic areas, it is well-established that antiseismic interventions must harmonize protection and conservation. The original approach of Antonino Giuffrè (Giuffrè 1988, 1991, 1993), regarding construction techniques and mechanical characteristics, seismic vulnerability and damage mechanisms, protection and rehabilitation, has been largely developed, in particular learning from periodical earthquake lessons (examples in Doglioni 1994, 2000). Furthermore, the new Italian seismic code (Presidente del Consiglio dei Ministri, 2003a, b, 2005), recently updated, contains the requirements for seismic retrofitting or improving existing MCUHESs. Specific criteria are also indicated in some decrees approved by the Molise Region and in the guidelines produced by the Italian Ministry of Cultural Heritage.

In order to avoid a possible conflict between the conservation requirements prescribed for MCUHESs (integrity, compatibility, reversibility and durability) and the antiseismic improvement, the philosophical approach can be summarized in these following simple statements:

a) because MCUHESs rehabilitation problems are much more difficult to solve than those related to modern r. c. or steel structures, interventions can derogate from the antiseismic design criteria foreseen for ordinary buildings;
b) in relation to the state limit analysis, the intervention must be defined as a "controlled structural improvement", i.e. accepting an antiseismic protection level lower than required, in order to reduce invasivity;
c) for each limit state, the improvement effectiveness must be quantified, evaluating the PGA levels which generate the local collapse mechanisms, before and after the intervention;
d) because the MCUHESs characteristics (history, material properties, construction details, quality of connections, state of integrity and maintenance, etc.) are frequently not well known, detailed survey, damage assessment and diagnostic campaigns must be carried out, in order to reach a knowledge level as deeper as possible; moreover, each MCUHES is different: therefore, it is necessary to undertake the rehabilitation design in a specific way, use of standardized procedures being not possible;
e) the observance of the "regola dell'arte", i.e. the unwritten construction rules for masonry elaborated by architects and bricklayers in centuries of work practice, is fundamental for protection (good overall static and dynamic behavior), conservation (durability in after years) and restoration (avoiding irreversible mistakes); the use of modern techniques and materials can be very useful to reduce seismic vulnerability, but it must be philologically correct, compatible and mechanically effective.

2 DESCRIPTION OF THE MARCHESALE CASTLE

Historical information on the Marchesale Castle is very scarce. Probably the first settlement existed since the Punic Wars. This fact is confirmed by the discovery (2003) of some archaeological remains of a Roman "villa rustica" (II-I century B.C.), during the works on a hill not far from San Giuliano, in order to realize the temporary houses for the earthquake homeless. Around the first millennium A.D., a fortress was already built, which entrance was permitted by three towered doors. The 1456 earthquake destroyed most of the buildings, including the original castle and the ancient church, which were reconstructed, together with the medieval center. Then, until present times, inhomogeneous works stratified, so that to diversify reworked parts from almost untouched ones.

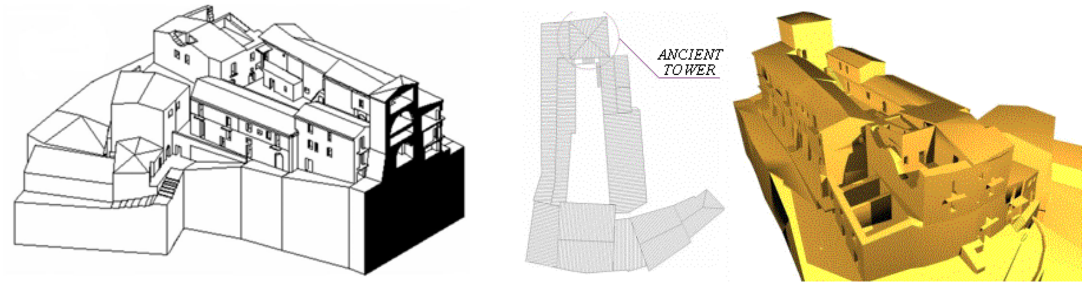


Figure 3. Geometry of the Marchesale Castle.

Figure 4. The old Castle Tower.

The Castle is a typical example of the South Italy historical architecture. Its multi-leaf stone-masonry walls, which suffered medium-high seismic damage, are characterized by poor materials, irregular morphology and voids presence, often concentrated in a loose internal core. Many researches (Tomaževič 2004, Modena 2004) focused the attention to the causes of the main structural problems (weakness of the internal layer, mortar deterioration in the external joints, lacking of connections among external leaves). In fact, these buildings are very sensitive to "brittle" collapse mechanisms, usually happening both under vertical and horizontal loads, by layers detachment and out-of-plane expulsions. The castle structure consists in several blocks interconnected together (Fig. 3). Taking as reference the castle internal court ground, four upper and three lower levels envelop the hill slope. The tower (Fig. 4) represents the most precious and ancient element of the entire complex. It is a squared-plan building, with buttresses on the West side and a Southern entrance portal (with a barrel vault) to the internal court. The tower upper quarters, covered by cross vaults, can be reached through external stairs. Most of the castle horizontal structures are generally wooden or steel-tied floors, but other original stone vaults, with different geometries, can be found at the lower levels (Fig. 5). The tower thick basement (until 2.90 m) shows a pronounced tapering with height (until 1.20 m), and an irregular masonry fabric is clear in the façades, made by heterogeneous materials (mainly corner squared stones, variously sized river pebbles and brick insertions), likewise the majority of the castle walls. In the tower front views it is still possible to identify pretty genuine architectonic evidences, the so called “buche pontaie” (small holes used to provide supplemental defense wooden scaffoldings) and the twice-line triangular pigeon houses located under the roof (Fig. 6). Other aspects are: generally deteriorated mortar courses, plaster traces, brick fillings (old openings and masonry past rehabilitation). After the seismic event the tower free top was tied up with steel cables (in order to avoid overturning collapse) and covered by a steel sheet.

Figure 5. Some vaults details.

Figure 6. Earthquake damage to the tower.

3 THE DIAGNOSTICS CAMPAIGN

Several methods with different complexity levels can be used in modeling MCUHESs, but planning detailed surveys and experimental campaigns is often mandatory. Investigation on material properties, masonry typology, construction details and structural damage is indispensable to get the information to manage the structure safety control and the choice of appropriate repair methods. Non destructive (NDT) or minor destructive (MDT) techniques are required, in order to avoid invasive tests (Binda 2004). A brief description of the work managed on the Marchesale Castle is given in this chapter, starting from surveys addressed to the description of geometrical and morphological features, up to tests aimed to evaluating mechanical and physical properties of materials and construction elements (Fig. 7).

The single flat jack test allows to evaluate the in-situ stress level of the masonry, measuring the stress relaxation due to a perpendicular cut to the wall surface. A thin flat jack is placed inside the cut and the pressure is gradually increased. The double flat jack test can be used to evaluate the masonry deformability characteristic. In this case, a second cut is made (parallel to the first one) and a second jack is inserted. At least two tests (Fig. 8) have been performed on each structural block, and the old tower has been investigated with particular accuracy. In presence of thick walls, tests have been performed on each external curtain. More than twenty single and double flat jack tests have been carried out. Local compression (1.0~4.0 kg/cm^2) and Elasticity Modulus (2000~3500 MPa), have been measured. The compressive resistance can be estimated around a value of 15.0~20.0 kg/cm^2.

The shear pull out test (Fig. 9) consists in the insertion of a tensile element (usually a steel bar) into a larger borehole. If used on different masonry portions, it aims to investigate the sliding behavior of the walls, identifying a local shear value (τ_{loc}) “marking” the wall out-of-plane mechanism. These tests generally have been done in the same positions of the flat jack tests, in order to correlate masonry sliding properties with local axial compression (experimental range of τ_{loc} values: 2.0~3.5 kg/cm^2).

The investigation using borehole with video endoscopy, performed on elevation and foundation walls, gives a general stratigraphy of the wall section (Fig. 10). Borehole coring (done with a rotary driller equipped by a diamond cutting edge in the most representative points of the walls) detects the quality of the original materials, but sometimes has some limits, especially when the extracted material shows lacking of cohesion. Further important data can be obtained by the use of video endoscopies by the insertion of a small camera into the borehole, allowing a detailed study of the wall cross section. The tests have been performed in several positions with particular attention to the old tower. A total of seventeen investigations were carried out with a maximum drilling depth of 350 cm. In most cases tests showed a poor internal core (small stones, lack of mortar and voids presence).

Sonic pulse velocity tests (Fig. 11), based on the generation of sonic/ultrasonic impulses at a point of the structure, are useful for different purposes, i.e. to qualify the masonry through the investigation of the wall section morphology, detect the presence of voids, and find crack and damage patterns. These tests have been performed widespread in all the Castle. In particular sonic tests have been carried out before and after absorption test to check repair effectiveness after mortar grout injections.

Absorption tests have been used to compare two different products for mortar injections, aimed to set up the main consolidation process parameters (e.g. pressure and time of the injection and number of injection holes). The tests (Fig. 11) have been performed on a representative building masonry portion. Subsequently mortar injections, sonic tests and boreholes with video endoscopy have been carried out, in order to check the quality of the consolidation process (demonstrated by a significant increase of mortar sonic velocity: 600 m/s ante injection, and 1300 m/s post injection).

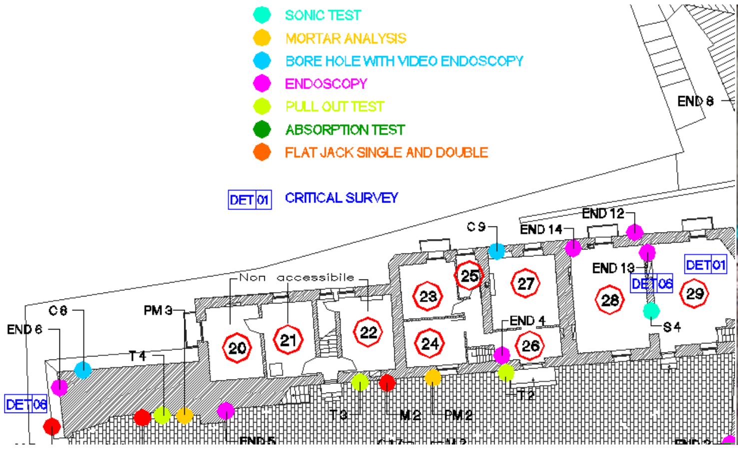


Figure 7. Examples of experimental tests on Marchesale Castle.

Figure 8. Flat jack tests.

Figure 9. Shear pull out tests.

Mortar analyses are oriented to evaluate the mortar conservation state, identifying composition, resistance and degradation. They have been performed widespread in all the castle (a total of six tests). The following main chemical and physical tests have been carried out: thermogravimetric analysis (TG-DTA) and petrography by polarizing microscope. An altered lime mortar (made by fluvial sand characterized by an high percentage of clay) has been identified and in particular the presence of magnesium salts has been pointed out deterring the use of cement mortars.

The construction details critical survey provides important data regarding quality of "T" and corner crossings of bearing walls, effectiveness of wall-floor nodes, presence or lack of steel ties, stability of vaults and arches. Similar results can be also carried out through the analysis of a generic transversal wall section, aiming to evaluate the voids percentage. In general, the masonry of the Marchesale Castle can be considered a poor construction typology (small-sized and bad shaped stones, except sometimes in the corners); the presence of transversal connections is very scarce and this aspect must be considered during the rehabilitation design.

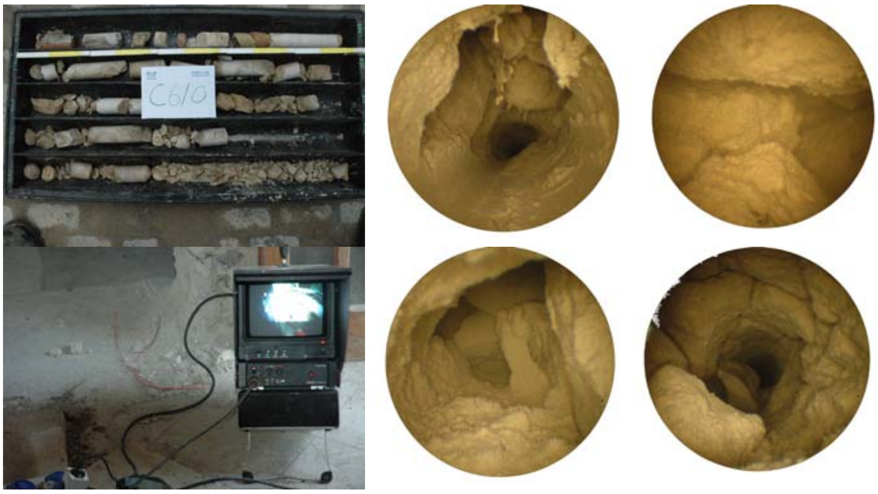


Figure 10. Boreholes and endoscopies.

Figure 11. Sonic (left) and absorption (right) tests.

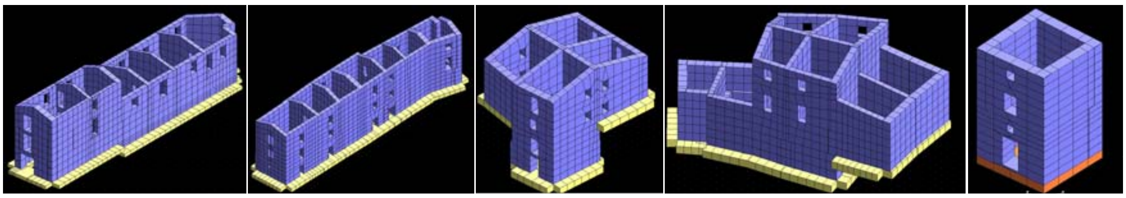
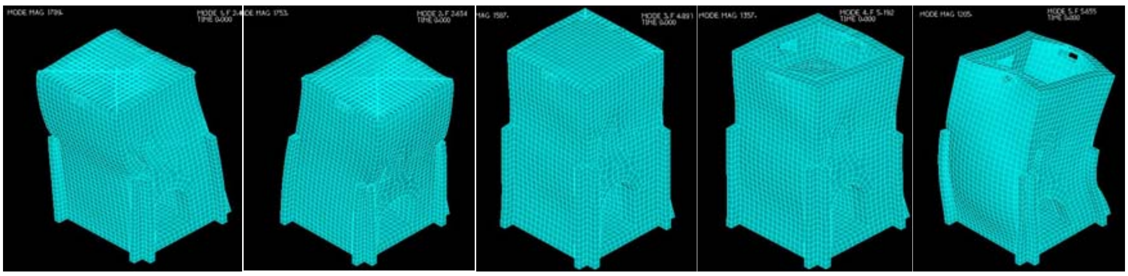


Figure 12. Simplified FEM of the whole structure.



2.475 Hz *2.654 Hz* *4.891 Hz* *6.064 Hz* *6.901 Hz*

Figure 13. More detailed FEM of the tower.

4 NUMERICAL MODELS

The use of Finite Element Models (FEMs) for MCUHESs (implemented by data coming from experimental investigations) can be helpful to understand static/dynamic behavior, identify modal frequencies, evaluate stress/strain, displacement and acceleration values, verify safety margins and quantify antiseismic rehabilitation effectiveness. Structural knowledge levels (geometry, construction details, properties of materials) and calculation procedures (limit state structural analyses), are clearly reported by the already mentioned new Italian seismic code.

An implementation of the FEM calculations was considered necessary, in order to refine the outputs regarding modal frequencies and safety margins. The calculations are still underway and two different FEMs have been developing. A simplified model of the entire Marchesale Castle (Fig. 12), done by the designer using a commercial structural analysis code, is composed by simple vertical wall panels and infinitely rigid horizontal floors. A more detailed model (at the moment only for the tower) for further checks is provided by ENEA, made by 8-nodes solid elements (Fig. 13), taking into account the interaction with adjacent blocks. It can give, at the moment, a preliminary idea of modal frequencies. In the next months, the final outputs of both the two models will be compared, also taking into account the dynamic campaign results recently completed by ENEA on the Marchesale Castle.

Due to the complexity of ancient MCUHESs (often characterized by the lack of connections of vertical masonry elements and between them and their floors), the Italian code foresees the analysis of local damage mechanisms, regarding the out-of-plane collapse of single panels, but also the overturning of entire vertical walls (if monolithic), as shown by many earthquake damage patterns. Due to the almost-zero tensile masonry resistance, structure geometry and constraint effectiveness are crucial factors for the origin of labilities under dynamic loads. Then, a kinematic approach is necessary, identifying the horizontal force which moves the structural element from its static equilibrium. In addition, structural aggregates must be closely studied, because often they can't be separated into smaller blocks to simplify the structural analysis.

5 THE REHABILITATION DESIGN OF THE MARCHESALE CASTLE

In the framework of the scientific advice provided to the Office of the Public Works Ministry for the Reconstruction of San Giuliano di Puglia, ENEA reviewed in detail the rehabilitation project entrusted, as other reconstruction works, to private consultants (Carpani and Indirli 2005). In order to make the project coherent with the Italian seismic code and the guidelines of Italian Ministry of Cultural Heritage, some remedial actions have been suggested. It was recommended to carry out deeper investigation campaigns (diagnostics, whose first results are given in chapter 3, and still underway dynamic characterization), in order to get a more exhaustive structural knowledge. An implementation of the FEM calculations was considered necessary (see chapter 5), with the aim to refine the outputs regarding modal frequencies and safety margins, integrated also by the analysis of local damage mechanisms. Finally, particular attention has been devoted to improve the rehabilitation techniques more suitable for effective protection and observance of the conservation criteria (see point 1.4) coupled with the expense reduction. In particular, the following aspects have been stressed. Strengthening the vertical walls (and their reciprocal interconnections) is recommended, throughout the insertion at each level of steel-ties in both the horizontal directions, together with the reconstruction of the most damaged masonry portions by using similar and compatible materials, avoiding local stiffening. Injections of compatible mortar, where necessary, have to be done after a detailed identification of mixtures and procedures. Vaults reinforcing has to be carried out by using conventional methods (repairing and thickening by layers of thin bricks) and, when possible, innovative materials as, for example, SMADs (Shape Memory Alloy Devices), but rejecting r. c. coping. Steel bars insertions in the stone-masonry have to be avoided. All the floors should be provided by adequate stiffness, anchoring them carefully to the vertical walls keeping off the use of floor r. c. string-courses and preferring steel string-courses; at the top level, a reinforced masonry-course can be provided, in order to stiffen as best as possible the roof to vanish pushing effects.

6 CONCLUSIONS

In the Italian scientific studies and Cultural Heritage Ministry recommendations regarding the restoration of historical centers and MCUHESs located in seismic areas, it is well-established that antiseismic interventions must harmonize protection and conservation. This approach guided the review (provided by ENEA to the Public Works Ministry for the Reconstruction of San Giuliano di Puglia, in the framework of a scientific collaboration agreement) to the Marchesale Castle rehabilitation project, entrusted, as other reconstruction works, to private consultants. If the new Italian code foresees clear antiseismic criteria, it also confirms the possibility for CUHESs to derogate from them, in order to reduce the conflict between strengthening and conservation. In fact, the goal is to reach a "controlled structural improvement", i.e. an antiseismic protection level lower than required for new buildings, but quantifying improvement effectiveness for each limit state. Furthermore, the execution of detailed diagnostic campaigns is encouraged, in order to maximize the knowledge level of the structure (geometry, construction details, properties of materials). Then, a wide series of experimental tests (including dynamic characterizations) has been recently completed on the Marchesale Castle, whose first results will implement the numerical models, which are still underway. The structural analysis results, together with other considerations coming from the study of local damage mechanisms and regarding structural aggregates, are bringing into focus the final intervention philosophy. In any case, in the authors' opinion, the observance of the "regola dell'arte" (i.e. the unwritten construction rules for masonry elaborated by architects and bricklayers in centuries of work practice), should be drive the rehabilitation approach. The use of modern techniques and materials can be foreseen in order to reduce the seismic vulnerability, but it must be philologically correct, compatible and mechanically effective.

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