Structural Rehabilitation of Historical Masonry Buildings

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Abstract. The rehabilitation of heritage buildings represents a challenge from two perspectives: from architectural point of view, which involves the conservation, repair and/or replacement of damaged elements and from structural point of view by adopting solutions to increase its bearing capacity with minimum intervention on structure.

Masonry is one of the oldest, traditional construction materials, used for religious and civil architecture in the world. Beside numerous advantages, masonry has some disadvantages on long term, which may lead to severe damage and even unfavorable failure mechanisms. Given the high number of historical masonry buildings, the article makes a review of the specific problems for these types of structures and presents some specific methods of intervention.

The article also presents a case study, in which a heritage building is analyzed. The monument is located in the Moldavia region from Romania. Its main damages and the proposed rehabilitation methods are shown, in order to ensure the structural safety increase, and to obtain a target structural safety level for the structure.

Keywords: Masonry · Failure mechanism · Rehabilitation · Heritage · Structural analyze

1 Introduction

1.1 Heritage

Heritage is an achievement of the mind or the hand of a man who comes out of the ordinary, distinguishing itself by its value or magnitude. In architecture, the heritage term applies to an important building, such as the Egyptian pyramids, the Greek temples and byzantine, roman or gothic churches, renaissance palaces and so on. The entire heritage of the past culture has become the subject of concerns to protect and restore it. As a result of this enlargement, the monument term, was limited only to objects with a unique character.

However, the notion of historical heritage was extended also to urban areas of historical interest, to historical centers and even entire cities, although the great mass of

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buildings, within the perimeter of these areas, give the historical and architectural value, compared to monuments with unique character.

Thus, concepts as historical area, historical center and historical city have developed along the years. In Fig. 1 an example of an historical center from Sibiu, Romania is presented [1]. Sibiu is one of the most important cultural centers of Romania and was awarded "the European Capital of Culture" in 2007, along with the city of Luxembourg.

Fig. 1. Historical center of Sibiu city [2]

In 2008, Forbes magazine ranked Sibiu as "Europe's 8th-most idyllic place to live". Sibiu city has one of the best-preserved historical sites in the country, many of its medieval fortifications having been kept in excellent state. Its old center has begun the process for becoming a UNESCO World Heritage Site in 2004.

1.2 The Masonry

The masonry has a long tradition and, for several hundreds of years, has provided empirically the most rational solution for the construction field. Throughout history, from modest houses up to palaces, churches, fortresses, bridges or aqueducts have been constructed by masonry.

Along the years, specific problems for masonry buildings had been noticed. Researchers worked hard to find appropriate solutions by permanently improving the technological progress. Some of the specific problems for masonry structures are:

- choosing the proper materials to build the masonry (natural stones or artificial);
- to associate the basic elements, so that the continuity of the masonry is ensured;
- achieving horizontal structures of coverage and separation between levels;
- making door and window opening;
- in seismic area, taking horizontal forces in addition to gravitational loads;
- the need to perform functions, other than the bearing, such as protection against climatic factors, but also aesthetic requirements.

In solving most of the above problems, the main limitation was represented by the weak tensile strength (practically negligible) of the masonry, resulting in a series of restrictions on the heights of the buildings, the distances between the supporting walls and the dimensions of the openings. On the other hands, civil engineer's creativity had offered various solutions to these problems, based on the available technical means from various historical eras [3].

Figure 2 presents an old photo of Noyon cathedral, France, with the gothic vault from the main nave. The vault is quadruped, that is, a vault module in 4 parts and covers the area between one 1 bay and one span from the church. The photo on the right gives some information regarding the execution technology used to build this challenging Gothic vault.

(a) (b)

Fig. 2. a.) Old photo of Noyon cathedral, France; b.) Construction stages for the quadruped vault [4]

1.3 Damages of Masonry

Masonry structures are vulnerable to water absorption and significant deterioration may occur if the drainage system is not fully functional. Another problem of heritage building is the susceptibility of failure to horizontal force caused by earthquake or wind. Being built in a period when seismic design codes did not exist, historic buildings are vulnerable to any kind of horizontal action and the absence of interventions on the structural system can lead to serious damages. Other structural damages can be produced by problems at the foundation soil which might overcome its bearing capacity [5].

The need to rehabilitate a building listed as heritage is obvious but, the applicable method and technology differs, producing numerous disagreements between the specialists involved. In case of masonry structures, the self-weight and the live loads are taken over by the walls. In other words, taller buildings require thicker walls, proportional to the number of levels. The lateral forces are taken over by the mortar between the brick or stone blocks. In case of masonry without mortar the lateral forces are balanced thanks to frictions between blocks. The erosion of the mortar, freeze-thaw cycles, rainwater not properly drained and the aging of the material cause loss of integrity and bearing capacity in case of masonry structure.

In cold climate areas, some types of masonry structures are more predisposed to degradation than others. Tall structures, with both sides of the masonry exposed to outside temperature, such as towers, chimneys, turrets, show strong damages caused by freeze-thaw cycles. Another factor which might speed up the erosion on the material is represented by the roof absence [6].

The structural damages of masonry structures can be grouped into direct and indirect. The direct degradations occur independently of damages to adjacent structures and causes deformation of the building leading to loss of bearing capacity. The direct causes of masonry degradation can be chemical, biological, but also thermal, such as the freeze-thaw phenomenon [7]. Deformations produced by mechanical actions generally occur due to overloading of the primary system of the structure. Dynamic forces from earthquake, wind or traffic actions produce major damage to the structures which are not designed to withstand such loads.

Indirect degradations are caused by the displacement of adjacent buildings. These damages occur at the foundation area due to soil deformations. Irregular settlement of the building, erosion of the foundation, lowering of groundwater level, produce cracks in the masonry. Major cracks and degradations of the structural system are also caused by extraordinary actions as fires, explosions, floods.

2 Heritage Building Assessment

A correct intervention to rehabilitate the structural system of a masonry heritage should have as a starting point a precise diagnosis of the building in order to minimize the interference of the structural intervention with history nature of the architecture.

The structural performance of an old masonry building can be understood and quantified by identifying the construction of the monument, with an analysis of its history and especially with an analysis of the current degradation state. In this direction, the aim is to obtain as many information as possible regarding the structure geometry (which is complex in case of historical monuments with elements such as arches, vaults, pendants, walls with conical opening etc.), characterizing the masonry texture and the cross sections of the elements (in one or more layers, with or without bound between layers), defining physical, chemical and mechanical properties of the material components (brick, stone, mortar) and masonry evaluation like a composite material.

With the same degree of interest, consideration should also be given to studying the area in which the historical monument is located, taking into account the destructive level of the external actions (seismicity of the area, wind and snow loads, humidity, etc.), the interference of the neighboring buildings and the characteristics of the foundation soil [5, 6].

2.1 Setting Performance Goals

The M.P. 025-04 methodology defines the term “historical monument”, as a construction that has an important “cultural value” that makes it necessary to guarantee its preservation without affecting its own architectural, typological and material characteristics [8].

In this direction, general requirements that ensure the fulfillment of the performance criteria necessary for the structural rehabilitation process are defined:

- designing and executing intervention works in compliance with the Venice International Book;
- all component parts of the structure are considered at assessing the safety level in accordance with „strength and stability requirements” (infrastructure, superstructure, nonstructural elements);
- „safety” includes also the limiting the degradation of cultural assets;
- anti-seismic protection principles and general aspects can be applied, as far as they do not contradict to provisions of the methodology;
- ultimate limit state principles are used for the dimensions and checking of the final cross-sections, so actual codes are considered;
- the seismic performance level pursued through intervention works is established, usually, for the maximum possible earthquake on site (with an average return period of 500 years) and is defined by two criteria:

  1. small damages and sometimes extended ones are acceptable, if repairable for structural and nonstructural elements;
  2. no irreparable damages are accepted at finishes and decorations levels, with cultural value;

- the technical report is mandatory and a minimal content, composed of: architectural and structural surveys, degradation surveys, photographic surveys, technical memory, computing notes, laboratory or non-destructive tests in situ, geotechnical study, proposed plans with the solution of recommended intervention, is necessary.

2.2 Evaluation Steps

The first stage of work consists of collecting information through the basic methods:

- available relevant documents;
- visual investigation of the objective, the location and summary of neighboring building;
- on-situ measurements;

– laboratory tests on materials and foundation soil;
– numerical simulation.

The specific failure mechanisms and principal damage causes are identified in this stage.

Based on the interpretation of the information from the analysis stage, the main objectives of diagnosing are set: establishing the causes of the damage, assessing the safety at the current state and deciding on the opportunity, urgency and intervention mode. The absence of these stages in the diagnosis or the superficiality of the process makes the presented solutions arbitrary and most often oversized, thus covering the lack of knowledge when making decisions [9].

The phase of diagnosis of the historical heritage consists of two distinct phases, with an equal role in the elaboration of the final conclusions, thus: qualitative evaluation and evaluation by calculation.

Represents in fact a final conclusion of the diagnostic phase, all the intervention works must satisfy the strength and stability requirements and comply with the specific provisions applicable to historical monuments.

2.3 Consolidation Solutions Classification

A classification of such consolidation techniques can be formulated [10] from constructive point of view, into:

– substitution consolidation refers to the replacement of structurally damaged areas, using higher performance materials and elements;
– passive consolidation has as a main objective the improvement of the material properties in the damaged structural areas;
– active consolidation involves the introduction of new structural elements, which can withstand the causes of structure failure;
– reconstruction involves the demolition of the destroyed elements and their restoration to the initial conditions.

Depending on the purpose of the intervention works on the structures, the consolidation techniques can be classified as:

– confinement, which is mainly used to increase the strength of the structural elements by preventing deformations;
– reinforcement, involves introduction of a new materials in the existing masonry, with superior mechanical properties, resulting an increase in structural strength and rigidity;
– the extension, refers to the modification of a section by supplementing it with new materials;
– material replacement, involves the repair and restoration of the damaged elements;
– binding/connecting the different structural elements or subassemblies in order to ensure a compatibility of the deformations;
– anchoring, consists of fixing an element or part of a structure to another supporting structure;

– structural development, implies the general improvement of the characteristics for the elements or of the entire structure;
– pretension, refers to changing the tensions state of an element by means of external loads or by prestressing;
– the isolation, consists of dissipation of the seismic energy and the vibrations through the external systems usually located at the foundation level.

The classification into two categories: reversible and irreversible techniques is the main criterion in choosing intervention techniques. If the interventions are reversible, the materials used impose relatively few restrictions, however, if the interventions are irreversible, compatibility with the original materials and long-term durability must be ensured. These restrictions force a thorough knowledge of the properties of the original materials, so that their characteristics constitute clear criteria for choosing the intervention materials [11].

3 Case Study

3.1 Building Description

The studied building is located in Pașcani city, in the north-east of Romania. It was built in the XVIIth century and is was included on the List of historical monuments in Iasi County in 2004 (Fig. 3). The original plans of the building have not been preserved, although it is assumed that there were no such plans and no other documents regarding its construction were discovered until now.

The construction has an irregular plan view, with the maximum dimensions of approximately 30 × 33 m, if the facades are also measured, and extends on basement (partially), ground floor, floor and attic (Fig. 4 and 5).

In one or more subsequent stages of consolidation, on the vaults from the ground floor, concrete was poured and a floor made of steel profiles and concrete slab was added. The structural system is made of brick walls and stone brick vaulted floors at the ground floor and concrete floors with I steel profiles at the first floor. The thickness of the walls varies from 60 cm to 130 cm. The attic rooms have a wooden floor at the top, which is currently partially collapsed. The stairs are made of reinforced concrete ramps and were probably made with the overcrowding of the vaults on the ground floor and the floor above. The foundation is made of stone masonry connected with clay mortar, having the same depth as the walls, going down to −2.50 m.

3.2 Causes of Damage

After a close investigation of damages for the analyzed heritage building, the following causes were emphasized:

3.2.1 Repeated Seismic Action

The repeated seismic action at which the structure was subjected in previous years lead to the necessity of consolidating the building. Such works were conducted prior to current

Fig. 3. The manor court and Cantacuzino manor throughout the 50's [12]

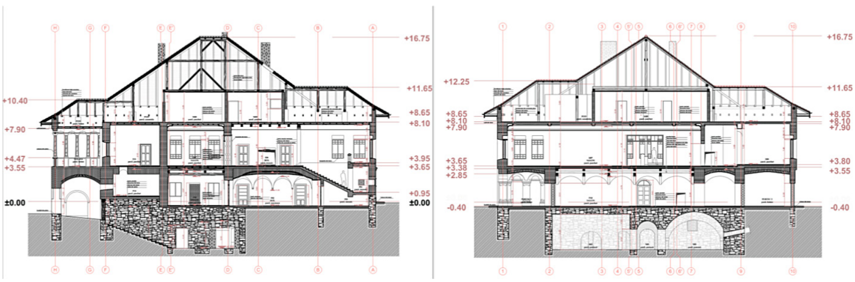

Fig. 4. The longitudinal and transversal cross-section

Fig. 5. Main façade of Cantacuzino manor

analysis. At present, the construction presents specific degradations to seismic action, as diagonal cracks in the full walls; indicating the tendency of the porches to detach from the main structure;

3.2.2 Water Action

The water infiltration due to lack of maintenance work at the roof level lead to the degradation of the steel structure and also to wall exfoliation of the paint and plaster. The missing drainage system produced water infiltration at the ground level producing damage at the ground floor and the basement level. Due to water infiltration at the attic level, the ceiling is partially collapsed and in case of continuing the water infiltration, a chain reaction with imminent danger regarding the stability and the strength of the roof system may occur leading even to global failure mechanism. The different settlements of the foundation soil marked the structural system of the building with visible vertical cracks;

3.2.3 Structural Interventions

The introduction of a mortar layer with copped masonry on the walls, the over-concreting of the ground floor vaults, adding a floor of steel profiles and concrete slab above the floor, building an area next to the old porch, filling of several windows and doors openings led to the changes of the building's structural characteristics and the loading capacity. The lack of maintenance work lead to vandalized action by destructive actions which increased building degradation.

3.3 Computation Summary

The structure was analyzed according to P100/3-2019 and CR6-2006 [13, 14] codes. The structural safety level for each masonry peer, at shear force, axial force and at bending moment was established. The computation was performed on the main directions, longitudinal and transversal one.

The numerical simulation was performed by ETABS software, which is a finite element program. The structural walls were discretized into surface elements (Fig. 6).

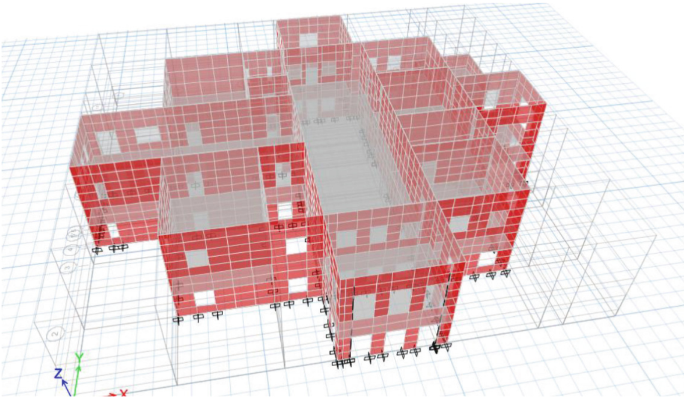

Fig. 6. The adopted design model

The program computes the stress state from which, through integration, the stress states result. The ratio between the minimum capable effort able from a section and the external one, represents the structural safety level, of the peer in this particular case.

A 3D model was considered in the numerical simulation. The masonry walls were modeled with shell elements. The efforts in the peers result from integrating stress values. For each wall, the minimum capable shear force and the probable breaking mode (fragile or ductile) in the base section are determined according to the P100-3/2019 code and is compared with the actual efforts resulting from the linear static analysis, obtaining the structural safety level, (Fig. 7).

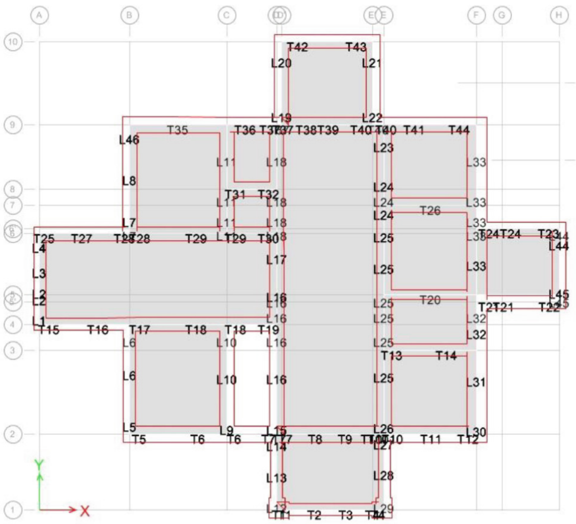

Fig. 7. Peers disposal

The structural safety level (R_{3i}) for the entire structure, on each direction is computed with:

$$R_{3i} = \frac{\sum_{jd} V_{fd} + \sum_{kf} V_{ff}}{F_b} \quad (1)$$

$\sum_{jd} V_{fd}$ - the sum of the wall's strength capacity with the ductile breaking;
$\sum_{kf} V_{ff}$ - the sum of the wall's strength capacity with the fragile breaking
F_b - base shear force [15] (Table 1).

Table 1. The structural safety level of the damaged structure

Direction	$\sum_{jd} V_{fd}$(kN)	$\sum_{kf} V_{ff}$(kN)	R_{3i}	$R_3 = \frac{R_{3L}+R_{3T}}{2}$
Longitudinal	15638	2829	0.181	0.173
Transversal	14990	2475	0.165	

According to P100/3-2019 the structural safety level should be greater than 0.65 for Vrancea seismic region. Taking into consideration this restriction, several consolidation works are proposed in order to increase R3. The load transfer improvement to the walls is realized by fixing the over concreting in a belt included in the walls.

The masonry consolidation by means of vertical straps inserted into drilled channels injected with mortar to ensure the achievement of an advantageous efforts state in case of horizontal action. Also, wall intersections confinement of the masonry is proposed.

Increasing the load bearing capacity of the masonry by reinforcing and pouring a lime mortar coating reinforced with supplementary polymeric grids after the thick layer of plaster with broken brick was removed.

At the foundation level an exterior waterproofing isolation and a clay plug, with a perimeter drainage system, connected to a functional system to efficiently remove water from the building. At the basement level, the water infiltration in the walls will be prevented by waterproofing the masonry with injections of hydro structural resins.

Repairing the cracks by local injectors and local weavings, where necessary.

Existing roof reconstruction with similar wood elements, properly connected in a belt constructed at the upper part of the masonry from the attic.

The numerical simulation was recomputed and in the modal analysis care, the fundamental period of vibration decreased from 0.18 s to 0.16 s, with approximately 10 %. Meanwhile the structural safety level increase from 0.173 to 0.964, with more than 80 %, exceeding the minimum recommended value from the norm.

4 Conclusion

The value of a construction considered a historical monument, does not refer only to its exterior or interior appearance, but encompasses all its components, as a result of the technology specific to the place and time in which it was made. The importance of the conservation of the built heritage puts into discussion the interventions that take place on such constructions, interventions that must not be realized improvably or by applying some norms that are addressed to the new constructions.

Even though the protection of the user's lives is very important, this does not mean neglecting the heritage and stresses that every generation has the architectural heritage only on a temporary basis and is responsible for transmitting it to future generations.

In our country it is necessary to elaborate specific norms for interventions on heritage constructions; in the absence of such regulations at this moment the application of the norms that are addressed to new constructions is practically obligatory also for this type of constructions. It should be noted that detailed rules are very difficult to elaborate, but from the experience of other countries (for example Italy) regulations can be made adaptable to the multitude of situations that can be encountered, to the technological or location characteristics, suggesting a design attitude that it takes into account the specificity of the object. Such regulations may take the form of a "restoration book" which would include the principles of intervention recommended in the existing international books.

The decision regarding the intervention on a building with historical value must take into account the desire to conserve, to emphasize its aesthetic or historical values, without neglecting the appropriate choice of materials or techniques of conservation and consolidation.

Through the materials and the constructive procedures used, it is necessary to keep in mind the preservation of the authenticity of the object that is to be protected. Thus, by this type of interventions the aim is not to obtain a structural safety level similar to the one related to the new buildings, the main intention being that of preservation and only exceptionally of adaptation to the current norms, in situations where the global restauration of the construction is provided.

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