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STRUCTURAL VULNERABILITY ASSESSMENT OF AN HISTORICAL MASONRY BUILDING – CASE STUDY

Abstract:

This paper presents a vulnerability assessment of an historical masonry building representative of early 20th-century construction. The structure consists of load-bearing masonry walls with timber floors and lacks seismic detailing. The methodology included visual inspection, typological classification and simplified control analysis. Observed damage includes masonry cracking, mortar degradation, timber floor deflections and local foundation settlements. The assessment indicates insufficient global structural integrity and pronounced vulnerability typical of historical unreinforced masonry buildings. The results support decision-making regarding strengthening or demolition of severely degraded masonry structures.

Keywords: masonry buildings, structural vulnerability, historical buildings, condition assessment

ПРОЦЈЕНА КОНСТРУКТИВНЕ УГРОЖЕНОСТИ ИСТОРИЈСКОГ ЗИДАНОГ ОБЈЕКТА – СТУДИЈА СЛУЧАЈА

Сажетак:

У раду је приказана процјена рањивости старог зиданог објекта типичног за градњу с почетка 20. вијека. Конструкцију чине носећи зидови од опеке са дрвеним међуспратним конструкцијама, без асеизмичких детаља. Методологија обухвата визуелни преглед, типолошку класификацију и поједностављену контролну анализу. Уочена оштећења укључују пукотине у зидовима, деградацију малтера, угибе дрвених таваница и мјестимична слијегања темеља. Процјена указује на недовољан глобални интегритет и изражену рањивост типичну за старе зидане објекте. Резултати представљају основу за одлуке о ојачању или уклањању тешко деградираних зиданих конструкција.

Кључне ријечи: зидане зграде, конструктивна угроженост, стари објекти, процјена стања

1. INTRODUCTION

Historical masonry buildings represent a significant number of the existing buildings in many ex-Yugoslavian cities [1], [2]. These structures were primarily designed to resist gravity loads, while horizontal actions such as seismic effects were not explicitly taken into account in the original design [1], [3]. As a result, these buildings typically exhibit low ductility, brittle material behavior and limited capacity for redistribution of internal forces under dynamic loading.

Unreinforced masonry (URM) structures are particularly vulnerable to seismic and other horizontal actions due to weak mortar joints, insufficient wall-to-floor connections and the absence of confinement and tie elements [1], [4], [6]. The lack of effective diaphragm action in timber floor systems further increases the susceptibility of masonry walls to out-of-plane failure mechanisms and progressive loss of global stability [1], [3].

In addition to inherent structural deficiencies, the safety of historical masonry buildings is often compromised by long-term material degradation, moisture ingress and lack of maintenance. Degradation of lime mortar, decay of timber elements and local foundation settlements reduce progressively both the stiffness and load-bearing capacity of the structural system, leading to the development of characteristic damage patterns [2], [4].

The aim of this paper is to present a vulnerability assessment of an historical masonry building through a systematic evaluation of its structural system, observed damage mechanisms and overall integrity. The study focuses on identifying dominant weaknesses of the structural concept and interpreting the implications of material degradation for the global structural behaviour of the building. The presented case study is intended to illustrate typical vulnerability patterns of old masonry buildings and to provide a basis for informed decision-making regarding strengthening or demolition.

2. METHODOLOGY

The assessment was performed using a qualitative approach commonly applied in preliminary evaluations of existing masonry structures. Field observations were combined with a simplified control structural analysis in order to identify dominant structural deficiencies and characteristic damage mechanisms. [2],[6].

The assessment included a visual inspection of the load-bearing system, comprising masonry walls, foundations, timber floor structures and the roof system. Observed damage patterns were documented and classified with respect to their potential influence on structural integrity and load transfer mechanisms. Particular attention was paid to cracking patterns in masonry walls, degradation of lime mortar joints, permanent deflections of timber floor elements and local foundation settlements.

The structural system was classified according to construction characteristics, identifying the building as an unreinforced masonry structure without seismic detailing elements such as reinforced concrete tie beams.

In addition to field observations, a simplified control structural analysis was performed to qualitatively assess the dynamic behaviour of the building. Modal analysis was conducted in structural analysis software to identify dominant local and global vibration modes of the structural system. The obtained mode shapes were used to evaluate the degree of global structural integrity and the effectiveness of wall-to-floor interaction [7].

The applied methodology does not aim to provide a detailed performance-based seismic assessment. Instead, it focuses on identifying critical structural deficiencies and dominant vulnerability patterns relevant for practical decision-making regarding possible strengthening measures or demolition of severely degraded masonry buildings.

3. CASE STUDY – OBJECT DESCRIPTION

The building is currently in a severely degraded structural condition; therefore, the assessment was primarily based on in situ visual inspection.

3.1. CONSTRUCTION HISTORY OF THE BUILDING

For the building in question, it was not possible to precisely determine the year of object completion of construction. However, it is known that the building dates back to the Austro-Hungarian period, so it can be assumed that it has existed for more than **a** century. More detailed information about the building was not available, but based on site inspection and discussions with representatives of the municipal administration, there are indications that an annex on the courtyard side of the building was added in the mid-20th century.

The aforementioned annex collapsed two years ago, and the site was subsequently cleared; however, visible traces of its existence remain. A visual inspection of the building did not reveal any recent interventions on the structure.

The building footprint is approximately 12 × 13 m, while the collapsed annex had approximate dimensions of 4 × 8 m. The building has a basement + ground floor + one storey (B + G + 1).

It was used for mixed residential and commercial purposes as shown on Fig. 1.

The building is registered as a cultural heritage asset by the Republic Institute for the Protection of Cultural-Historical and Natural Heritage of the Republic of Srpska.

The building is currently not in use, as certain zones are in an advanced stage of degradation and collapse.

Figure 1. Current state of the object – façade (photography by author)

3.2. STRUCTURAL SYSTEM INFO

A review of the available technical documentation and a visual inspection of the building, with sufficient certainty, could establish that the main above-ground structure was constructed by building load-bearing walls of solid clay bricks of standard dimensions in lime mortar. These are massive walls 51 and 38 cm thick (layers of two bricks and layers of one and a half bricks, with vertical and horizontal mortar joints). The partition non-load-bearing walls were also made of solid bricks 25 and 12 cm thick (layers of one transverse and layers of one longitudinal brick).

The walls of the basement part of the building, in the lower part, are made of semi-finished stone in lime mortar, while the upper part of these walls is made of clay brick, also in lime mortar, in the thicknesses already mentioned. It can be assumed that the foundations under the load-bearing walls are also made of semi-finished stone in lime mortar, or, possibly, of lean concrete. When it comes to the sub-foundation soil, some more specific data are not available, or are not known.

The mezzanine ceilings, staircases and roof structure are made of classic wooden structures of usual dimensions for these elements and spans, while the building is covered with clay tiles.

According to the typology, it can be stated that the building structure belongs to massive masonry structures without vertical RC ties. The mezzanine structures are wooden without horizontal bracing, and cannot be treated as sufficiently rigid slabs. The roof structure is classic wooden, and the foundation is made via buried foundation strips under the load-bearing walls. A two-flight wooden staircase was constructed for vertical communication.

3.3. EXISTING STRUCTURAL CONDITIONS

The visual inspection revealed characteristic damage resulting from aging and lack of maintenance of the building over a long period of time. Significant structural deficiencies were also noted as a result of the construction method of most buildings in that period (early 20th century). More precisely, damage to individual elements and parts of the structure is a direct result of aging of the installed material, lack of maintenance and its poor initial quality. Also, the damage is directly related to the concept of the structure characteristic of the construction period, and to the various conditions and effects on the building that occurred and changed over time.

The later-built annex, which completely collapsed, left traces on the main building in the form of pronounced cracks and fissures in the walls. In addition, individual elements and parts of the building are in an active phase of degradation and collapse.

The remainder of this Finding and Opinion describes the damage to the main structural elements that has occurred over time, as well as the inherited defects from the period of construction of the building.

3.4. STONE FOUNDATIONS AND PLINTH

Type of damage as shown on Fig. 2:

- Cracks were observed in the massive plinths due to their brittleness and degradation of the mortar in the joints and on the external surfaces**,**
- In some areas, the soil and foundation gave way, i.e., there was local uneven subsidence of the building**.**

Deficiencies from the construction period:

- The foundation and plinth masonry was made of semi-finished stone in poor quality lime mortar;
- The foundation and plinth walls do not have elements for adequate weighting and preservation of the necessary connection and integration of the soil-structures.

Figure 2. Current state of foundations (photography by author)

3.5. BRICK MASONRY WALLS

Type of damage as shown on Fig. 3:

- Vertical and diagonal cracks in walls and parapets, especially at wall intersections and around openings;
- Spalling and detachment of bricks in walls;
- Detachment and falling off of mortar from wall surfaces.

Deficiencies from the construction period:

- Lack of vertical and horizontal reinforced concrete tie-columns/ring beams to provide confinement and preserve the integrity of massive brittle masonry walls;
- Lack of reinforced concrete lintels and tie beams above openings to ensure continuity of masonry around openings;
- Low shear resistance of masonry piers between openings;
- Poor quality of lime mortar in joints (the mortar crumbles easily when pressed with fingers), resulting in low shear resistance of masonry walls.

Figure 3. Current state of walls (photography by author)

3.6. WOODEN MEZZANINE CONSTRUCTION

Type of damage as shown on Fig. 4:

- Permanent sagging of ceilings;
- Damaged and broken wooden beams;
- Cracks and fissures in ceilings;
- Peeling of ceiling plaster and filling;
- Damaged wooden floors.

Defects from the construction period:

- Wooden ceilings were constructed without special elements for their high-quality weighting and connection to the walls, i.e. without a rigid (e.g. reinforced concrete) layer. Such ceilings cannot be treated as rigid horizontal slabs, because they are not able to safely accept and distribute horizontal (seismic) forces to the load-bearing walls. In other words, wooden ceilings cannot play the role of floor "RC ties" that would significantly improve the stability of the walls and the building as a whole.

Figure 4. Current state of mezzanine construction (photography by author)

3.7. WOODEN STAIRCASE

Damage Type of damage as shown on Fig. 5:

- Permanent sagging of stair treads;
- Damaged and broken wooden beams;

Construction defects:

- Wooden staircases are not recommended for residential buildings for several reasons.

Figure 5. Current state of staircase (photography by author)

3.8. WOODEN ROOF STRUCTURE

Type of damage:

- Permanent damage to the timber;
- Loosening and breakage of parts of the roof beams.

Deficiencies from the construction period:

- The wooden roof structure is not suitable for modern roofs, as it lacks elements of better hydro and thermal protection and insulation, and thus better protection of the wooden elements.

4. RESULTS AND DISCUSION

4.1. SEISMIC REGULARITY OF CONSTRUCTION

The subject building was built more than 100 years ago and it was not common to take into account horizontal forces from earthquakes, so construction was mainly adapted to successfully overcome the gravitational load. The influence of wind could not have played a more significant role, because most of the buildings were built of massive masonry.

After the earthquake and destruction of Skopje in 1963, the first regulations for seismic construction were adopted, which were modernized in 1981, and which are still relevant in some countries. Also, today, newer European regulations are used for the design and construction of buildings - the Eurocodes for structures [5]. It is quite common that most buildings that are subject to new regulations do not meet all the rules and principles of construction in seismic areas. This is also the case with the object in question. Namely, taking into account the current regulations, it can be concluded that the object in question was built without some of the basic principles and rules for designing seismically resistant structures.

The vertical structure of the building in question was constructed by building load-bearing walls with solid brick and crushed stone in lime mortar (wall thickness 51 and 38 cm) without vertical RC ties, which is in accordance with the principles of construction of masonry buildings in that period. Such buildings, which feature heavy and brittle masonry walls, do not have the ability to easily resist the effects of seismic forces. It is well known that vertical RC ties, when properly positioned, connect and stiffen walls, and significantly contribute to the resistance of masonry structures to stronger dynamic effects in earthquake conditions [1],[3]. These RC ties also contribute to the integrity of the structure and prevent the collapse and disintegration of possibly cracked parts of masonry walls.

The absence of vertical RC ties calls into question the safety of the object in question, especially in the absence of some other elements that could replace their role.

For modern conditions, the quality of existing masonry walls is below the limit of acceptability, primarily due to the use of a weak binding agent - lime mortar, and its aging and degradation over time [8]. Such mortar was used (without the addition of cement) which is considered to have a weak resistance to shear forces, and its use is prohibited by modern aseismic regulations [4], [8].

The inter-window columns are not framed with reinforced concrete, which is why they represent the most critical zones that can be significantly damaged or collapse under the action of seismic forces.

The above-mentioned defects, in superposition with the degradation of the material, when it comes to the applicable regulations, sufficiently indicate the degree of aseismic irregularity of the masonry building in question.

The foundation structure consists of strips of stone in low-quality lime mortar. The lack of ductile elements (reinforcement) is an important factor that can jeopardize the safety of the foundation and the building as a whole, in asynchronous conditions of soil oscillation.

Wooden inter-floor structures, which transfer the load in one direction, and which do not have stiffening elements, do not meet the basic requirements for seismically regular ceilings [1], [6]. The distribution of horizontal floor forces on the load-bearing walls is problematic due to the insufficient rigidity of such ceilings and their weak connection to the walls. It is well known that reinforced concrete slabs meet these conditions and ensure the aseismic regularity of buildings, while wooden ceilings are most often unable to provide this. In the case of the building in question, wooden ceilings are not able to connect the walls as required by modern principles of aseismic construction. This condition promotes progressive cracking and separation of masonry wall panels under horizontal loading, especially in the absence of strong connections from the other direction, i.e. in the absence of horizontal RC ties.

It can be accepted as an advantage that solid brick walls of considerable thickness (51 and 38 cm) have a high load-bearing capacity, and enough space for the appearance and development of damage without collapse in an earthquake. Also, it is advantageous that the walls are not randomly intersected by openings and that they are represented in two orthogonal directions.

The aforementioned area is located in the VIII seismic zone, and according to the current regulations, the construction of masonry buildings without vertical reinforcements up to two floors above ground is permitted. It can be stated that the subject building, with its number of floors (Basement + Ground floor + 1), satisfies this prescribed boundary condition.

4.2. REGULARITY TO GRAVITATIONAL ACTIONS

Buildings with massive masonry load-bearing walls generally exhibit satisfactory performance under gravity loads [1]. The very fact that the building in question has existed for more than 100 years confirms the aforementioned rule. The problem that is still present is the degradation of the materials due to aging and lack of maintenance of the building. This has led to the weakening and partial collapse of a number of main elements – walls, ceilings, stairs and roof.

It is particularly emphasized that the building in its current state is not suitable for use, as further collapse would endanger human lives and material goods.

4.3. CONTROL STATIC CALCULATION

As part of this analysis, a control static calculation was also performed, for comparison with the on-site condition. Primarily, attention was paid to the seismic analysis of the building. The calculation showed the irregularity of the building's construction even during the modal analysis itself. Most of the first tones show a local type of oscillation of the building's elements, i.e. the walls of the building are the first to enter the oscillation phase, which would result in their lateral overturning and falling out [1], [7]. Only at higher tones did the building as a whole begin to oscillate. Such dynamic behavior indicates a high probability of local wall failure and potential progressive collapse under seismic excitation [1], [7], as shown on Fig. 6, 7, 8 and 9.

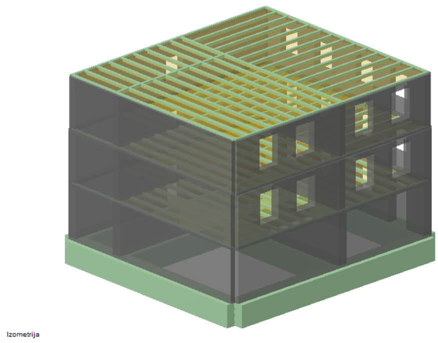

Figure 6. Static calculation - Isometric view of the model (drawing by author).

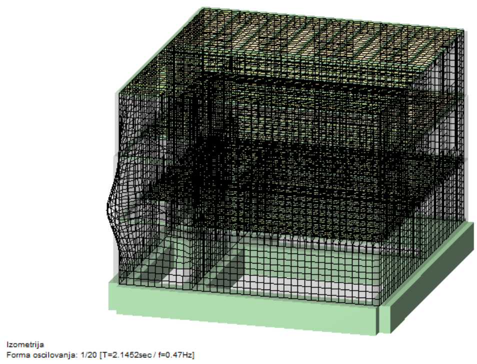

Figure 7. Static calculation - modal tone 1/20 (drawing by author).

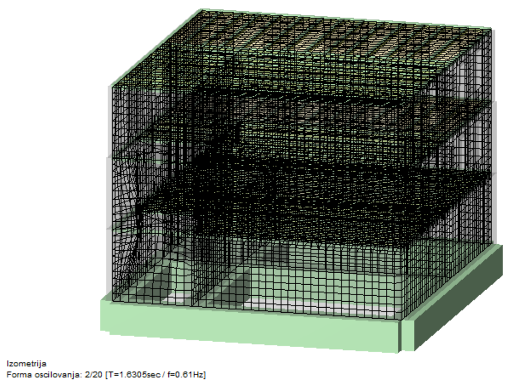

Figure 8. Static calculation - modal tone 2/20 (drawing by author).

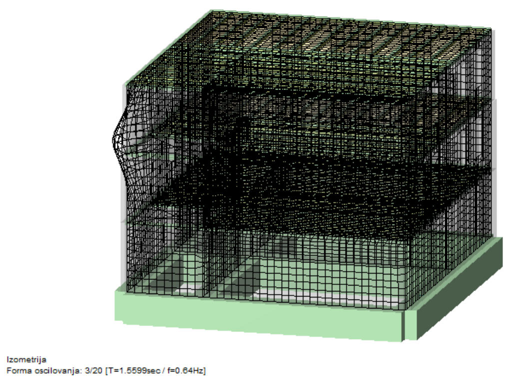

Figure 9. Static calculation - modal tone 3/20 (drawing by author).

4.4. POSSIBILITY OF REINFORCEMENT AND RENOVATION

The analysis showed that the object in question does not have sufficient seismic resistance for the design earthquake for the area in which it is located. It should be borne in mind that an earthquake is a random phenomenon and cannot be predicted. The characteristics of a possible earthquake (predominant periods, intensity, duration, etc.) cannot be predicted either. In addition, a large number of the existing building stock are not in accordance with modern achievements in the theory and practice of designing and building seismically resistant structures. This especially applies to masonry buildings built before the first aseismic regulations, to which group the object in question also belongs.

The adoption of the Rules for the Construction of Aseismic Structures creates a contradictory situation: newer buildings provide (or should provide) a certain degree of protection to people and property located in them, because they were built (or should have been built) in accordance with the applicable aseismic standards, while the entire remaining building stock, which has been caught up in new knowledge and rules, is most often insufficiently resistant and hides potential dangers of varying degrees in the event of future earthquakes. The very introduction of new (modern) regulations is a negative assessment of buildings that do not meet the requirements of those regulations. The question arises as to how to treat these structures, and this should be the attitude of the authorities, but also of professional organizations and society as a whole.

Strengthening a structure involves increasing the load-bearing capacity and/or ductility of existing and/or adding missing aseismic structural elements. However, it should be borne in mind that in order to absorb seismic loads, it is necessary to ensure adequate behavior of the structure as a whole. Objects under cultural and historical protection, when the authentic appearance is to be preserved, often have limiting factors for more extensive interventions.

Interventions aimed at reducing the existing mass of the object, centering the stiffness and masses and constructing new walls are, realistically speaking, not possible. Hence, a solution is imposed in interventions on load-bearing walls, e.g. by introducing RC ties and/or reinforced parts in the form of wall cladding with shotcrete concrete. In doing so, it is very important to ensure a good connection of the newly added elements/cladding with the existing walls and foundations. It is best to cover the walls with reinforced concrete on both sides, with anchor connections of these coverings through the wall. If it is a case of covering on only one side, then, in order to form a better bond of the wall panel, in addition to the usual use of anchors, it is necessary to use concrete plugs. Prestressing the walls provides certain advantages, because it does not change the appearance of the walls/building, which is important for protected objects. However, this is a specific procedure that requires special equipment and experience, and such interventions have not been carried out in our area so far. Something similar can be said about the use of carbon strips and canvas, although this method of reinforcement could be considered with proper installation and protection.

Masonry foundation strips, as a rule, require reinforcement in order to form a well-connected system. In the case at hand, it would be most appropriate to envisage the construction of a reinforced concrete ring around the building, with adequate anchoring to the existing foundations, with additional pouring of concrete and the formation of plugs.

Wooden ceilings are a particular problem for several reasons that have been previously stated. That is, it is necessary to ensure that the ceilings have sufficient load-bearing capacity and stiffness to reliably accept all the anticipated impacts. It should be borne in mind that the existing wooden ceilings do not meet the above conditions and are significantly degraded. Partial or complete construction of new wooden ceilings requires a series of additional operations in the form of their weighting and connection to the walls, which is not an easy task. However, this can be achieved by connecting wooden beams with a reinforced concrete slab and adequately connecting them as a whole to the load-bearing walls (e.g. horizontal braces). Another option would be to completely remove the existing wooden ceilings and construct new reinforced concrete slabs. Wooden stairs also require similar work, but it is best to replace them with reinforced concrete or steel ones, considering that this is a building for collective housing.

The need for a detailed “revision” of the roof structure is particularly emphasized, because it is currently in very poor condition. This involves partial or complete replacement of the roof covering (tiles and ridges) and sheet metal flashings and gutters. It is also necessary to strengthen or replace all damaged wooden elements of the roof. The best solution would be to completely replace the roof structure with a new one. It is recommended to perform roof flashing over the rafters and to install a waterproofing membrane, which is common for all types of roofs today. In this case, when it comes to a roof covering in the form of tiles, it is necessary to foresee the roof battens with counter battens and battens. In addition to the construction work, it is necessary to take into account the necessity of performing trade and other works for all phases (construction, hydro, electrical, mechanical, exterior decoration) in order to bring the facility to its intended purpose. It is also necessary to anticipate and subsequently carry out all works on regular maintenance of the facility. In the case of strengthening and rehabilitation of the facility, it is necessary to prepare a project that would cover all works and would include costs in order to consider the economy in terms of the investment-return ratio. It is also emphasized that the reconstruction of a facility in such conditions is very demanding and involves a large investment in terms of material costs.

4.5. FINAL REMARKS

The assessment was carried out on the basis of the submitted technical documentation and a visual inspection of the facility. The existing condition was compared with current knowledge and regulations in this area. Based on the observation of the characteristics and condition of the structure and materials on site, the following remarks are highlighted:

- The facility in question contains defects and is significantly damaged and degraded (roof, ceilings, stairs, walls, foundations), and the attached annex was removed after a recent collapse;
- The facility is registered as a cultural asset as already stated;
- The facility in its existing condition is not suitable for use and poses a risk of collapse of the roof, ceilings and stairs, as well as the detachment and collapse of parts of the walls and plaster coverings;
- The structure of the building does not have the necessary seismic resistance for the design earthquake for the area in which it is located (VIII seismic zone).

5. CONCLUSION

The conducted assessment indicates that the analyzed masonry building exhibits pronounced structural and seismic vulnerability. The structural system is characterized by massive unreinforced masonry walls constructed without vertical reinforced concrete ties, flexible timber floor systems lacking diaphragm action, and foundations executed in stone masonry without ductile elements.

Long-term material degradation, including deterioration of lime mortar, damage to timber elements and local foundation settlements, has significantly reduced the stiffness and load-bearing capacity of the structure. The observed cracking patterns and partial collapses confirm the advanced stage of deterioration.

The simplified control structural analysis, including modal evaluation, revealed dominant local vibration modes of masonry wall panels, while global structural response occurred only at higher modes. Such dynamic behavior indicates insufficient global structural integrity and an increased likelihood of local wall instability under seismic excitation.

Considering the required strengthening measures, the complexity of interventions, heritage protection constraints and the associated economic implications, full structural rehabilitation would demand extensive and technically demanding interventions. From a structural safety and cost-effectiveness perspective, demolition and reconstruction in accordance with current regulations represent a rational engineering option.

In the event that rehabilitation is pursued, it should be based on a detailed strengthening design ensuring adequate global behavior of the structure and compliance with applicable seismic regulations.

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