DVANAESTO MEĐUNARODNO NAUČNO – STRUČNO SAVETOVANJE
OCENA STANJA, ODRŽAVANJE I SANACIJA GRAĐEVINSKIH OBJEKATA

Pregledni rad

Marko Marinković[1], Svetlana Brzev[2]

DAMAGE OF MASONRY BUILDINGS DURING EARTHQUAKES AND RETROFITTING AND STRENGTHENING EXAMPLES FROM PRACTICE

Summary: *Masonry buildings constitute a major fraction of the building stock in Serbia and other countries in the region, and they are highly exposed to the earthquakes and affected due to their vulnerability to seismic effects. This paper presents observations related to the seismic behaviour of masonry structures during recent earthquakes in the region, and outlines the common damage patterns. This was used as a basis for understanding the seismic behaviour of masonry buildings and choice of the feasible seismic retrofitting techniques. Finally, an overview of seismic retrofitting techniques for masonry buildings is presented, along with the examples of field applications.*

Key words: *masonry buildings, URM, seismic effects, seismic retrofitting, structural rehabilitation.*

OŠTEĆENJA ZIDANIH ZGRADA PRI DEJSTVU ZEMLJOTRESA I PRIMERI SANACIJE I OJAČANJA IZ PRAKSE

Rezime: *Kako zidani objekti čine najveći deo građevinskog fonda u Srbiji i drugim zemljama, oni su veoma pogođeni zemljotresima, posebno zbog njihove osetljivosti na oštećenja usled seizmičkog dejstva. U okviru ovog rada sumirana su zapažanja ponašanja zidanih konstrukcija tokom nedavnih zemljotresa kako bi se prikazali glavni oblici oštećenja zidanih konstrukcija. Ovo je korišćeno kao osnova za razumevanje njihovog ponašanja i podrška pri izboru optimalne tehnike ojačanja. Potom je prikazan pregled postupaka sanacije zidanih objekata, praćen primerima iz prakse.*

Ključne reči: *zidane zgrade, nearmirana zidarija, seizmičko dejstvo, seizmičko ojačanje, sanacija.*

[1] Assistant Prof. PhD, Faculty of Civil Engineering, University of Belgrade, Belgrade, Republic of Serbia, mmarinkovic@grf.bg.ac.rs
[2] Adjunct Prof. PhD, Department of Civil Engineering, University of British Columbia, Vancouver, Canada, sbrzev@mail.ubc.ca

1. INTRODUCTION

Historically, earthquakes have always represented one of the main causes of damage and loss in buildings. The damage observed in various countries due to recent earthquakes shows that there is an urgent need for better understanding the seismic behaviour of existing structures and, consequently, for greater reliability of assessment methods and, subsequently, intervention techniques. A significant fraction of building stock in Serbia consists of building typologies which use traditional construction materials, such as masonry (usually clay bricks or blocks) and wood, together with modern technologies, such as steel and reinforced concrete (RC). However, the most common building types in Serbia are load-bearing masonry and RC construction systems [1]. This paper is focused on the damage of masonry buildings during recent earthquakes seismic retrofitting techniques for masonry buildings. Masonry buildings represent an important cultural and economic heritage, which is at risk due to inherent seismic deficiencies of masonry buildings and high seismic hazard, particularly in the Mediterranean region. Recent seismic events in the region have confirmed vulnerability of unreinforced masonry (URM) buildings to seismic actions [5-10]. The main causes of damage and collapse are due to ageing, poor quality of construction materials, deterioration, inadequate connections between vertical elements or between vertical and horizontal elements, lack of adequate stiffening of the horizontal bearing elements, poor interventions during the life span of the building and other vulnerability factors highlighted within these construction types.

To understand the seismic behaviour of masonry buildings and decide on the strategy for increasing the safety with respect to seismic action, it is necessary to reliably assess their seismic vulnerability. Seismic retrofitting needs to be investigated both from the point of view of construction methods and, above all, on the available seismic intervention techniques, in order to select the most suitable technique to improve the level of safety.

A good way to learn and decide on the seismic intervention is to observe the behaviour and damage of buildings during earthquakes. Therefore, the first part of the paper presents representative examples from the reconnaissance missions of authors in the areas affected by earthquakes. Main findings and conclusions derived from the materials collected during the visits are presented. Afterwards, an overview of the most common seismic intervention techniques is given, followed with the examples of field application.

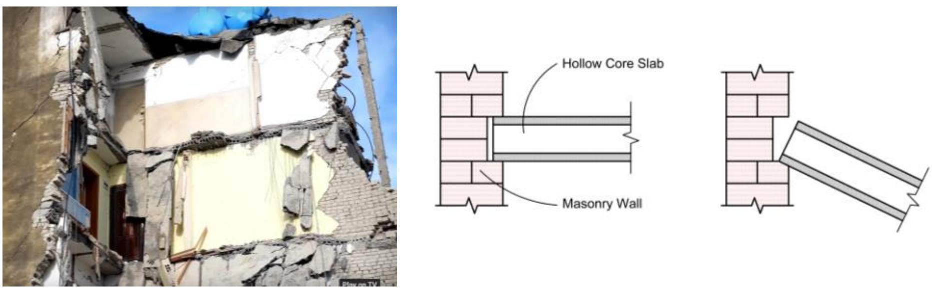
2. DAMAGE OF MASONRY BUILDINGS IN RECENT EARTHQUAKES

Although masonry technologies are different in various parts of the world, damage patterns in these buildings caused by earthquakes seem to be similar. In most cases, significant damage has been observed in older URM buildings, mostly due to absence of integrity caused by flexible timber diaphragms, and also limited capacity of masonry walls for in- and out-of-plane seismic actions. At the same time, buildings constructed using modern masonry technologies such as confined masonry (CM), performed well and did not experience significant damage in moderate earthquakes. For example, our neighbouring countries, Albania and Croatia, were recently hit by four significant earthquakes, out of which two had the same magnitude (M_w 6.4). The first earthquake hit Durrës, Albania on November 26, 2019, while the second earthquake hit Petrinja, Croatia

on December 29, 2020. Both events significantly affected building stock in the epicentral areas, in which masonry construction was prevalent, similar to Serbia and other countries in the region. The damage observed in masonry buildings in these earthquakes, particularly in single- and multi-family residential buildings, is relevant for Serbia and will be discussed in this section.
More than 90% of the residential building stock in Albania consists of low-rise single-family masonry buildings (one- or two-storey high) [2]. However, majority of population affected by the November 2019 earthquake (more than 60%) occupied multi-storey residential buildings, because the earthquake affected the country's two largest cities (Tirana and Durrës). Majority of affected buildings consisted of RC frames with masonry infill walls, while masonry buildings were generally not severely affected. Low-rise URM masonry buildings were mostly damaged due to flexible floors or roof structures. Typical damage patterns were diagonal tension cracks caused by in-plane shear demand, such as shown in Fig.1. Majority of masonry buildings constructed before 1990 used solid clay bricks, which were of variable quality. Poor quality of masonry materials (e.g. hollow concrete blocks) and construction were identified as major causes of damage in these buildings [3].

a) b)

Figure 1. a) Damaged low-rise masonry building made of hollow concrete blocks and b) partial collapse of the demolished building in Thumanë (Albania)



a) b)

Figure 2. Collapse of mid-rise URM buildings in Thumanë, Albania: a) partial collapse of the building caused by the collapse of the floor slabs and b) detail of a simply supported hollow-core slabs

Majority of multi-storey URM masonry buildings with solid RC floor slabs were not significantly damaged in the earthquake, however some buildings with prefabricated hollow-core RC slabs experienced severe damage. In the town of Thumanë, four 5-storey URM buildings of this type collapsed in the November 26, 2019 earthquake, causing 24 casualties. It is important to mention that these buildings were originally damaged in an earlier earthquake which occurred on September 21, 2019. The major deficiency was insufficient slab support length, which led to the total slab collapse (Fig. 2) [4,5,6].

Low-rise masonry residential buildings (either single- or multi-family buildings) were the most common form of housing construction in the area affected by the December 29, 2020 Petrinja earthquake, and many buildings of that type experienced damage or collapse [7]. Older two-storey URM buildings with wooden floors experienced damage or failure of walls due to out-of-plane (OOP) seismic effects (Fig. 3). Excessive horizontal displacements of flexible floor diaphragms caused the walls to act as vertical cantilevers and experience damage or collapse (toppling). The main prerequisite for an efficient seismic behaviour of URM buildings is adequate connection between the masonry walls and between the walls and the floors. Masonry buildings ought to act like a box made up of vertical and horizontal structural elements (walls and floors/roofs). For a good box-like behaviour, the floors should act like rigid diaphragms, and internal seismic forces should be distributed between parallel walls in proportion to their stiffness. This configuration allows to limit lateral displacements (drift) in a masonry structure during an earthquake and prevent extensive damage and collapses. Unfortunately, older masonry structures rarely act as box-like structures, due to inadequate wall-to-floor and wall-to-roof connections, and also due to flexible timber diaphragms; these deficiencies were confirmed by field observations made by the SUZI-SAEE team after the 2020 Petrinja earthquake.

Figure 3. OOP Collapse of URM walls in buildings in Petrinja, Croatia

Numerous low- to mid-rise masonry apartment buildings in the epicentral area were affected. Several multi-storey apartment buildings in Petrinja experienced heavy damage. Fig. 4 shows a building which experienced shear cracking in the walls at the ground floor level. The cracking can be attributed to high in-plane seismic demand and excessively high tensile stresses.

Figure 4. Shear cracking at ground floor level of multi-storey URM apartment buildings in the 2020 Petrinja earthquake

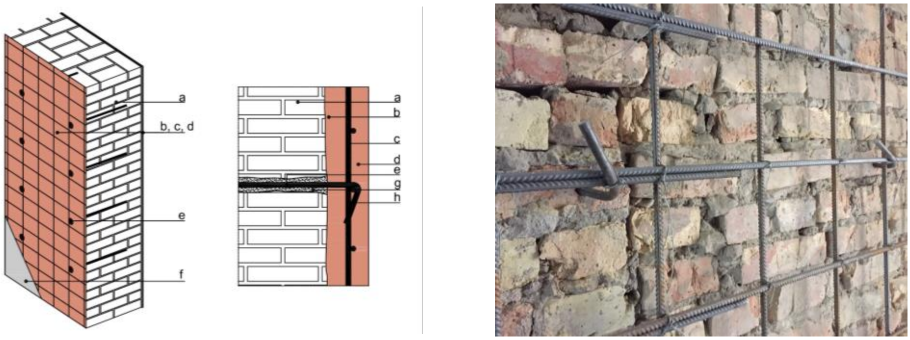
3. SEISMIC RETROFITTING TECHNIQUES FOR MASONRY BUILDINGS

To evaluate the influence of any structural/seismic intervention on an existing building, it is important to predict how such intervention may modify the building's response to seismic actions. First of all, it is important to determine the mechanical characteristics of structural elements and the geometry of the building, which significantly influence structural/seismic response. In case of an earthquake-damaged building it is critical to understand the cause of damage and damage patterns. The knowledge of these basic elements should help determine the principal vulnerabilities of the structure, and subsequently select an optimal intervention for achieving an enhanced strength and/or ductility of the entire system.

The choice of the most appropriate type, technique, extent and urgency of the intervention depends on the results of the seismic assessment. The ability of the structural elements to resist predictable static and dynamic actions strongly depends on the characteristics of the materials and their condition. If structural elements are deficient in terms of their lateral load-resisting capacity, analytical assessment of seismic improvement interventions is deemed to be ineffective. Seismic interventions must be correlated to the seismic damage/failure mechanisms (in-plane or out-of-plane failure, presence or absence of connections, pounding effects, subsidence of the foundations, etc.). In the end, the goal is to identify the most suitable intervention(s) targeted at mitigating specific seismic deficiencies.

Seismic retrofitting techniques for masonry buildings have been well established and have been implemented on various projects in the region after past earthquakes since the 1980s [11]. In the context of seismic retrofitting, interventions may be required for i) masonry walls, ii) floor/roof systems, and iii) the foundations. In most cases, it is critical to enhance the in-plane shear resistance of existing masonry walls for the effect of seismic loading. Although several alternative techniques are available, the most common techniques are: i) RC jacketing and ii) Fiber Reinforced Composite (FRC) overlays.

RC jacketing technique (Fig. 5) consists of double-sided RC jackets which are attached to masonry walls (exterior and interior wall surface). An RC jacket is usually attached to an existing masonry wall via steel anchors which are embedded in drilled holes in the wall, and grouted using cement- or epoxy-based resin. Either cast-in-place concrete or sprayed concrete (shotcrete/torcrete) can be used for RC jackets. International codes recommend different thickness for a concrete overlay. Minimum recommended jacket thickness of 40-50 mm was used after the 2010 Kraljevo, Serbia earthquake [12]. Thicker RC jackets (80-100 mm) may be beneficial for preventing corrosion of new reinforcement and achieve higher stiffness of RC jackets relative to the existing wall [13]. One of the critical aspects of RC jacketing is to ensure continuity of vertical reinforcement through the existing floor slabs.



Legend: a) existing masonry; b) first layer of concrete; c) steel wire mesh; d) second layer of concrete; e) steel anchors; g) hole in the masonry wall filled with epoxy resin or cementitious grout; h) steel anchor with a 90-degree hook.

a) b)

Figure 5. Seismic retrofitting of masonry walls using RC jacketing: a) features of the technique and b) field application in a school retrofit project in Kyrgyzstan [14]

FRC overlays act in similar manner like RC jackets, and are suitable for application to existing masonry walls with deficient shear capacity [13]. This technology has been used in the last 30 years both for structural rehabilitation purposes (e.g. existing bridges) and also for seismic retrofitting of RC and masonry structures before and after earthquakes. This technique consists of applying FRC overlays or strips to wall surfaces that were previously saturated by an epoxy resin binder (Fig. 6). FRC overlays can be applied over the entire wall surface; alternatively, horizontal and vertical FRC strips can be connected with fiber anchors. In both applications, fibers are used as tension reinforcement for the wall and should be aligned in the direction of tensile stresses. Design procedure for FRC-based retrofit of masonry structures is well established [15]. FRC overlays and strips can be used either as one-sided or two-sided applications. They should be wrapped around the wall ends to ensure adequate bond to the wall surface and anchorage. Alternatively, fiber anchors can be installed along the wall perimeter. The shear resistance contribution from the FRCs can be determined in a similar manner to that used to determine the required amount of wall reinforcement. The required effective fiber area per unit width (corresponding to the thickness) and its contribution to shear resistance are governed by the bond and anchorage strength at the FRC-to-wall interface .

RC jacketing technique is often considered as a more feasible solution due to lower construction costs compared to the retrofit performed using FRC technologies. Another advantage of RC jacketing is that advanced construction skills are not required, but on the negative side the disturbance to the occupants during the construction is significantly higher than for the FRC retrofit. Advantages of FRCs include ease and speed of application, thus resulting in minimal disruption to the occupants. FRCs are corrosion-resistant and have high strength-to-weight ratio.

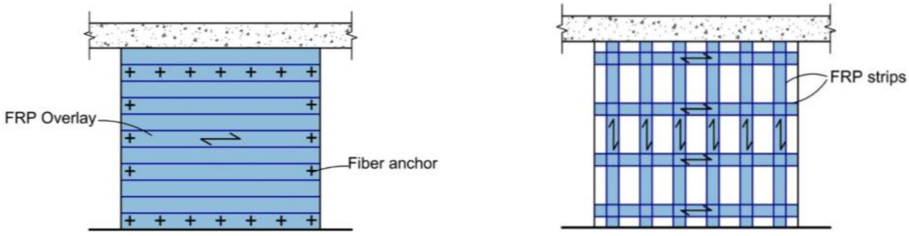


Figure 6. Retrofitting of masonry walls using FRCs: a) FRC overlay with fiber anchors and b) horizontal and vertical FRC strips [13]

Since most of the older masonry buildings have timber floors, they are highly vulnerable to earthquakes due to flexible diaphragm behaviour. This is something that should be definitely prevented with pre-earthquake interventions. Although timber floors are often replaced with reinforced concrete slabs, there are several other measures for their strengthening such as: i) Installation of additional beams under the floor, ii) Joist strengthening with nailed timber elements, iii) Use of tension elements (steel or carbon fiber polymers) connected to timber joists, iv) forming a composite cross-section (usually concrete is added to the timber joists and mechanically connected with steel fasteners. These measures mostly increase the vertical load-bearing capacity of timber floors. To provide higher in-plane strength and stiffness of timber floors, the following measures (Fig. 7) can be applied: i) Adding second layer of wood planks crossly arranged and fixed to the existing ones by means of steel studs/nails or glued, ii) diagonal bracing of the existing wood planks by means of steel or FRP plates, iii) RC slab cast on top and connected with studs to form composite slab. Nowadays, also cross-laminated timber elements are used for forming a composite cross-section [16]. Casting of new RC slab on top of wooden planks to form timber-concrete composite cross-section that provides at the same time in-plane and out-of-plane strengthening of floor is shown in Fig. 8.

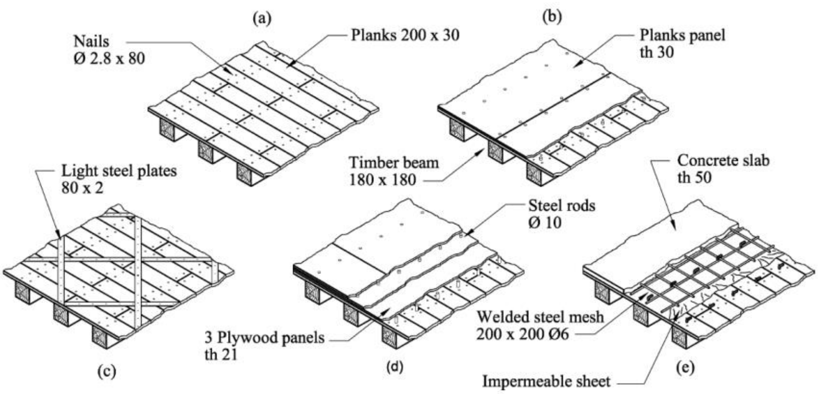
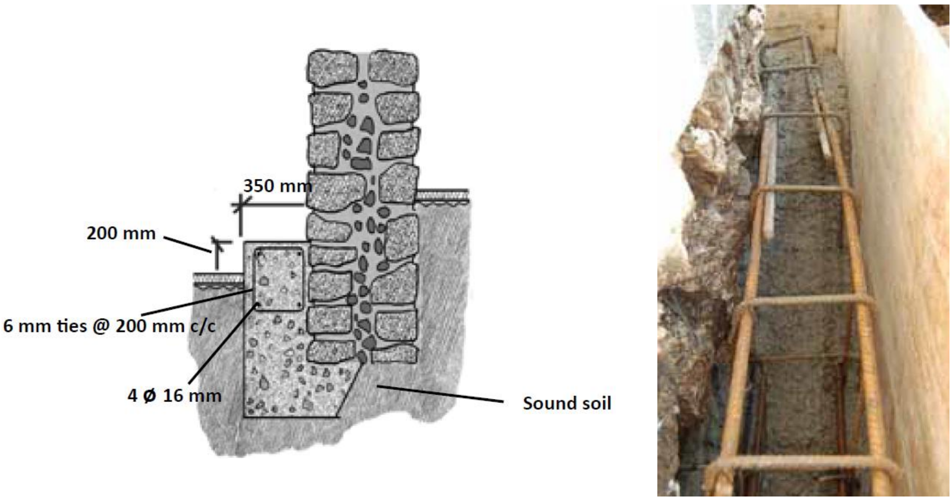


Figure 7. In-plane strengthening techniques for timber floors: a) layer of wooden planks on the timber beams, b) second layer of wood planks crossly arranged and fixed to the existing ones by means of steel studs/nails, c) diagonal bracing of the existing wood planks by means of steel or FRP plates, d) three layers of plywood panels glued on the existing wood planks, e) cast-in place RC slab connected with studs [17]

Figure 8. Timber-concrete composite floors: Strengthening of wooden floors with cast in place RC in Tbilisi, Georgia

Retrofitting of the existing wall foundations may be required in some cases, in order to account for increased shear forces and bending moments resulting from the retrofit [13]. Strengthening existing foundations is a difficult and expensive task. A special investigation is recommended before any such intervention. A few foundation strengthening schemes are discussed in [18-20]. Fig. 9 shows sketch of foundation strengthening with external RC belt (tie beam), placed around the building at the foundation level with reinforcing detail from practice.



a) b)

Figure 9. Strengthening of existing foundations: a) external RC belt and b) reinforcement cage and formwork [21]

4. SUMMARY

In this paper, observations of the seismic behaviour of masonry structures during the November 26, 2019 Albania earthquake (M_w 6.4) and December 29, 2020 Petrinja earthquake (M_w 6.4) were summarized. Serbian Association for Earthquake Engineering (SUZI-SAEE) organized an expert teams to visit the affected areas. Recent earthquake in Albania showed disastrous consequences in the case of inadequate seismic design and poor detailing, whereas earthquake in Petrinja (Croatia) confirmed significant vulnerability of masonry walls in older buildings with flexible wooden floors and roofs. Observations of the damage modes of the structures after earthquakes show that walls are less resistant to actions that are perpendicular to the wall surface (out-of-plane actions) than to actions parallel to their plane (in-plane actions). Satisfactory seismic behaviour is achieved when out-of-plane collapse is prevented and the in-plane strength and deformation capacity of the walls can be fully exploited. Furthermore, if there is a sufficient connection between the vertical bearing structures and a floor system, the distribution of seismic actions occurs according to the stiffness of the walls. In this case, it is more likely that the masonry will break due to the reaching of the in-plane ultimate resistance and will not collapse in out-of-plane. Thanks to the connection between vertical and horizontal elements, a box-like system is thus generated.

Afterwards, a short overview on the main retrofit techniques for masonry buildings is given. Mostly used approaches for walls and floors are presented, followed with the examples from practice. The topic is treated with a broad perspective, which ranges from the investigation of the construction techniques used for seismic improvement interventions to the materials combined and assembled to create typical construction schemes.

The decision which technique is the best and optimal taking into account resources, knowledge of workers, time and costs is not easy and it needs a good overview of the existing approaches. Therefore, it would be good if each country would develop the guidelines to be followed for the selection of most compatible techniques in terms of effectiveness, ease of construction and costs.

5. ACKNOWLEDGEMENTS

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