1st Croatian Conference on Earthquake Engineering
1CroCEE
22-24 March 2021 Zagreb, Croatia

DOI: https://doi.org/10.5592/CO/1CroCEE.2021.242

Out-of-plane behaviour of loadbearing and non-structural masonry walls during recent earthquakes

Marko Marinković[1], Svetlana Brzev[2], Markel Baballëku[3], Brisid Isufi[4], Nikola Blagojević[5], Ivan Milićević[6], Željko Žugić[7], Petar Bursać[8]

[1] *Assistant Professor*, University of Belgrade, Faculty of Civil Engineering, *mmarinkovic@grf.bg.ac.rs*
[2] *Adjunct Professor*, University of British Columbia, Vancouver, Canada, *svetlana.brzev@gmail.com*
[3] *Professor*, Polytechnic University of Tirana, Faculty of Civil Engineering, Tirana, Albania, *markel.baballeku@fin.edu.al*
[4] *Postdoctoral Fellow*, Department of Civil Engineering, NOVA School of Science and Technology, Universidade NOVA de Lisboa, Caparica, Portugal, *b.isufi@campus.fct.unl.pt*
[5] *PhD student*, Institute of Structural Engineering, ETH Zurich, *blagojevic@ibk.baug.ethz.ch*
[6] *PhD student*, University of Belgrade, Faculty of Civil Engineering, *ivanm@imk.grf.bg.ac.rs*
[7] *Project Coordinator*, Public Investment Management Office, Serbia, *zeljko.zugic@obnova.gov.rs*
[8] *PhD student*, University of Belgrade, Faculty of Civil Engineering, *pbursac@grf.bg.ac.rs*

Abstract

Recent earthquakes in Balkan, including the September 21 and November 26, 2020 Albania earthquakes, March 22, 2020 Zagreb earthquake, and the December 29, 2020 Petrinja, Croatia earthquakes had devastating consequences for the affected population of these countries. Besides substantial structural damage of RC buildings as well as loadbearing masonry buildings, these earthquakes caused significant damage of non-structural masonry elements. This paper presents examples of the damage for loadbearing and non-structural masonry walls (infills and partitions) due to out-of-plane seismic effects, as observed by the authors during the reconnaissance visits to the affected areas. This type of damage can prevent the evacuation of people from the buildings during the earthquake, as the falling masonry elements block the evacuation routes, and hinder the reoccupancy and functional recovery of affected buildings after an earthquake. The authors recognize that both loadbearing and non-structural walls (infills and partitions) experienced out-of-plane collapse due to lack of connection to the floor/frame. Using the examples of the damage or failure of masonry walls during the recent earthquakes, their failure mechanisms were explained and the lessons learned were summarized in the paper.

Key words: loadbearing masonry, infills, earthquake damage, Albania earthquake, Croatia earthquake

1 Introduction

Masonry is the most common technology for building construction on a global scale. Clay bricks have been used for at least 10,000 years. Sun-dried bricks were widely used in ancient civilizations such as Babylon, Egypt, Spain, South America etc.[1]. Older buildings mostly consist of loadbearing unreinforced masonry (URM) walls. On the contrary, in modern mid- and high-rise buildings, masonry infill walls which are extensively used to enclose reinforced concrete or steel frames are typically considered as non-structural elements in design. Furthermore, for the separation of internal spaces within the buildings masonry partition walls are mostly used. High impact resistance, very good heat and sound insulation properties as well as attractiveness from the architectural perspective and a very efficient cost-performance have resulted in a wide use of masonry walls all over the world including earthquake prone areas. Therefore, both loadbearing and non-structural masonry walls are affected by earthquakes.

Masonry structures have a satisfactory loadbearing capacity under compression due to the action of gravity loads, but masonry is characterized by a very low tensile strength, which is often exceeded in the walls exposed to earthquakes, and results in the cracking and damage of these walls. Figure 1 shows typical earthquake-induced damage of URM structures due to the action of earthquakes in the plane of the wall and perpendicular to the wall plane (out-of-plane). Damage due to the earthquake excitation in the plane of the wall, primarily the characteristic diagonal ("X") cracks caused by exceeding the tensile strength, is marked in red in Figure 1. In addition, typical damage patterns due to the effect of the earthquake perpendicular to the plane of the wall are marked in blue in Figure 1. Vertical cracks at the joints between longitudinal and transverse walls are also common, especially in buildings with flexible floors or in cases when the walls are not adequately connected to the slab. Horizontal cracks at the top and/or in the middle of the wall height are also a consequence of the earthquake action perpendicular to the wall plane.

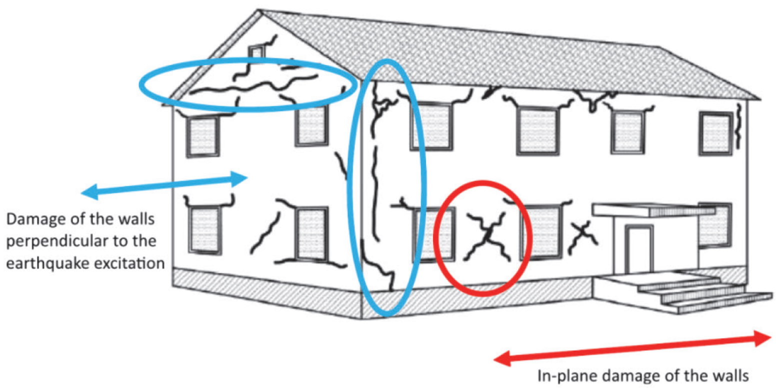

Figure 1. Typical damage of masonry buildings (according to [2])

Infill and partition walls are not designed nor expected to act as loadbearing elements. However, infill walls often participate in carrying earthquake-induced lateral loads, where the lateral load resistance of infill walls is achieved through a composite action with the surrounding frame until the appearance of first cracks. Additionally, due to the acceleration and mass of the wall, infills and partitions are subjected to inertial forces acting perpendicular to the wall plane. These out-of-plane (OOP) loads can cause significant damage to the walls, or even their complete collapse. Recent damaging earthquakes including Duzce (Turkey, 1999), L'Aquila (Italy, 2009), Lorca (Spain, 2011), Christchurch (New Zealand, 2011) and Emilia-Romagna (Italy, 2012) have revealed that the failure of infill walls frequently occurs during earthquakes and that mitigation of potential damage in infill and partition walls is a very important public safety issue. This type of failure may cause injuries or even casualties, which are sometimes caused by moderate earthquakes. Also, the damage of infills/partitions may be significant from the economic point of view due to the need for repair or reconstruction, reducing building functionality, as well as causing rental and relocation costs and general income losses. Damage of masonry infills was observed in the recent earthquakes in Albania which occurred on September 21, 2019 (M_w = 5.6) and November 26, 2019 (M_w = 6.4), while loadbearing walls in URM buildings were severely damaged in the March 22, 2020 Zagreb earthquake (M_w = 5.5) and December 29, 2020 Petrinja earthquake (M_w = 6.4). Figures 2 and 3 show typical in-plane and OOP failure modes of masonry infill walls.

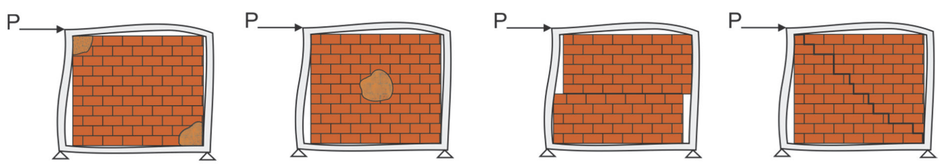

Figure 2. In-plane failure modes of masonry infills subjected to earthquake effects [3]

This paper is focused on the OOP behaviour of masonry walls in recent earthquakes in Albania and Croatia based on the observations of SUZI-SAEE (Serbian Association for Earthquake Engineering) team members regarding the causes of damage and failure of loadbearing and non-structural masonry walls.

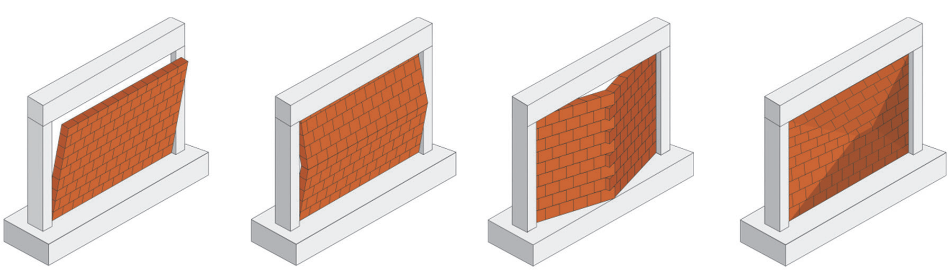

Figure 3. Failure modes of masonry infills subjected to OOP earthquake effects [3]

2 Damage of loadbearing URM walls

2.1 Albania earthquakes (September 21 and November 26, 2020)

In Albania, masonry is a traditional construction technology for low-rise single-family residential buildings 1 to 3 storeys high. However, from 1960 to 1990 this technology was also used for the construction of multi-family residential buildings (mostly 3 to 5 storeys). Based on the field reconnaissance of several affected towns and villages in Albania, the members of the SUZI-SAEE team concluded that masonry buildings did not suffer extensive damage due to these earthquakes (except in place Thumanë). One of the causes of damage to masonry buildings in Albania is the low quality of materials and construction and the resulting low loadbearing capacity of the walls, which primarily depends on the mechanical characteristics of the masonry compressive and shear strength, as well as the wall thickness. An example is the single-storey URM house in the Bubq village with a wooden roof structure (Figure 4) that was damaged in November 26 earthquake. It can be seen that the transverse wall suffered damage due to the OOP earthquake action. The damage is in the form of vertical cracks at both ends of the wall, with the crack on the right side extending over the entire wall height at the first floor. The absence of a horizontal RC confining element at the roof level can be noticed, which is critical for maintaining the integrity of the building during an earthquake. This type of damage can lead to the collapse of individual walls and culminate in partial or complete collapse of the entire structure.

Figure 4. Out-of-plane damage of URM building with flexible floor [4]

Multi-family apartment URM buildings with RC floors cast-in-situ were either not damaged or they suffered minor damage in the Albanian earthquakes. This can be explained by the presence of rigid floors and the regularity in plan configuration. Figure 5 shows minor damage to the building of this type. Diagonal cracks caused by the earthquake can be noticed in the plane of the wall, mainly at the level of the lower three floors.

Figure 5. Damage of five storey URM building in Fushe Kruje [4]

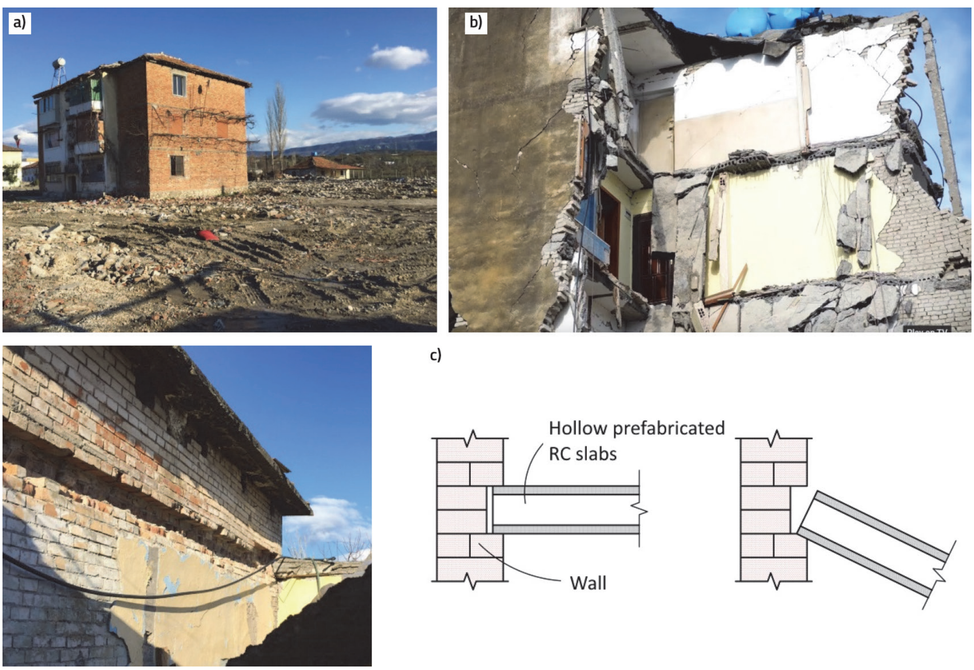

Figure 6. Collapse of 5-storey URM residential buildings in Thumanë, Albania: a) a low-rise masonry building in the background of the cleared area of demolished URM buildings; b) partial collapse of the demolished building; c) detail of the slab-wall connection [4]

In the town of Thumanë, four 5-storey URM buildings with hollow prefabricated RC slabs collapsed in the November 26, 2019 earthquake, causing 24 casualties. Note that these buildings were damaged in the September 21, 2019 earthquake. It is important to note that in the immediate vicinity there were other URM buildings with monolithic RC slabs that did not suffer any structural damage. We believe that the collapse of these buildings was caused by simply supported slabs, as well as the lack of integrity of prefabricated RC elements due to the absence of a reinforced concrete topping cast in-situ after slab installation, as well as inadequate or absent RC ring beams at the floor level. Definitely the major culprit was insufficient slab support length, which led to the total slab collapse (Figure 6). In addition, it appears that the solid silicate bricks used for the wall construction were of poor quality, which contributed to the low strength of the masonry.

2.2 Croatian Earthquakes (March 22, 2020 Zagreb and the December 29, 2020 Petrinja)

Low-rise masonry residential buildings (either single-family or multi-family buildings) are the most common form of housing construction in Petrinja. The December 29, 2020 Petrinja earthquake and its aftershocks affected low-rise masonry buildings, which experienced damage or collapse. Older two-storey URM buildings with wooden floors experienced damage or failure of walls due to OOP seismic effects (Figure 7). Excessive horizontal displacements of flexible floors caused these walls to act as vertical cantilevers and experience damage or collapse (toppling). In some cases, wall collapse induced the roof collapse. Damage of masonry gable walls was prominent in mid-rise masonry buildings exposed to the March 22, 2019 Zagreb earthquake. The damage can be attributed to inadequate wall-to-roof connections. Figure 8 shows collapse of URM gables in Petrinja and Zagreb.

Figure 7. OOP Collapse of URM walls and timber floors in older buildings in Petrinja, Croatia (SUZI-SAEE)

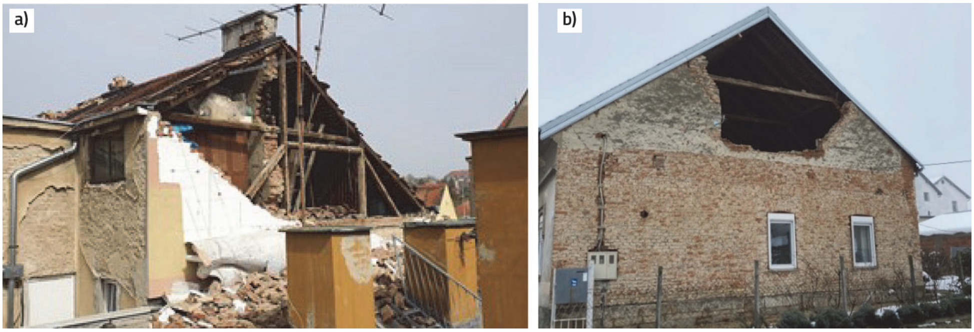

Figure 8. OOP failure of URM gables in the Croatian earthquakes: a) Zagreb (author: Karlo Jandrić) and b) Petrinja (SUZI-SAEE)

3 Damage of non-structural masonry walls (infills and partitions)

3.1 Albania earthquakes (September 21 and November 26, 2020)

Masonry infills are very common treated as "non-structural elements" in RC frame buildings in Albania. Figure 9 shows typical damage of masonry infills, while the RC structures remained undamaged. Figure 9b shows collapse of infill walls in a RC building behind an undamaged URM building.

Figure 9. Failure of infills in RC high-rise buildings in Durrës, Albania: due to OOP earthquake effects [4]

It is believed that infill walls experienced damage due to combined in-plane and OOP earthquake effects. Floor accelerations induced OOP inertial forces in infill walls. In a large number of RC buildings, infills experienced OOP damage at the lower floors, while the infill walls at the upper floors remained intact. OOP damage of the infills at the lower floors of building is not expected because floor accelerations increase at higher floors.

Figure 10. Collapse of masonry infills in RC buildings in Durrës, Albania [4]

From a simplified perspective, a higher level of in-plane damage may be expected at lower floors due to the higher in-plane deformation of the frame, but more significant OOP damage is expected at higher floor levels, due to higher floor accelerations. Therefore, the OOP damage of infills on lower floors can be explained by the fact that during an earthquake, the infill walls are simultaneously exposed to the in-plane and OOP deformation, where the in-plane deformations weaken the infills making them more susceptible to OOP failure [3]. Such a combination may lead to extensive damage of masonry infills, as observed after the November 26, 2019 earthquake (Figures 10 and 11). Also, it is important to mention that a lot of interaction of infills with the surrounding frame was observed in Albania, leading to the formation of soft stories and other damages to RC elements (short columns, etc).

Figure 11. OOP damage and collapse of masonry infills in RC buildings in Durrës, Albania [4]

3.2 Croatian Earthquakes (March 22, 2020 Zagreb and the December 29, 2020 Petrinja)

The March 22, 2020 Zagreb earthquake caused damage mostly to URM buildings. In general RC frame buildings with masonry infills were not significantly affected by the earthquake; however some hospitals and schools experienced damage [5]. Although damage and collapse of loadbearing URM walls was dominant in Petrinja [6], SUZI-SAEE team documented damage and failure of URM partitions (Figure 12a) and infills in residential buildings and schools (Figure 12b), and a retirement home (Figure 13). The damage of partitions and infills in Dec. 29, 2020 earthquake can be attributed to high ground accelerations in the epicentral area.

Figure 12. OOP damage of masonry infill walls in RC buildings in Petrinja, Croatia (SUZI-SAEE)

4 Conclusions

Recent Croatian earthquakes confirmed significant vulnerability of masonry walls in older buildings with flexible wooden floors and roofs, while Albanian earthquakes caused significant damage of masonry infills in RC framed buildings. In both cases the damage was caused primarily by out-of-plane earthquake effects, which in case of infills were amplified due to simultaneous in-plane deformation. Although in most cases RC buildings in Albania did not experience structural damage, they had to be vacated after the earthquake due to the masonry infill damage. In most cases loadbearing masonry walls in Croatian URM buildings experienced only localized damage or failure, however in some cases building occupants had to vacate their apartments after the earthquake. One of the main lessons learned from these earthquakes is that localized damage of structural or non-structural elements may have significant long-term consequences and disrupt functionality of the affected buildings. Safety of these walls is of critical importance during an earthquake, since their collapse could disrupt evacuation routes and prevent the exit of occupants from these buildings. Retrofitting of existing URM walls is a high priority for mitigating effects of future earthquakes.

Figure 13. Combined in-plane and OOP damage of infills in retirement home in Petrinja, Croatia (SUZI-SAEE)

Acknowledgements

The authors of this publication are grateful to the Serbian Association for Earthquake Engineering (SUZI-SAEE) for the support to visit earthquake-affected areas in Albania and Croatia and gain valuable experience regarding damage of the buildings and other earthquake consequences. Team members from the Republic of Serbia are especially grateful to the colleagues from Albania and Croatia, for cooperation during and after the visits. Their knowledge and experience significantly contributed to the quality of the visits and this publication.

References

[1] Hamid, A.A. (2018): *Masonry Structures: Behavior and Design*. The Masonry Society, United States.

[2] Grünthal, G. (ed.) (1998): *European Macroseismic Scale 1998 (EMS-98)*. Centre Europèen de Géodynamique et de Séismologie, Luxembourg.

[3] Butenweg, C., Marinković, M., Salatić, R. (2019): Experimental results of reinforced concrete frames with masonry infills under combined quasi-static in-plane and out-of-plane seismic loading. *Bulletin of Earthquake Engineering*, 17(6), 3397-3422.

[4] Nikolić-Brzev, S., Marinković, M., Milicević, I., Blagojević, N. (2020). *Posledice zemljotresa u Albaniji od 26.11.2019. na objekte i infrastrukturu* (Consequences of the November 26, 2019 Albania earthquake on the buildings and infrastructure). Serbian Association for earthquake engineering (SUZI-SAEE), Serbia (in Serbian).

[5] Šavor Novak, M., Uroš, M., Atalić, J., Herak, M., Demšić, M., Baniček, M., Lazarević, D., Bijelić, N., Crnogorac, M., Todorić, M. (2020): Zagreb earthquake of 22 March 2020 – preliminary report on seismologic aspects and damage to buildings. *Građevinar*, 72 (10), 843-867, https://doi.org/10.14256/JCE.2966.2020

[6] Miranda, E., Brzev, S., Bijelić, N., Arbanas, Ž., Bartolac, M., Jagodnik, V., Lazarević, D. et al. (2021): *StEER-EERI: Petrinja, Croatia December 29, 2020, Mw 6.4 Earthquake Joint Reconnaissance Report (JRR)*. The Structural Extreme Events Reconnaissance (StEER) Network, United States.