Reinforced concrete frames with masonry infills. Out of plane experimental investigation

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Abstract

This paper presents a synthesis of the typical damages recorded in reinforced concrete frames and masonry infills after recent earthquakes. The behaviour and failure modes of the infill walls are of great importance, especially since no clear recommendations are provided in the current design codes for the performance of these types of walls. In the present time, masonry infill walls are considered to be non-structural building elements, while the seismic behaviour of reinforced concrete frame structures having these type of walls, indicated a structural behaviour of the infills. Several proposals for the improvement of the out-of-plane behaviour of infill walls are presented in this paper, together some experimental results of tests performed on a simple masonry wall. The investigation of these solutions can lead to the development of innovative systems of masonry infills, and can also provide viable consolidation measures for existing buildings.

1. Introduction

The present paper extends the previous study carried out by the authors in “Reinforced concrete frames with masonry infills. Damages and consolidation measures” (Petrus et.al. 2014) with a chapter representing the experimental tests performed on a simple masonry wall specimen. Masonry infill walls in reinforced concrete frames are widespread in many countries. The use of veneer walls for the enclosure of reinforced concrete frames represents also a current trend. This practice is derived from the evolution of the traditional building technique, based on masonry walls. At the beginning of the XXth century, the use of reinforced concrete for the bearing elements of structures underwent an exceptional growth, transforming the infill walls into surface elements of negligible volume, mass and stiffness in comparison to traditional masonry walls. This evolution unveiled a series of drawbacks related to the structural conformation, and suitable solutions are yet to be found, which should comply with code requirements related to performance, safety, aesthetics and design. These problems are pronounced when the non-structural elements, which are the infill walls, are subjected to actions which make them behave in a structural manner, like earthquakes strong winds, settlements, etc.

The INSYSME European research program studies the behaviour of these types of walls and is searching for a solution to enhance their behaviour and to fill in the gaps which are in the current guidelines and design codes (www.insysme.eu).
2. Damages recorded in reinforced concrete frames with masonry infills

Recent seismic activities revealed that a lot of structures having masonry infills recorded an extensive amount of damage. These walls can detach from the structure and collapse, due to a combination of in-plane and out-of-plane demand, as it can be seen in Figure 1. The out-of-plane failure of the enclosure walls, are dangerous, causing fatalities and large economic loss, as it was the case for the L’Aquila, Italy earthquake from 2009, which had a magnitude of 6.3 on the Richter scale (EEFIT report 2009). Widespread extensive damage of the masonry infills and partition walls caused the highest losses in reinforced concrete buildings. A detailed analysis was carried out after the seismic event in order to evaluate the repair costs for the clay units of the infill walls, equipment and interior finishing (Migliavacca 2010). This analysis pointed out the fact that the costs related to the enclosure walls repair, even in a severe earthquake, can be more relevant than the cost related purely to structural interventions (Santagata 2010). Such is the case of veneer walls which are susceptible to cracks and failures in case of poor detailing of the connection to the reinforced concrete bearing structure, Figure 2.

Figure 1. Examples of in-plane and out-of-plane seismic damage to clay unit masonry infill walls.

Figure 2. Examples of in-plane and out-of-plane seismic damage to clay unit masonry veneers.

Figure 3 presents the failure of the masonry infill and veneer wall of a relatively new building, after the earthquake from L’Aquila. Poor constructive detailing can lead to damages in buildings which were constructed previous to modern seismic design codes, but even in newly constructed buildings, thus a call for the development of new and improved systems is necessary. Examples of in-plane and combined in-plane and out-of-plane damages can also be observed in newly constructed buildings from Emilia, Italy, after the 6.0 magnitude earthquake from 2012 (Magenes et.al. 2012), as it can be seen in Figure 4.
The 2011 earthquake from Van, Turkey had a magnitude of 7.1 on Richter scale (EERI report 2012) and demonstrated the highly variable nature of the seismic damage to the infill walls in reinforced concrete frame buildings. In some cases, the infill walls had a major contribution in the overall behaviour of the building, influencing its strength and ultimately preventing an early collapse. In other situations, the masonry infills detached from the structure, as it can be seen in Figure 5, due to combined in-plane and out-of-plane solicitations, proving a dangerous failure mode for the occupants.

**Behaviour of masonry infills subjected to seismic actions**

Regarding the behaviour of the non-structural masonry infills, it has to be underlined that they prove inadequate performance under serviceability states (Calvi et.al. 2004), and with no clear design regulations, they present unpredictable ultimate limit state behaviour which can ultimately lead to the
element or structure collapse. The damages of these types of walls are responsible for a considerable percentage of the recorded damages in buildings. Recent studies have shown that one of the reported causes of damage is the short support of the external walls on the concrete slabs, in the case of slender veneer enclosures designed to ensure a good thermal insulation of the building (Da Silva and Mendes da Silva 2007). This aspect can lead to severe cracking or even collapse of the veneer walls. Another factor influencing the behaviour of these walls is represented by the lack of detailing provided in the design procedure, and together with the poor workmanship can have unfavourable results in the case of seismic activities (Lourenco 2004). The Romanian seismic design code (P100-1/2013) states that the interaction between the masonry infill and the frame structure can only be accounted for if there can be identified a set of compressed diagonals in the masonry infill. This is particularly difficult to identify due to the uncertainties based on the actual execution and collaboration between the structural and non-structural elements. A set of unfavourable effects are suggested to be taken into account, which are related to the modification of the behaviour factor $q$ and the introduction of local effects in the frame structure, due to the presence of the infill wall. These effects are to be countered only by some constructive detailing related to the strengthening of the frame structure. In the design code for masonry structures from Romania (CR6 2006), the in-plane resistance of an infill masonry panel is given by the smallest of three failure modes of the masonry panel, as it can be seen in Figure 6, corresponding to rupture due to shear sliding in the horizontal joint (Figure 6a), cracking along compressed diagonal (Figure 6b) and crushing of the compressed diagonal at the corners (Figure 6c). All these failure modes do not account for the degree of interaction between the infill and frame structure.

![Figure 6. In-plane failure modes of the infill wall panel](image.png)

The same design code for masonry structures in Romania points out two possible out-of-plane failure modes for walls subjected to bending parallel ($f_1$) and perpendicular ($f_2$) to the mortar joint, as it can be seen in Figure 7. The flexural strength of the infills is given by a ratio accounting for the interaction of the two possible failure modes ($\mu=f_1/f_2$), but due to a large number of factors influencing the walls resistance to bending (resistance of the masonry elements in relation to the mortar adhesion strength, percentage of holes in the masonry elements, value of vertical compression efforts and dimension ratio of the masonry elements), this value is within a wide limit range of 1.5 – 8.0.

![Figure 7. Out-of-plane failure modes of the infill wall panel, parallel and perpendicular to the mortar joint.](image2.png)
2.1. Consolidation measures

Within the INSYSME research program (www.insysme.eu) there are sought out new and improved methods for the construction, design and calculation of infill walls, for new buildings. Another direction related to the behaviour of these walls is represented by the consolidation of the existing structures having infill and veneer walls. Within the “Politehnica” University of Timisoara, at the Faculty of Civil Engineering there are studies ongoing related to the improvement of the out-of-plane behaviour of masonry infill walls (Mosoarca et.al. 2014). In collaboration with student architects and PhD students from the Civil Engineering Faculty, a set of consolidation measures were proposed. Among the proposed solutions, one refers to an exterior consolidation with steel profiles of the building frame (Daraban 2014). This method is generally used and accepted for the retrofit of damaged buildings. In order to satisfy the lighting, energy consumption and aesthetical requirements, the solution is based on a concept of sustainability. This consolidation measure aims to consolidate the building frame and masonry infill panels, in order to avoid out-of-plane failure. Energy efficiency for the building represents another advantage of this solution. As it can be seen in Figure 8, a four layer curtain wall system constitutes a support for the existing veneer wall.

![Figure 8. Proposal of a 4 layer exterior consolidation method](image)

The first layer has small reservoirs for cleaning the façade and provides shade during periods with sun exposure, while the second layer represents the fixing layer made of steel profiles. The third layer has perforated steel profiles which protect the building from external actions. The forth layer is given by the steel structure used for strengthening the existing building on both in-plane and out-of-plane directions. This system could increase the rigidity of the structure, limiting the degradations and providing a seismic protection. The ease of construction, without affecting inside activities could represent another benefit factor, together with the enhancement of the architectural expressivity of the building.

Another direction for the improvement of the out-of-plane behaviour of infill walls is given by the exterior application of a thermo-insulation system, as in the case of new buildings. The study of the influence of this system will be performed within the Civil Engineering Faculty from Timisoara, as a PhD thesis which will be part of the INSYSME research program (www.insysme.eu).

The construction of an experimental stand was necessary in order to perform the proposed investigations. As it can be seen in Figure 9, the size of the stand can allow full scale tests on masonry walls and also it could facilitate a parameterization in function of the maximum span of the infill wall.

![Figure 9. Design and construction of the experimental stand](image)
Since a large amount of new buildings are constructed having a thermo-insulation system applied to the exterior façade, the influence of the glass fibre mesh from this system is going to be studied, as well as various consolidation measures using technologies already available on the market, such as a mortar grouting with aramid mesh (www.kerakoll.com) used as an exterior reinforcement solution and reinforcement using a mesh of polypropylene bands as a rapid and cost-effective solution. These consolidation measures will be then subjected to a cyclic out-of-plane force. A benefit factor of these proposed solutions is given by the fact that the ongoing activities inside the buildings are not affected by the interventions at the exterior veneers.

Tests will be performed on 4 sets of infill walls:

1. MW1 – reference wall specimen;
2. MW2 – wall with 10 cm thermo-insulation system with steel fibre mesh applied;
3. MW3 – wall reinforced with reinforced grout with aramid mesh;
4. MW4 – wall reinforced with a polypropylene band mesh.

The first reference wall will be constructed according to the current design provisions, using ceramic blocks with vertical openings, using horizontal mortar joints of 12mm. The thermo-insulation system of the second wall specimens will be installed as per producer’s requirements (www.baumit.ro) regarding the materials used and technology of application. The third wall specimen is a consolidation of the first wall specimen and consists of an exterior grout reinforcing with an aramid mesh. For the wall panel consolidated using a polypropylene band mesh, previous studies were carried out on structural walls made of unreinforced masonry (Sathiparan and Meguro 2013) and tests revealed a considerable improvement of the out-of-plane behaviour of the walls, as it can be seen in Figure 10. This mesh of polypropylene bands is fitted to the surface of the masonry wall, by means of steel connectors and radial grouting with an aramid mesh which will ensure a tight connection between the two materials and can be later covered with plaster which improves the aesthetical factor. The consolidation method with the polypropylene bands is applied on the second wall specimen, after removing the polystyrene from the wall surface. The loading protocol for these wall specimens will be performed in displacement control, having 3 cycles per loading step, as it can be seen in Figure 11.

![Figure 10. Failure patterns of the tested masonry wallets and out-of-plane load variation (Sathiparan and Meguro 2013)](image-url)
2.2. Experimental testing

For the all the experimental test specimens there have been used M5 mortar and ceramic blocks (375x250x238) with vertical openings having a 53% volume of holes from the gross volume of the ceramic with a compressive resistance of 10 N/mm². The infill masonry panels were simply supported at the bottom part, and at the superior part there was provided a mortar layer with wooden wedges between the ceramic blocks and the steel beam of the experimental stand. The interaction with the columns was not accounted for. The cyclic load was applied by an actuator having a maximum compression capacity of 160 kN and tensile capacity of 100 kN, through the means of a steel system composed of angle profiles and steel bars through the masonry wall. A special layer of rubber was placed between the angle profile flanges and the surface of the masonry wall in order to avoid local crushing of the ceramic blocks. Three cycles were performed for each loading step in the north and south direction, reaching a maximum displacement of 45 mm. The maximum recorded force for the test specimen MW1 was 56.6 kN, as it can be seen in the graph presented in Figure 12.

At a displacement of 10 mm, a horizontal crack appeared in the horizontal mortar layer, followed by horizontal cracks at the bottom part and top part of the masonry wall. Increasing the displacement, the crack in the middle part of the wall opened as much as 8 mm, as it can be seen in Figure 13.
For the test specimen MW2, the influence of the steel fibre mesh from the thermo-insulation system was studied. In order to perform a cyclic test on MW2, a cut-out was provided in the polystyrene from the thermo-insulation system for the steel profiles acting on the surface of the wall. An additional glass fiber mesh was then applied over the steel profiles in order to have a continuity of the mesh. From the force-displacement diagram presented in Figure 14, it can be observed a significant increase of the rigidity of the masonry infill wall, while the force recorded at the maximum applied displacement of 45mm was 60.4 kN, representing an increase of 6.2% in comparison with the test specimen MW1.

The first cracks appeared at a displacement of 5 mm at the superior part of the steel profiles on the side with the thermo-insulation system. The appearance of the cracks in this zone was expected, due to the configuration of the presence of the steel profiles which were wider than the width of the thickness of the polystyrene. The first crack in the horizontal mortar joint of the masonry appeared at a displacement of 7.5 mm. The maximum opening of the crack in the horizontal joint was 13mm at an imposed displacement of the masonry infill of 45mm.
For the test specimen MW3 having an exterior grouting with an aramid fibre mesh, the hardening period for the grout was 28 days in order to reach its required strength. The mesh had aramid fibres on longitudinal direction (the direction of bending), and glass fibre mesh in the transversal direction. Together with the mortar grout, this consolidation solution proved to increase the rigidity of the infill wall in the south direction, as it can be seen in Figure 16, but at a displacement of 17.5mm, the fibre mesh reached its failure point, beyond which it had no more effect on the out-of-plane behaviour of the test specimen MW3. The first cracks appeared in the horizontal joint of the masonry at a displacement of 7.5mm. Together with the appearance of this crack, there were also recorded two cracks in the adjacent horizontal mortar joints. These cracks did not develop as the displacement increased, but rather indicated that the aramid fibre mesh was active. At a displacement of 35mm, the opening of the horizontal crack in the mortar joint was approximately 13mm. The experimental testing ended at a displacement of 37.5mm when it was recorded a force 35% smaller than in the previous loading step.
In Figure 18, there is presented a comparison of the force-displacement of the first cycle of loading for the tested specimens in south (pushing) direction.

![Figure 18. Force-displacement comparison between MW1, MW2 and MW3 – south direction](image)

### 3. Conclusions

In this paper, there was performed a synthesis of the recorded damages in reinforced concrete frame structures with masonry infills after recent earthquakes. From this synthesis it was observed that damages can occur in buildings which were constructed prior to modern seismic design codes, but also in newly constructed ones. The authors proposed some intervention measures which aim to improve the overall out-of-plane behaviour of the masonry infill walls. These proposals have the advantage that they do not affect the ongoing activities in the buildings chosen to be retrofitted, and they prove to be an inexpensive solution for an otherwise expensive problem. In order to improve the seismic behaviour of reinforced concrete frames with masonry infills, the proposed solutions offer a degree of sustainability to the addressed problem, preventing the overturning of the walls. There were also presented some first results of the experimental testing of masonry infills, which revealed that the main source of energy dissipation was the mortar layers.
The presence of the glass fibre mesh from a traditional thermo-insulation system present in the majority of newly constructed buildings, increases the rigidity of the masonry infills subjected to cyclic forces. Exterior reinforcing with grout mortar and aramid fibre mesh proved to increase the rigidity of the masonry infills, only up to a brittle failure mode. Further investigations must be performed in order to evaluate the effectiveness of last consolidation measure with a mesh of polypropylene bands on the out-of-plane behaviour of masonry infill panels.

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