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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 behavior 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 behavior of reinforced concrete frame structures having these type of walls, indicated a structural behavior of the infills. Several proposals for the improvement of the out-of-plane behavior 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.

Rezumat

În acest articol este prezentată o sinteză a avariilor înregistrate de clădirile în cadre de beton armat cu pereţi de închidere din zidărie de cărămidă în urma cutremurelor recente. Comportarea şi modurile de cedare ale pereţilor de compartimentare şi închidere din zidărie de cărămidă sunt foarte importante deoarece nu exista specificaţii clare referitoare la performanţele acestor elemente în codurile de proiectare curente. În prezent, aceşti pereţi sunt consideraţi ca fiind elemente nestructurale ale unei clădiri, dar totodată, comportarea seismică a acestora a demonstrat un comportament structural. În acest articol sunt prezentate câteva propuneri pentru creşterea capacităţii portante perpendiculare pe planul pereţilor, precum şi rezultate experimentale ale unor teste efectuate pe un perete simplu din zidărie. Investigarea acestor soluţii pot conduce la dezvoltarea unor sisteme inovative de pereţi de compartimentare şi închidere din zidărie de cărămida sau pot fi considerate ca soluţii viabile de consolidare pentru clădirile existente.

Keywords: masonry infill, seismic behavior, out-of-plane, damages, consolidation measures

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” [1] with a chapter representing

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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 behavior of these types of walls and is searching for a solution to enhance their behavior and to fill in the gaps which are in the current guidelines and design codes [2].

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 [3]. 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 [4]. 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 [5]. 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 [6], as it can be seen in figure 4.

Figure 3. Typical damage of infill wall after the L'Aquila, Italy earthquake.

Figure 4. Masonry inill and veneer damage after the earthquake from Emilia, Italy.

The 2011 earthquake from Van, Turkey had a magnitude of 7.1 on Richter scale [7] 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 behavior 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.

Figure 5. In-plane and out-of-plane failure of masonry infills after the Van, Turkey earthquake.

2.1 Behavior of masonry infills subjected to seismic actions

Regarding the behavior of the non-structural masonry infills, it has to be underlined that they prove inadequate performance under serviceability states [8], and with no clear design regulations, they present unpredictable ultimate limit state behavior 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 [9]. This aspect can lead to severe cracking or even collapse of the veneer walls. Another factor influencing the behavior of these walls is represented by the lack of detailing provided in the design procedure, and together with the poor workmanship can have unfavorable results in the case of seismic activities [10]. The Romanian seismic design code [11] 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 unfavorable effects are suggested to be taken into account, which are related to the modification of the behavior 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 [12], the 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.

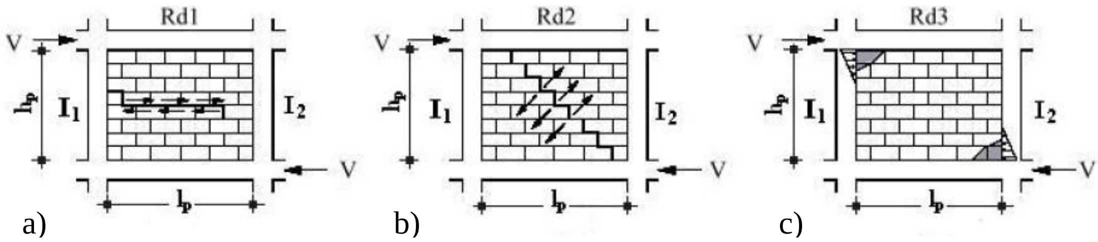

Figure 6. Failure modes of the infill wall panel

3. Consolidation measures

Within the INSYSME research program [2] 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 behavior 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 behavior of masonry infill walls [13]. 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 [14]. 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 6, a four layer curtain wall system constitutes a support for the existing veneer wall.

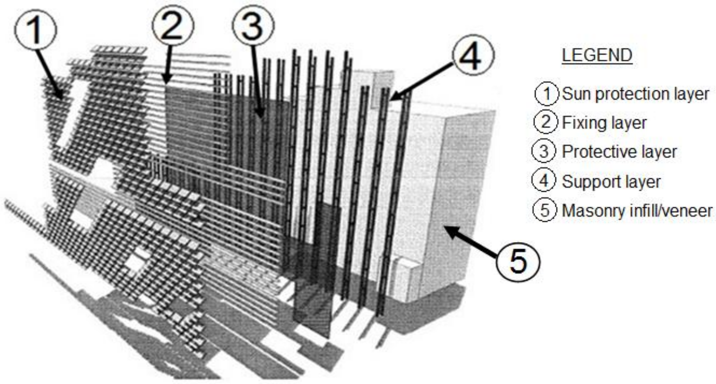

Figure 6. Proposal of a 4 layer exterior consolidation method

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 behavior 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 [2].

The construction of an experimental stand was necessary in order to perform the proposed investigations. As it can be seen in figure 7, 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.

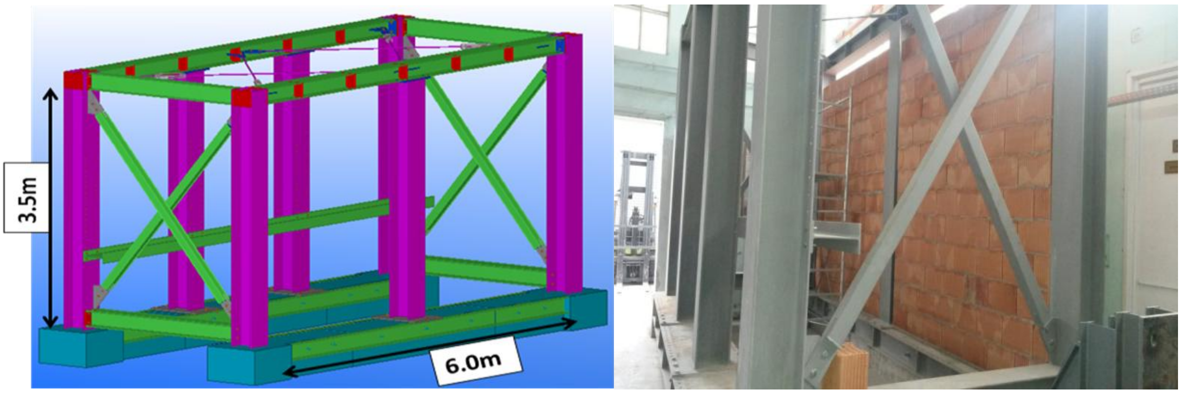

Figure 7. Design and construction of the experimental stand

Since a large amount of new buildings are constructed having a thermo-insulation system applied to the exterior façade, the influence of the glass fiber 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 GeoSteel grid [15] covering the cracks and Helifix bars in the mortar joints [16]. Another innovative solution will be to study the influence of a mesh of polypropylene bands on the exterior surface of the infill wall, being 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 5 sets of infill walls, in three stages:

(a) First stage – first wall (MW1) will represent the reference specimen, second wall (MW2) will have a 10 cm thermo-insulation system applied;

(b) Second stage – third wall (MW3) will have a 20 cm thermo-insulation system applied, fourth wall (MW4) will be a consolidated version of (MW1) using GeoSteel grid mesh and Helifix bars in the mortar joints, figure 8;

(c) Third stage – the influence of a mesh of polypropylene bands will be studied on the fifth wall specimen (MW5).

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 and third masonry wall specimens will be installed as per producer's requirements [17] regarding the materials used and technology of application. The technology used for the fourth wall specimen is presented in figure 8 and refers to a mesh of steel fibers applied together with an adhesive to the damaged surface of the masonry wall. This application will cover the cracks developed in the wall, without affecting the overall rigidity of the wall, while ensuring a good load transfer. The Helifix bars will be introduced in the horizontal mortar joints and covered with an adhesive substance, thus restoring the continuity of the damaged mortar joint. For the wall panel consolidated using a polypropylene band mesh, previous studies were carried out on structural walls made of unreinforced masonry [18] and tests revealed a considerable improvement of the out-of-plane behavior of the walls, as it can be seen in figure 9. This mesh of polypropylene bands is fitted to the surface of the masonry wall, by means of steel connectors which ensures a tight connection between the two materials and can be later covered with plaster which improves the aesthetical factor. The loading protocol for these wall specimens will be performed in accordance with ECCS provisions, having the reference value e_y multiples and submultiples of the bending resistance of the masonry. All tests will be performed in displacement control, see figure 10, and will have the following values: $\pm e_y/4$, $\pm 2e_y/4$, $\pm 3e_y/4$, $\pm e_y$, $\pm 2e_y$, $\pm 4e_y$, $\pm 6e_y$.

Figure 8. Technology of application of the consolidating materials

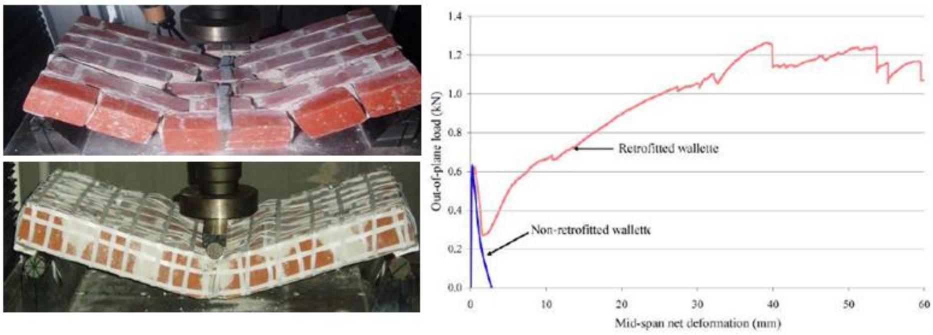

Figure 9. Failure patterns of the tested masonry wallets and out-of-plane load variation [18]

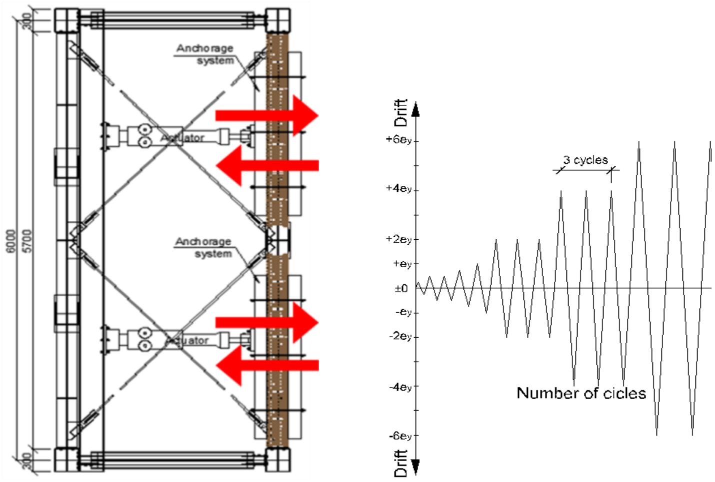

Figure 10. Testing procedure and loading protocol

4. Experimental testing

For the experimental testing of the reference wall (MW1) 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/mm^2. The infill masonry panel was 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 was 56.6 kN, as it can be seen in the graph presented in figure 11.

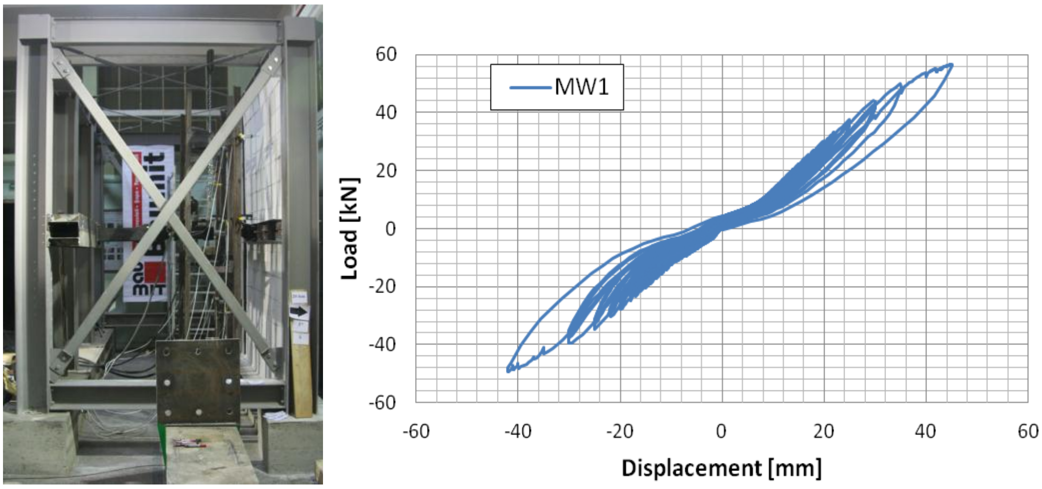

Figure 11. Experimental setup and load-displacement diagram for MW1

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 12.

Figure 12. Experimental setup and opening of horizontal crack in MW1

5. 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 behavior 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 behavior 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. Further investigations must be performed in order to evaluate the effectiveness of the proposed consolidation measures on the out-of-plane behaviour of masonry infill panels.

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