IN-PLANE AND OUT-OF-PLANE RESPONSE OF THE CURRENTLY CONSTRUCTED MASONRY INFILLS

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ABSTRACT

In most of the Reinforced Concrete buildings in Greece, as well as in other earthquake prone countries, the current infill construction, for the exterior walls of the buildings, consists in a cavity masonry wall, made of two thin walls. The two walls are not transversely connected. The seismic vulnerability of those infill walls (to in-plane and out-of-plane actions) is high, as many seismic events have shown.

In the last decades, emphasis was given to the study of Innovative Infill Systems with improved seismic behaviour. The in-plane and out-of-plane behaviour of the (vulnerable) currently constructed masonry infills has not been systematically studied, experimentally and analytically. Within the present work, two full scale RC infilled frames were tested. One was subjected to in-plane cyclic displacements; the second specimen was subjected to repeated out-of-plane displacements, until severely damaged. Hysteresis loops for the entire loading history, the observed damage at several drift values and the overall behaviour of the infill are presented and discussed upon. The obtained results are compared to the results recorded during testing of innovative infill systems. It is shown that the performance of the currently constructed infill system is inferior in terms of both load and deformation capacity.

Keywords: Currently constructed masonry infill; In-plane cyclic tests; Out-of-plane repeated tests; Innovative infill systems

1. INTRODUCTION

Masonry infill walls currently constructed in most European countries are made of clay bricks. Traditionally, but also according to current Codes, masonry infills are considered as non-bearing elements and they are not explicitly taken into consideration in the aseismic design of structures. However, experimental work, numerical calculations and, indeed, numerous seismic events have proven that masonry infills may have a significant effect on the seismic behaviour of RC buildings. This effect depends on several parameters, such as the distribution of the infills (in-plane and in-height), the relative frame-infill stiffness, the infill-RC column interaction, etc. On the other hand, the premature failure of (brittle) infills during an earthquake has a significant economic impact (repair or reconstruction of infills, repair of damages to facilities, plasters, paintings, etc.) (Magenes et al., 2012). The significance of the behaviour of infill walls is recognized by EC8 (EN 1998-1, 2005), where qualitative guidance is included for the protection of infills against premature cracking and failure.

In several earthquake prone countries (e.g. Greece, Italy, Portugal, Turkey) a very vulnerable infill

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system was adopted in the ‘70s. The system consists in a cavity wall, made of two rather thin and transversely unconnected leaves. Although the seismic behaviour of those infills was repeatedly proven to be poor (Figure 1), they are still in use, whereas the available Literature on their behaviour is rather scarce.

This paper presents the results of two full-scale tests on RC frames filled following the currently applied infill system (CIS). This research is motivated by the EU funded project INSYSME. In the framework of that project, two innovative infill walls systems were developed at the Laboratory of Reinforced Concrete, NTUA. It was felt that, to document the preponderance of the innovative systems, their comparison with the behaviour of the currently applied system was necessary. As to the best of the authors knowledge-there are no published data on the behaviour of the CIS, the current experimental program was conducted.

![Figure 1. (a) In-plane and (b) out-of-plane failure of infill walls during earthquake.](image)

2. LITERATURE SURVEY

The Literature is quite rich in experimental results obtained from testing small or large scale RC or steel infilled frames. Actually, significant effort was devoted to the subject-in recognition of its significance for the seismic behaviour of buildings-both in testing and in modeling. A vast variety of masonry units, either in material (clay bricks, concrete blocks) or in geometry and pattern of perforations were used in testing infilled frames. Furthermore, various ratios of frame to infill stiffness were examined, along with various Codes applied for the design of the frame (sub-standard or conform to current Codes), in order to investigate the effect of infills to the surrounding frame elements. It seems though that a large number of experimental investigations were performed on monotonically loaded infilled frames (see i.a., Thomas, 1953, Holmes, 1963, Stafford-Smith, 1968, Zarnic and Tomazevic, 1984). More recently, the behaviour of infilled frames subjected to cyclic in-plane loads or displacements was investigated. To this purpose, scaled specimens were tested (e.g. Mehrabi et al., 1994-scale 1:2, Valiasis and Stylianidis, 1989, Manos et al., 1993, Altin et al., 2007, Yuksel et al., 2010-scale 1:3, Manos et al., 1993-scale 1:9). Several investigations focus on the development of innovative infill systems (Tasligedik et al., 2012, www.insysme.eu), on masonry made of large width clay bricks (Penna et al., 2008), or on repair and strengthening of existing infill walls (Altin et al., 2007, Yuksel et al., 2010, Kyriakides, 2011, Pujol et al., 2008). The available literature related to the out-of-plane behaviour of masonry infills is not as rich as for their in-plane behaviour. In a number of investigations the out-of-plane behaviour of bare masonry walls is investigated (Griffith and Vaculik, 2005, Vintzileou and Palieraki, 2007, da Porto et al., 2010, Papanicolaou et al., 2011), or thick masonry infills are tested (Hak et al., 2014).

Last but not least, several full-scale tests (either cyclic or repeated) were performed on infilled frames
in- or out-of-their-plane, within the Project INSYSME. In the framework of this project, aiming at the development of innovative infill systems, NTUA has developed two infill systems, in cooperation with the Greek brick manufacturing industry XALKIS S.A. Data on the performance of those two systems (both granted with a patent by the Greek Patent Office) can be found elsewhere (Vintzileou et al., 2016, 2017a, 2017b).

Although rich and conclusive in many aspects, the available literature does not provide any information about the seismic behaviour of the cavity infill walls, still constructed in several earthquake prone countries.

3. EXPERIMENTAL PROGRAMME

It is reminded that the current infill construction for perimeter walls (CIS) consists in a cavity masonry wall. The exterior leaves (typically, 90mm thick), transversely unconnected, leave a space where the insulating material is accommodated, along with sliding doors and windows. As a means for the improvement of the behaviour of this type of enclosures, a RC tie beam is typically constructed at mid-height of perimeter infill walls, providing some extra bearing capacity to the area diagonal cracks are expected to occur. However, as RC tie-beams are constructed independently to each exterior leaf, they do not provide any transverse connection to them. Furthermore, those enclosures are not fixed to the surrounding RC frame.

This system was reproduced in the full-scale specimens tested within the present work (Figure 2). More specifically, a reinforced concrete frame was designed according to EC8-Part1 (EN 1998-1, 2005) (Figure 3). To investigate the in-plane seismic behaviour of the CIS, a cavity infill wall was constructed within the frame (Figure 2). Each leaf (90mm thick) was made of horizontally perforated clay bricks. A general purpose cement-lime mortar, classified as M1-M2 (EN 1996-1-1, 2005) was used ($f_{m}=0.85-1.50$MPa, $f_{m,fl}=0.40-0.80$MPa) for the construction of the infill. Perpendicular mortar joints were filled. Each leaf (3.0m long and 2.3m high) was provided with a RC tie beam (90mm thick, 120mm high) approximately at its mid-height. The reinforcement of the tie beam consists in one longitudinal bar (8mm diameter, characteristic yield strength=500MPa, located at mid-width of each leaf). After completion of the in-plane test, the failed infill was removed and the frame was filled again with a wall that was tested out-of-its plane. In this case, only one leaf (and not the entire cavity wall) was constructed. Actually, as no connection is provided to the two leaves, each of them behaves independently from the other.

It should be noted that no damage due to RC frame-infill interaction was observed during testing. Limited cracking of RC members was recorded. However, this aspect of the experimental results is not presented here, as this paper focuses on the behaviour of the infill wall.

3.1 Test setup

3.1.1 In-plane tests

Figure 4a shows the test setup used for the in-plane tests: The RC frame is provided with a strong footing, which is fixed to the strong floor of the laboratory. A servo-controlled hydraulic actuator (maximum capacity: ±1000kN), supported by a stiff steel frame, was used. The actuator applies horizontal in-plane cyclic displacements at mid-height of the beam. The columns of the frame are not axially loaded.

3.1.2 Out-of-plane tests

The test set-up consists in a steel frame, designed to comply with the requirement of significant stiffness and, hence, of minimal deformations during testing. A hydraulic jack (capacity ±500kN) is connected to a steel system with multiple hinges (Figure 4b), allowing for (as uniform as possible)
application of deformations to the infill wall. During testing, the RC frame was transversely supported and repeated loading was applied to the infill alone. The test was displacement-controlled.

Figure 2. (a) Construction of the Current Infill System, preparation for the construction of the RC tie-beam (b) The infilled frame in position for in-plane testing.

Figure 3. (a) The reinforcement of the RC frame, designed according to EC8 (EN 1998-1, 2005), (b) Section of the beam and the column of the RC frame.

Figure 4. Test setup used for (a) in-plane and (b) out-of-plane tests.
3.2 Instrumentation and Test protocol

Figure 5a shows the instrumentation of the specimen tested in its plane. The resistance of the specimen to the imposed displacements was measured by a load cell, whereas twenty six (26) displacement transducers (LVDTs) were installed to record absolute and relative displacements (e.g. the lengthening/shortening of the diagonals of the infill, the relative displacement at infill-frame interface, the relative displacement between the RC tie beam and the infill, etc.). Strain gauges were positioned on the reinforcing bar of the RC tie.

The CIS specimen is subject to stepwise increasing imposed horizontal displacements. Three full displacement cycles are imposed for each preselected value of maximum displacement.

In case of out-of-plane test, twenty seven (27) measuring devices were installed at various locations (Figure 5b) to record the deformations of the infill, the differential out-of-plane deformation at infill/frame interface and at infill/RC tie-beam interface, etc. In this case, repeated out-of-plane deformations were imposed to the infill. The mobilized resistance was measured by a dynamometer incorporated to the hydraulic jack.

The imposed displacement (measured at the centre of the infill, LVDT N°3 in Figure 5b) was increased stepwise. Three cycles were performed at each maximum displacement level.

![Diagram](image)

Figure 5. Instrumentation: (a) In-plane test, (b) Out-of-plane test.

4. TEST RESULTS

4.1 In-plane cyclic response

The main results of the in-plane tests carried out on the CIS specimen are shown in the following Figures. The test was concluded after the occurrence of non-repairable damages to the infill associated with a degradation of resistance larger than 20%.

The hysteresis loops for the infilled frame are shown in Figure 6a. A maximum lateral resistance equal to 500.0kN was recorded at a drift value of approximately 1.10%. The test was concluded soon after the attainment of the maximum resistance, at a drift value approximately equal to 1.60%. Actually, a steep falling branch (typical for brittle behaviour) was recorded. The force-response degradation due to cycling was approximately equal to 20% between the first and the second cycle (Figure 6b). Practically no further degradation occurred during the third loading cycle.
Figure 6. In-plane test: (a) Hysteresis loops, (b) Normalized resistance vs. displacement envelopes.

Figure 7. Deformations along the diagonals, plotted against the imposed displacement.

The deformation along the diagonals of the infill (Figure 7) reached values as large as 25-30mm. While the elongation of a diagonal is due exclusively to the opening of cracks (as the tensile deformation of masonry is minimal), the shortening of the diagonals includes the closing of the cracks, the compressive deformations of masonry and, at more advanced stages of loading, the deformations due to the cracking and failure of bricks.

The significant contribution of sliding between masonry wall and RC tie-beam, an important characteristic of the CIS, is depicted in Figure 8a, where the deformations measured by the LVDTs 25, 26, 11 and 17, are shown. LVDTs 25 and 26 are measuring the relative displacement between the RC tie beam and the infill, in the upper and the lower part of the RC tie beam respectively. LVDT 11 is measuring the relative displacement between the RC beam and the infill wall, while LVDT 17 is measuring the relative displacement between the RC footing and the infill wall. The data plotted in Figure 8a show that horizontal sliding takes place between the RC tie-beam and the infill (D25 and D26), as well as between the infill and the RC beam (D11) and the infill at its base (D17). It is interesting to observe that the portion of the infill between the RC tie-beam and the beam of the frame seems to move as a solid body (compare the measurements of measuring devices D25 and D11). The same holds true for the lower portion of the infill, between the RC tie-beam and the base, as the
comparable values of horizontal sliding measured by D26 and D17 show. Obviously, the upper portion of the infill moves more than the lower one. It seems that the sliding between the tie-beam and the infill is initiated at low drift values. This observation is in accordance with the measurements provided by the strain gauges installed on the tie-beam reinforcement (Figure 8b): The strain at the reinforcement did not exceed 0.2‰, showing the rather low degree of mobilization of the tie-beam and, hence, its limited contribution to the lateral resistance of the infilled frame.

On the contrary, as shown in Figure 9, the presence of the tie-beam drastically modifies the failure mode of the infill wall. Actually, horizontal cracks occur along concrete to masonry interfaces, for small values of the imposed drift. This failure mode is typical for infill walls with RC tie-beam (Vintzileou and Palieraki, 2007). From then on, significant sliding takes place along those horizontal interfaces (see Figure 8a), although this sliding does not prevent the opening of bi-diagonal cracks at larger drift values. The significant contribution of the shear-sliding mode to the behaviour of the infill (due to the RC tie-beam) may adversely affect the behaviour of the adjacent RC columns. Actually, it may impose an additional shear force to the columns close to their mid-height, a location where the shear reinforcement is not as closely spaced as within the critical regions (close to the ends) of the columns. It has to be admitted though that such a negative effect on the columns was not observed during this test, as cracking and spalling of bricks (Figure 9 and 13a) led to the completion of the test at a rather small value of drift.

Figure 8. (a) Sliding along interfaces between the infill and the frame or between the infill and the RC tie-beam, (b) Force vs. strain of the reinforcing bars curves for the tie-beam of the CIS wall.

Figure 9. In-plane tests. Crack pattern at various drift values: (a) d=0.2%, (b) d=1.10% (at maximum lateral resistance), (c) d=1.57% (at maximum imposed drift).
4.2 Out-of-plane response

This section summarizes the results of the out-of-plane test of the infill. Its maximum resistance was equal to 75.6kN; it was mobilized for a deflection value (measured at the centre of the wall, D3) equal to 30mm. The maximum deflection imposed to the infill was equal to 60mm. The force-response degradation between the first and third cycle was approximately equal to 15%. At the maximum imposed deflection, a force-response loss of 30% to 50% (compared to the maximum resistance) was recorded (Figure 10).

Interesting features of the out-of-plane behaviour of the infill are illustrated by the distribution of deflections along the length and the height of the infill (Figure 11), as well as by the crack pattern (Figure 12). Actually, it seems that the infill panel behaves like a slab loaded by a uniformly distributed load, as demonstrated by the “yield lines” of Figure 12. However, early separation between the infill and the RC tie-beam was also recorded. Those observations are confirmed by the profile (both horizontal and vertical) of the deflections (Figure 11a and b). It should be pointed out though that, as the RC frame was transversely fixed and, hence, not moving out of its plane, the displacements measured close to the interfaces between the infill and the RC elements show that the infill was slipping out of the frame, along the separating cracks formed for rather small values of the imposed deflection.

![Figure 10](image1.png)

**Figure 10.** Out-of-plane tests: (a) Hysteresis loops, (b) Normalized resistance vs. displacement curves.

![Figure 11](image2.png)

**Figure 11.** Out-of-plane tests: (a) Deflections along the height, measured at mid-length of the infill, (b) Deflections along the length, measured at mid-height of the infill, (c) Deflections along the length, measured by D14, D3 and D9 (Figure 4) above the RC tie-beam.
Figure 12. Out-of-plane tests. Crack pattern of the CIS specimen at various deflection values: (a) defl.=5mm, (b) defl.=30mm, at maximum resistance, (c) defl.=60mm, maximum imposed deflection.

Figure 13. Cracking of the CIS specimen at the end of testing (a) In-plane, (b) Out-of-plane.

5. COMPARISON WITH THE BEHAVIOUR OF INNOVATIVE SYSTEMS

Figure 14a presents the hysteresis loops envelope obtained from in-plane testing of an RC frame filled with a cavity infill wall (CIS). For the sake of comparison, the hysteresis loop envelopes for two innovative systems are plotted in the same Figure 14a. In INSYSTEM1, the infill wall was separated into three wallettes, by means of vertical joints, constructed using a mortar of reduced modulus of elasticity, to allow for increased deformations along the predetermined planes between consecutive wallettes (Vintzileou et al., 2016). In INSYSTEM2, the infill is horizontally and vertically reinforced. For the construction of INSYSTEM2 infills, the innovative brick units designed and produced on purpose were used (Vintzileou et al., 2017a). It should be noted that in INSYSTEMS1&2, infills consist of single leaf 250mm and 280mm thick respectively, made of vertically perforated clay bricks.

As long as it regards the in-plane behaviour, one may observe that the proposed infill systems, namely INSYSTEM1 and INSYSTEM2, were quite efficient, as they led to significant increase of the maximum drift values underwent by the respective infilled frames, as well as to increase of the drift values corresponding to damage that can be considered as non-repairable. Actually, the value of drift for which the maximum load is recorded is approximately equal to 1.10% for the CIS, 1.85% for INSYSTEM1 and 2.70% for INSYSTEM2. It is also to be noted that an acceptable force-response degradation on the falling branch (by approximately 20%) occurs at imposed of 2.60% and 3.60% for INSYSTEM1 and 2 respectively. The respective drift value for CIS is equal to 1.60%.

As long as it regards the out-of-plane behaviour, the preponderance of the reinforced infill is obvious in terms of combined bearing capacity and deformability (Figure 14b). Both innovative systems exhibited significant out-of-plane resistance, in contrast to the CIS. The latter was, on the other hand, able to sustain large deformations.
6. CONCLUSIONS

The paper presents the results of full scale testing of the Current Infill System (CIS), which is used in Greece as well as in other earthquake prone countries. The current infill construction consists in a cavity masonry wall, made of two thin, transversely unconnected exterior leaves. The tests results are compared with those obtained from testing innovative infill systems.

On the basis of the results of the experimental work presented in this paper, the following conclusions can be drawn:

1) The currently used system exhibits a rather poor in-plane behaviour. Actually, it underwent significant damages under low drift values (1.10%) and it suffered significant force-response degradation at a drift value of 1.60%. Due to the fact that in the RC frame only minor damage occurred, the limited drift values are due to the behaviour of the infill wall.

2) The Current Infill System (CIS) was able to sustain large out-of-plane deflection; its resistance was, however, quite low.

3) It has to be admitted that further research on the Current Infill System is needed. Actually, as numerous earthquakes have shown, the main disadvantage of this system is its poor behaviour under combined in- and out-of-plane actions. On the contrary, biaxial shaking table tests on RC frames infilled according to INSYSTEM1 (to be presented elsewhere, not yet published) and INSYSTEM2 (Vintzileou et al., 2017b) exhibited a very good behaviour.

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8. REFERENCES


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