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IN-PLANE AND OUT-OF PLANE RESPONSE OF A REINFORCED MASONRY INFILL MADE BY AN INNOVATIVE NEW BRICK UNIT

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Abstract

Within the framework of INSYSME project (www.insysme.eu) [1], an innovative solution for infill walls has been developed by the authors and the firm XALKIS S.A. A special, vertically perforated, brick unit has been designed and produced. Vertical holes are located close to the faces of the masonry unit, to serve two needs, namely (a) the enhancement of the out-of-plane bearing capacity of the infill, using vertical reinforcement and (b) the positioning of installations (electrical and plumping). In the current practice of infill wall construction in Greece, all facilities are installed on the walls by forming the necessary recesses through breaking of the clay units. Such a (quite extensive, even though local) intervention is avoided, thanks to the use of the designed clay unit. It should be noted that the vertical reinforcement is positioned only to a limited number of vertical holes along the infill wall, as the required percentage of reinforcement is rather small. Therefore, the brick was constructed not to have open vertical holes close to the faces of the infill, because they should be filled with mortar to reach a plane surface of the wall before plastering. However, in order to facilitate both the positioning of vertical reinforcement and the installation of facilities, the exterior shell of each vertical hole is provided with two grooves that make the exterior brick wall easy to remove during construction.

The horizontal reinforcement of the infill is positioned in the bed joints during the construction of the wall, whereas the vertical reinforcement is placed (in the special vertical holes) after the construction of the wall. Additionally, simple sliding connectors between the infill and the beam above it may be used to prevent out-of-plane collapse, if needed. It should be noted that the reinforcement (either horizontal or vertical) is not anchored into the RC elements.

In order to assess the performance of the proposed solution, an experimental campaign is carried out on a one-bay single-storey RC infilled frame. Two full scale specimens are tested. The first is subjected to in-plane cyclic tests, whereas for the second one repeated out-of-plane test are performed. Hysteresis loops for the entire loading history, the observed damage at several drift values and the maximum resistance of the infill are presented and discussed upon. The obtained results are compared to the results recorded during testing of the infills currently used in Greece. It is shown that the performance of the innovative solution minimizes damage risk and human lives risk, as it ensures a significantly enhanced behaviour of the RC-infilled frame in terms of both load and deformability capacity.

Keywords: infilled frame; new brick unit with special vertical cavities; horizontal and vertical reinforcement; in-plane cyclic tests; out-of-plane repeated tests

1. Introduction

Brick masonry infills, widely used as enclosures to RC buildings, offer an economic and durable solution, as they may ensure adequate insulation properties, whereas they contribute to the seismic behaviour of the structural system. Traditionally, enclosures and partition walls in RC structures are considered as non-structural elements and, thus, they are not explicitly taken into account in the aseismic design of buildings.

It is well known that theory and practice have repeatedly proven that masonry infills may affect in a positive way the seismic behaviour of buildings, provided that possible negative structure-infill interaction is avoided [2]. This fact is recognized by current Codes for Earthquake Resistant Design either explicitly or implicitly. Thus, according to EUROCODE 8 [3], infills are taken into account when assessing the in-plane and in-height regularity of the structure, whereas design and detailing rules are given with the aim to avoid brittle failure of adjacent to infills RC columns, as well as extensive damage of the infills themselves.

On the other hand, the behaviour of the infills themselves is significant both from the Public safety and economy point of view: Failure of infill walls may cause injuries or even casualties, whereas extensive damages of infills (caused by earthquakes with a smaller return period than the design one) have a significant economic impact (repair or reconstruction of infills, repair of damages to facilities, plasters, painting, etc) [4]. In recognition of this fact, EC8 [3] includes (qualitative) guidance for the improvement of the seismic behaviour of infill walls. Quantification of the EC8 [3] rules, as well as innovative infill systems-fully documented through experiments and analysis-is the aim of the EU-funded project INSYSME.

In the framework of INSYSME project, one of the two innovative solutions for infill walls developed by the authors and a brick manufacturing industry, INSYSTEM 2, aims at enhancing the in-plane and out-of plane deformability of the infill wall. The infill, which is not fixed to the elements of the surrounding RC frame, is horizontally and vertically reinforced. The innovation of the systems lies in the design (jointly by NTUA and the the firm XALKIS) of a multi-purpose vertically perforated brick unit.

Although the idea of reinforcing the infill wall is quite common, the use of the available on the market vertically perforated bricks allows for positioning of the horizontal reinforcement, whereas (as the infill is constructed after the completion of the RC structure) only external vertical reinforcement can be provided to the infill [5], [6], [7], [8], [9]. The system developed at NTUA allows for efficient positioning of both horizontal and vertical reinforcement within the thickness of the infill, whereas the construction process does not lead to significant increase of the construction time and cost.

It should be noted that the current practice in Greece, as well as in other European countries, regarding infills has proven to lead to very vulnerable enclosures: Cavity brick masonry walls are constructed. The typical thickness of each leaf is equal to 90mm. The space between the two leaves is used to accommodate insulation and, alternatively, sliding doors and windows. The two leaves are transversely unconnected, whereas, typically, a RC tie beam at mid-height of perimeter infill walls [10].

This paper presents details of the developed solution together with experimental results on the behaviour of INSYSTEM 2 against in-plane cyclic and repeated out-of-plane actions. In order to further document the advantages of the proposed system, the obtained experimental results are compared with the behaviour of the typical infill system currently applied in the country (Current Infill System-CIS).

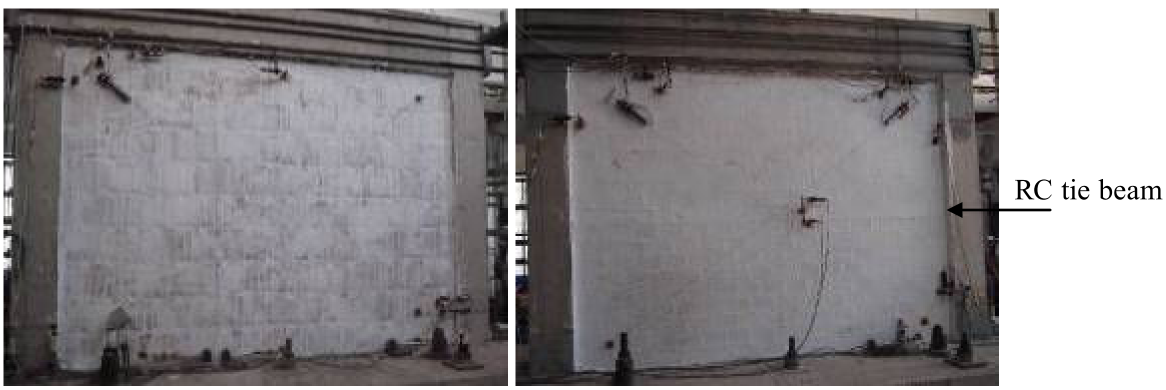
2. Construction Technique

2.1 Developed INSYSTEM 2

INSYSTEM 2 consists in a single leaf clay masonry infill (Fig. 1a). A mortar joint is provided along the surrounding infill-to-RC concrete interfaces. The enclosure is not fixed to the RC frame elements.

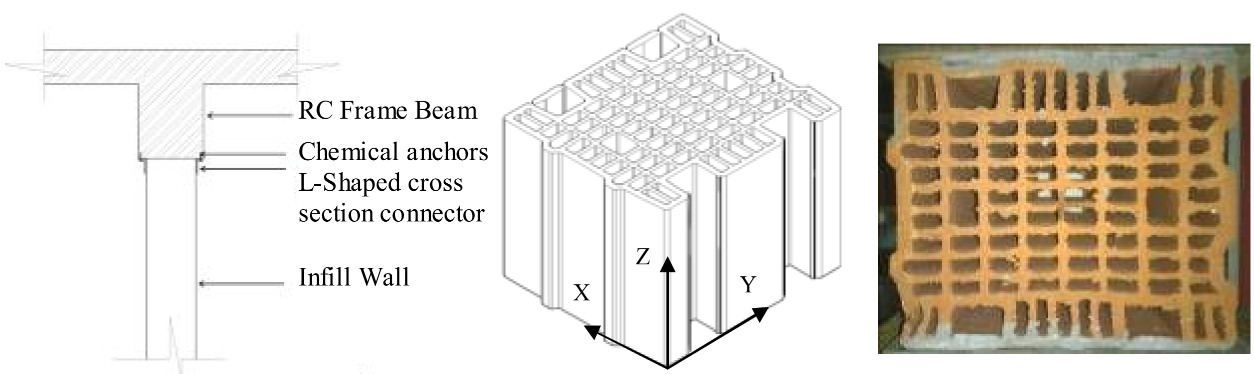
INSYSTEM 2, in which the infill is horizontally and vertically reinforced, depending on the percentage of the reinforcement that is used, may be applied in medium to high seismicity areas. The reinforcement (horizontal and vertical) is calculated in accordance with the performance criteria set by the Designer (based on serviceability and ultimate limit state criteria). To serve the purpose of the system, a special unit was designed by

NTUA and XALKIS (Fig. 2a). The horizontal reinforcement is positioned in the bed joints during the construction of the wall, whereas the vertical reinforcement is placed in vertical holes after the construction of the wall. The vertical holes are located close to the faces of the masonry unit, to serve two purposes, namely the (a) enhancement of the out-of-plane bearing capacity of the infill and (b) the positioning of installations (electrical and plumping). It should be noted that in CIS construction, all facilities are installed on the walls by forming the necessary recesses through breaking of the clay units. This procedure that reduces practically without control (as far as the locations and the extent of bricks breakage) the thickness of infills is avoided, thanks to the use of the designed clay unit. It should be noted that the vertical reinforcement is positioned only to some of the vertical holes along the infill wall, as the required percentage is rather small. Therefore, the option was selected not to have open vertical holes close to the faces of the infill, because they should be filled with mortar to achieve a plane surface of the wall before plastering. However, in order to facilitate the positioning of vertical reinforcement, as well as the installation of facilities, the exterior shell of each vertical hole is provided with two grooves that make the exterior wall of the large vertical holes easy to remove during construction. The thickness of the vertically perforated masonry units is equal to 250mm. The compressive strength along the two horizontal axes of the unit is adequate, in order for the wall to be able to sustain high in-plane deformations and not to fail prematurely against out-of-plane actions (Table 1). It is noted that, even though the designed unit has grooves and tongues, the head joints are filled with mortar.



(a) (b)

Fig. 1 – (a) The infill wall constructed with the new brick (INSYSTEM 2), (b) The CIS wall.



(a) (b)

Fig. 2 – (a) L- shaped cross section connectors with chemical anchors (b) Brick unit.

For the construction of the infill walls, a typical general purpose cement-lime mortar, classified as M2-M3 (EN 1996, [11]) was used. The mortar, used to both bed joints and vertical joints of the infills, ensures good bond with the masonry units. Moreover, due to the presence of lime, it has adequate workability and plasticity. In order to fill cavities were the vertical reinforcement is placed, a cement mortar is used. The main mechanical properties of the mortars used for the: a) construction of the walls, b) the special mortar for the cavities in INSYSTEM 2, are presented in Table 2. Their compressive and flexural strength was determined according to the EN196:1:1994 [12]. Tests were carried out at the age of testing the infilled frames.

The out-of- plane collapse of the wall is prevented using simple sliding steel connectors (Fig. 2b). The positioning of those connectors depends on the aspect ratio of the infill. Actually, for normal storey heights, resulting to rather limited slenderness of the infill walls, the use of connectors may not be needed.

It is noted that the specimen constructed to be tested under in-plane actions is only horizontally reinforced (ρ=0.35%), while the specimen constructed to be tested to out-of-plane actions is provided with both vertical (ρ=0.75%) and horizontal reinforcement (ρ=0.35%). The horizontal reinforcement, located at every other mortar joint, consists in prefabricated trusses (Murfor RND). The bed joint reinforcement consists of two parallel wires, 5mm diameter, welded together with a continuous truss wire of 3.75mm diameter. The distance between the two parallel wires is equal to 200mm. The vertical reinforcement (consisting in 8mm diameter B500C bars) is placed in both sides of the infill wall.

Table 1 – Mechanical properties of the brick unit

Compressive strength along axis (MPa)		
X-X	**Y-Y**	**Z-Z**
1.50	3.20	5.70

Table 2 – Physico-mechanical properties of mortar

Type of mortar	**f_{mc} [MPa]**	**$f_{m,fl}$ [MPa]**	**ρ [kg/m^3]**
	Range	**Range**	**Range**
Construction of walls	2.0-3.5	0.5-1.1	1.80-1.90
Special mortar for INSYSTEM 2 (i.e. for vertical cavities)	10.0-12.0	2.8-3.5	1.85

2.2 Current Infill System (CIS)

The current infill construction (Fig. 1b) consists in a cavity masonry wall. In real structures, in the space between the two leaves, the insulating material is accommodated, with the exception of regions close to openings. There, the cavity is used to accommodate sliding doors and windows. In the specimen constructed for the in-plane tests, the space between the two leaves is not filled. Each leaf is reinforced by means of a RC tie beam. The tie beam is reinforced with 1 bar, 8mm diameter, positioned in the middle of the section. In the specimen for the out-of-plane tests, only the one leaf is constructed, given that the two leaves are not connected, and, hence, each one behaves independently from the other.

3. Experimental Programme

The behaviour of the two types of infills, namely, of INSYSTEM 2 and of the CIS, was investigated experimentally through in-plane cyclic and repeated out-of-plane tests. In total, 4 full scale specimens were constructed and tested. The dimensions of the infills were approximately equal to 3.00x2.30 [m^2]. In the following sections, the test setup, the instrumentation and the test protocol are presented. Subsequently, the test results (i.e. the hysteresis loops for the entire loading history, the observed damage at several drift values and the maximum resistance of the infills) are presented and discussed upon. Finally, a comparison of the response of the two systems is attempted. It should be noted that no damage due to RC frame-infill interaction was observed during testing. Limited cracking of RC members were recorded. However, this aspect of the experimental results is not presented in this paper that concentrates on the behaviour of the infill walls.

3.1 Test setup

3.1.1 In-plane tests

Figure 3a shows the test setup used for the in-plane tests. Horizontal cyclic displacements are imposed at mid-height of the top RC beam. A hydraulic jack (maximum capacity: ±1000kN), supported by a strong steel frame, was used. The RC frame is provided with a strong footing, which is fixed to the strong floor of the laboratory hall. During the execution of the tests, no axial load was applied to the columns of the RC frame. It is noted that the same frame was used for all four tests, as (according to its design) it underwent limited damage during testing.

3.1.2 Out-of-plane tests

For the out-of-plane repeated tests, a stiff steel structure (Fig. 3b) was designed, able to distribute actions more or less uniformly on the tested infill. In this case too, displacement controlled tests were performed, using a hydraulic jack (maximum capacity: ±500kN).

(a) (b)

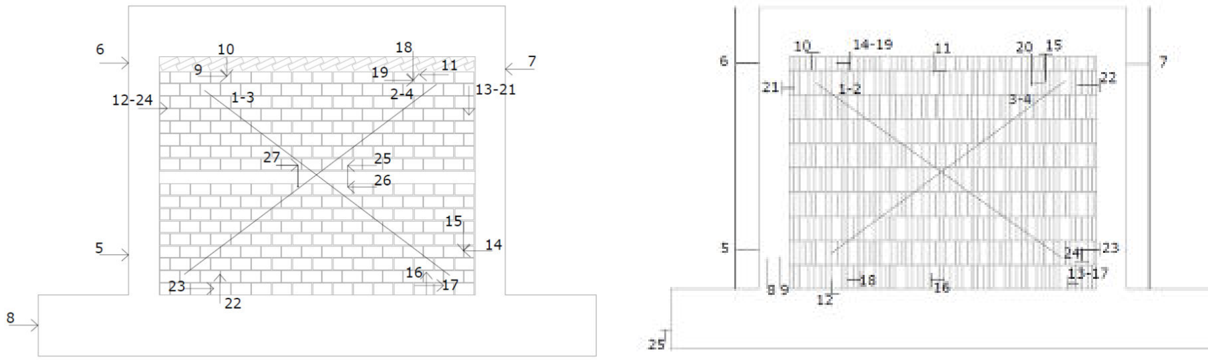
Fig. 3 – Test setup used for (a) in-plane and (b) out-of-plane tests.

3.2 Instrumentation and Test protocol

3.2.1 In-plane tests

Figures 4a and 4b present the instrumentation for the in-plane tests, for the CIS and INSYSTEM 2, respectively. The resistance of the infilled frame to the applied displacements was measured by a load cell, whereas more than 25 displacement transducers (DT) were positioned at several locations to record absolute or relative displacements, on both faces of the infills. The position of the DTs differs from specimen to specimen, depending on the specific characteristics of each system. There are, however, measurements common to the two systems, namely, the overall deformation of the two diagonals of the infill, the relative displacement at infill-frame interface, the horizontal displacement of the infilled frame at mid-height of the upper beam, etc. In the INSYSTEM 2 specimens, the strains of the vertical and the horizontal reinforcement are measured, while in the CIS specimens, the strains of the reinforcement of the RC tie beam are measured. The relative displacement between the RC tie beam and the infill is also recorded.

Both CIS and the developed infill INSYSTEM 2 are subject to stepwise increasing imposed horizontal displacements. Three full displacement cycles are imposed for each preselected value of maximum displacement.



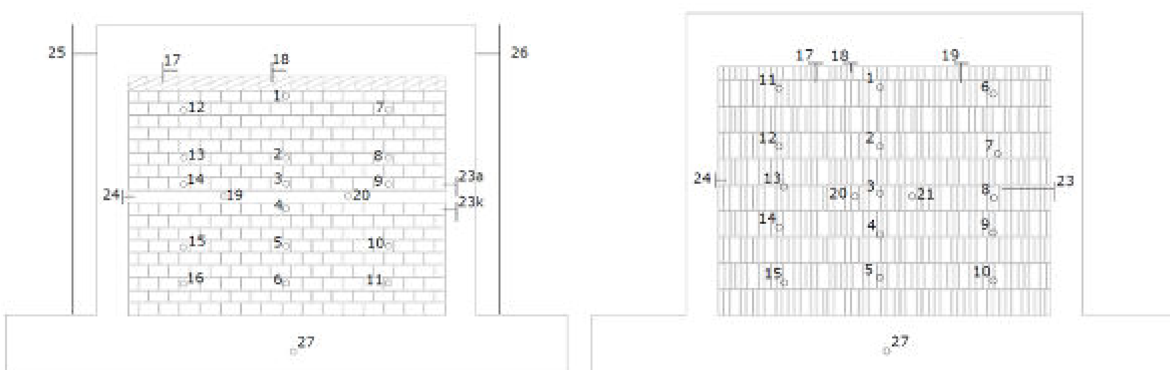
(a) (b)

Fig. 4 – In-plane tests. Instrumentation setup used for the (a) CIS and (b) INSYSTEM 2 specimens.

3.2.2 Out-of-plane tests

Out-of-plane displacements were measured at different locations, as shown in Figure 5.

The specimens are subject to stepwise increasing repeated displacements. Three cycles are imposed at each level of preselected values of maximum displacement. It is noted that the control displacement was that measured at mid-height of the infill wall (measuring device 3).



(a) (b)

Fig. 5 – Out-of-plane tests. Instrumentation setup used for the (a) CIS and (b) INSYSTEM 2 specimens.

4. Test Results

4.1 In-plane cyclic response

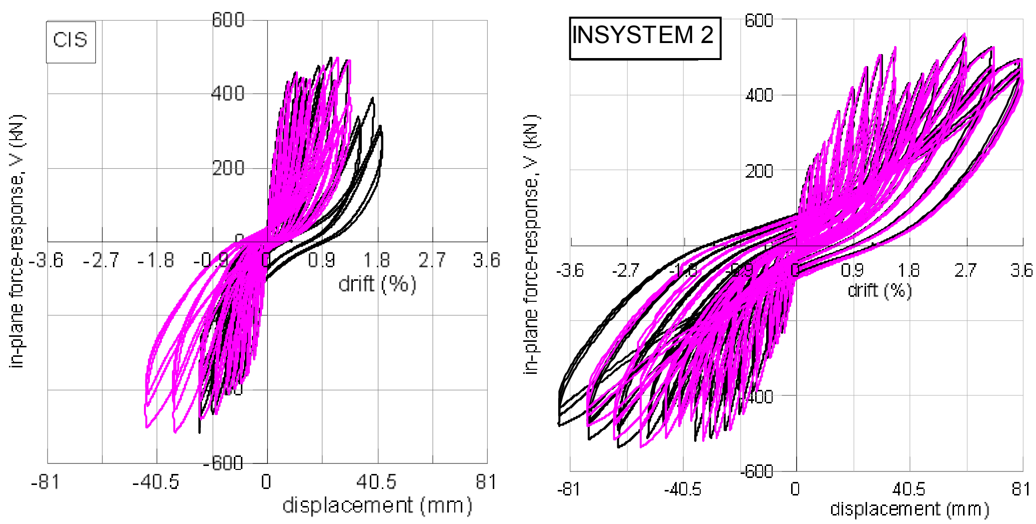
The main results of the in-plane tests carried out on the two infilled frames are shown in Figures 6-8. For the CIS, hysteresis loops, force vs. displacement envelopes and crack patterns at several drift values are presented in Figures 6a, 7a and 9. The same results are shown for INSYSTEM 2 in Figures 6b, 7b and 9. It is noted that, the tests were concluded after the formation of non-repairable damages to the infills associated with a degradation of resistance larger than 20%.

4.1.1 CIS

It is noted that the contribution of the RC frame to the lateral resistance of the system is included in the hysteresis loops shown in Fig. 6a. For the CIS, the maximum resistance was equal to 500.0kN and it corresponds to a drift value of the order of 1.10%. A force-response degradation of approximately 20% was recorded during the third cycle (Fig. 7a), at the same imposed drift. The maximum drift applied to the specimen was approx. equal to 1.57%. After the maximum resistance was reached, a relatively steep falling branch followed. This suggests a quite brittle response for the CIS.

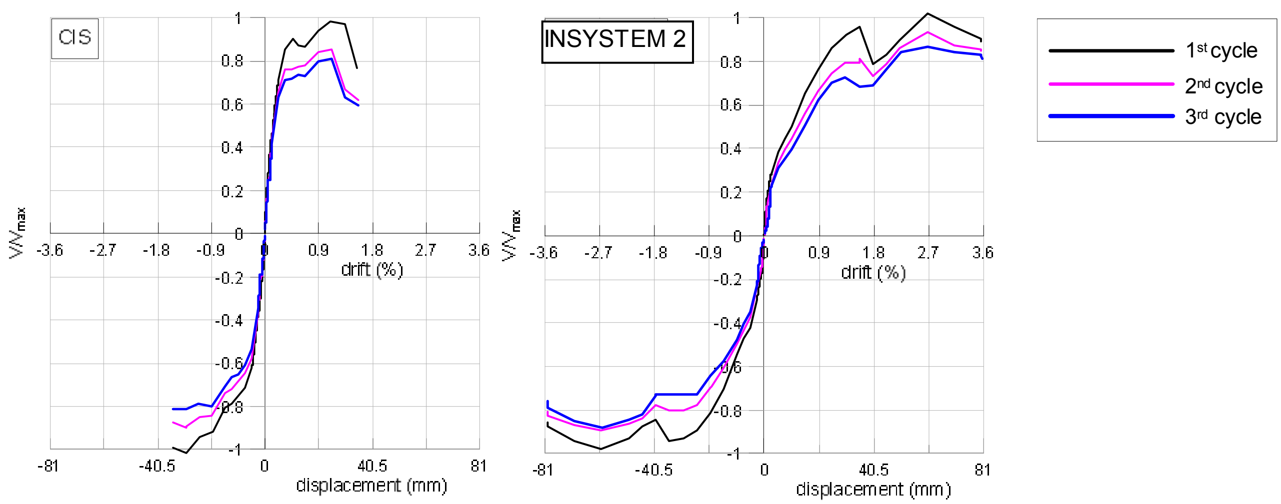
In Figure 8a, a plot of force-response vs. strains of the bars used for the reinforcement of the RC tie beam is provided for the CIS. It is observed that the maximum absolute value of strain of the bars is almost equal to 0.2‰, hence, significantly lower than the yield strain of steel.

Figure 9 shows the damage occurred to the CIS for various values of the applied drift (i.e. at 0.2%, at the drift corresponding to the maximum resistance and at the maximum drift applied to the specimen). For small values of the imposed drift, a detachment of the infill from the RC frame occurs, as well as a detachment of the RC tie beam from the wall. In fact, the RC tie beam at mid-height of the infill modifies the failure mode (from diagonal cracking to shear sliding along a horizontal joint). This is a failure mode that may adversely affect the behaviour of the RC columns, adjacent to the infill. For larger values of the applied displacement, extensive diagonal cracking is also observed. Close to the maximum applied drift value, extensive cracking and spalling of a significant portion of bricks is observed.



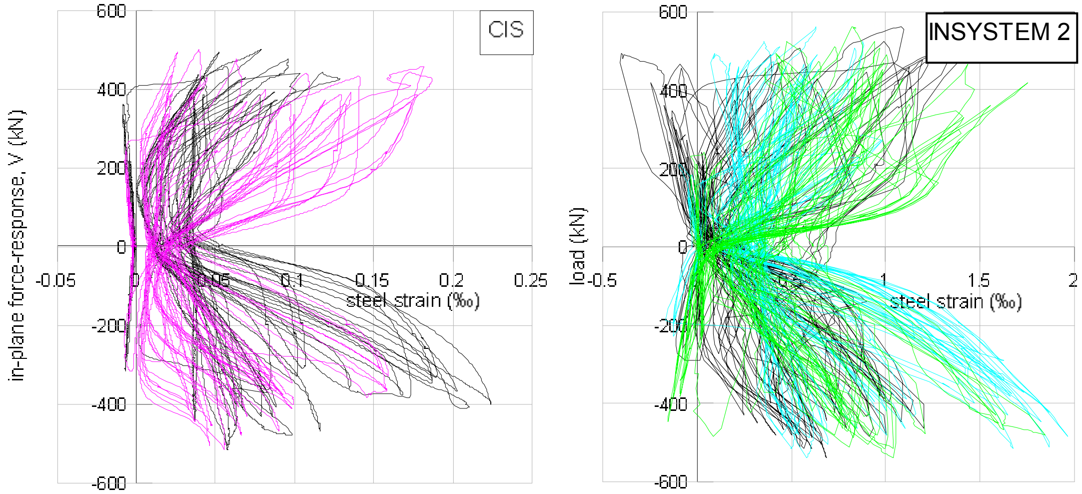
(a) (b)

Fig. 6 – In-plane tests. Hysteresis loops for the (a) CIS and (b) INSYSTEM 2 specimens.



(a) (b)

Fig. 7 – In-plane tests. Normalized resistance vs. displacement envelopes for the (a) CIS and (b) INSYSTEM 2 specimens.



(a) (b)

Fig. 8 – In-plane tests. Force vs. strain of the reinforcing bars curves for (a) CIS wall and (b) INSYSTEM 2 (measured at mid-height of the infill).

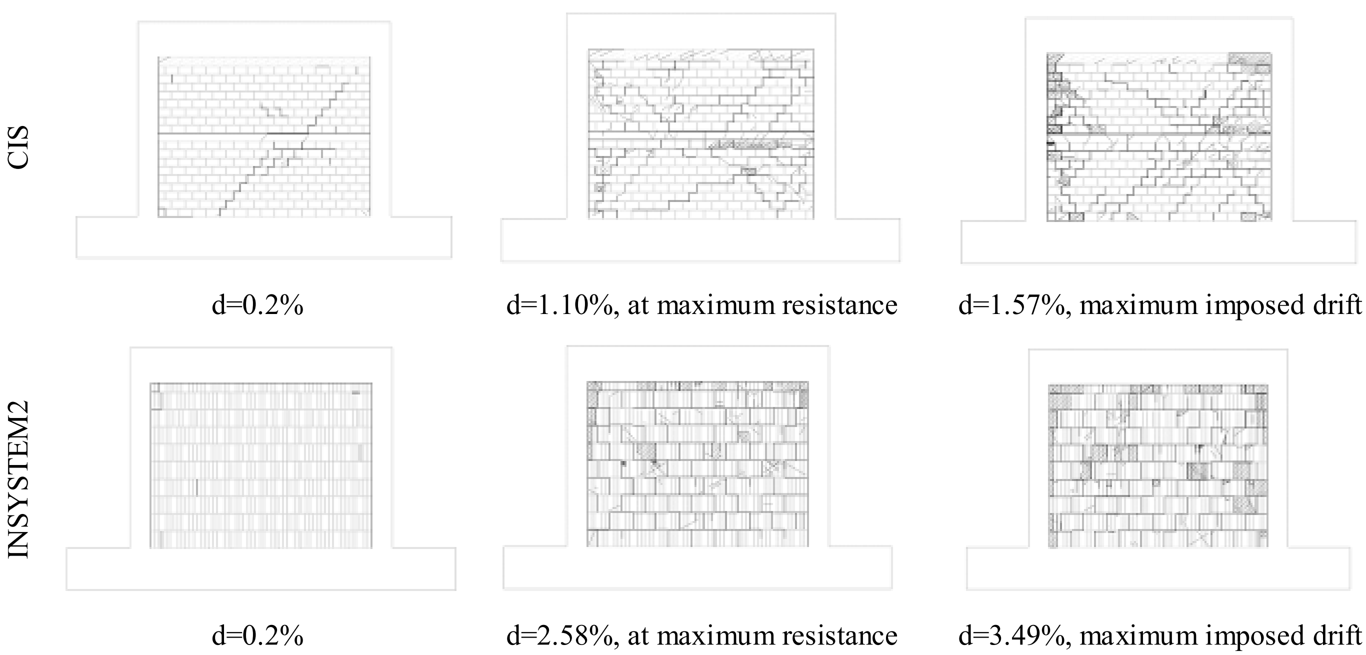


Fig. 9 – In-plane tests. Crack pattern of the CIS and INSYSTEM 2 specimens at various drift values.

Fig. 10 – In-plane tests. Cracking of the CIS and INSYSTEM 2 specimens at maximum imposed drift.

4.1.2 INSYSTEM 2

Figure 6b shows the hysteresis loops for specimen INSYSTEM 2. Even though the initial stiffness of INSYSTEM 2 is lower than that of the CIS (compare Fig. 6a and 6b), its maximum resistance is slightly higher (equal to 549.0kN). Moreover, the maximum resistance of INSYSTEM 2 was obtained at a significantly higher drift value (equal to 2.58%). The maximum drift applied to INSYSTEM 2 was equal to 3.49%.

The hysteresis loop envelopes for the three loading cycles of INSYSTEM 2 are presented in Figure 7b. One may observe force-response degradation by 10-15% during the second loading cycle, whereas the reduction of the force-response during the third cycle is rather limited. It is noted that after the attainment of the maximum force-response, no significant force-response degradation is observed.

In Figure 8b, strains of the horizontal reinforcement of the bed joint at mid-height of the wall are plotted against the force-response values. The strain gauges were positioned at the two ends and at mid-length of the reinforcing MURFOR bars. The results show that the maximum absolute value of strain of the bars is almost equal to 2‰, which is almost equal to the strain corresponding to yielding of the bars. The horizontal reinforcement is mobilized after the occurrence of diagonal cracks in the infill

In Figure 9, the damage of the INSYSTEM2, for various values of the applied displacement, is shown. In Figure 10, photos of the specimens at maximum imposed drift can be seen. It is noted that for small values of the applied displacement, only separation of the infill wall from the RC frame is recorded, while no diagonal cracking was observed. It is underlined that cracking of the bricks only occurred for values of the imposed drift higher than 1.00%. One should notice that the damage is concentrated along the bed and head joints. At the maximum achieved drift value (equal to 3.49%), extensive cracking and spalling of bricks in the corner of the infill and along the diagonal was observed.

4.2 Out-of-plane response

In this section, the results of the out-of-plane tests are shown for the CIS and the INSYSTEM 2 infill. Hysteresis loops, force vs. displacement envelopes, crack patterns at several deflection values and cracking at the maximum imposed deflection are presented in Figures 11 to 14, for the two specimens.

4.2.1 CIS

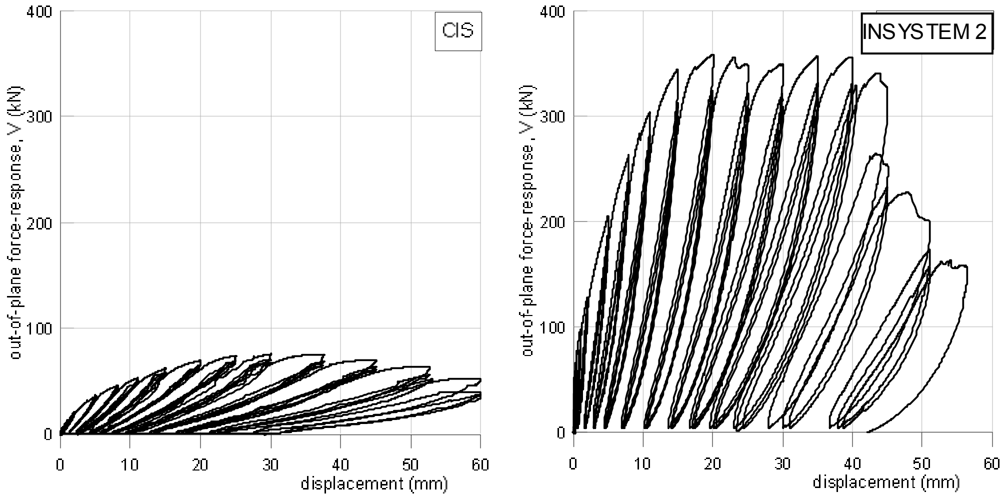
The maximum resistance of the CIS Wall (equal to 75.6kN) was obtained at a deflection value (measured at the middle of the wall) equal to 30mm, whereas the maximum deflection applied to the infill was 60mm. The force-response degradation between the first and third cycle was almost equal to 15%. At a deflection value equal to 60mm, the force-response during the first cycle is almost 70% of the maximum force-response.

Regarding the crack pattern, the infill detaches from the RC frame at low values of deflection. Moreover, yield lines due to bending are formed. Even for small values of the applied deflection, cracking along the interface between the RC tie beam and the infill is recorded.

4.2.2 INSYSTEM 2

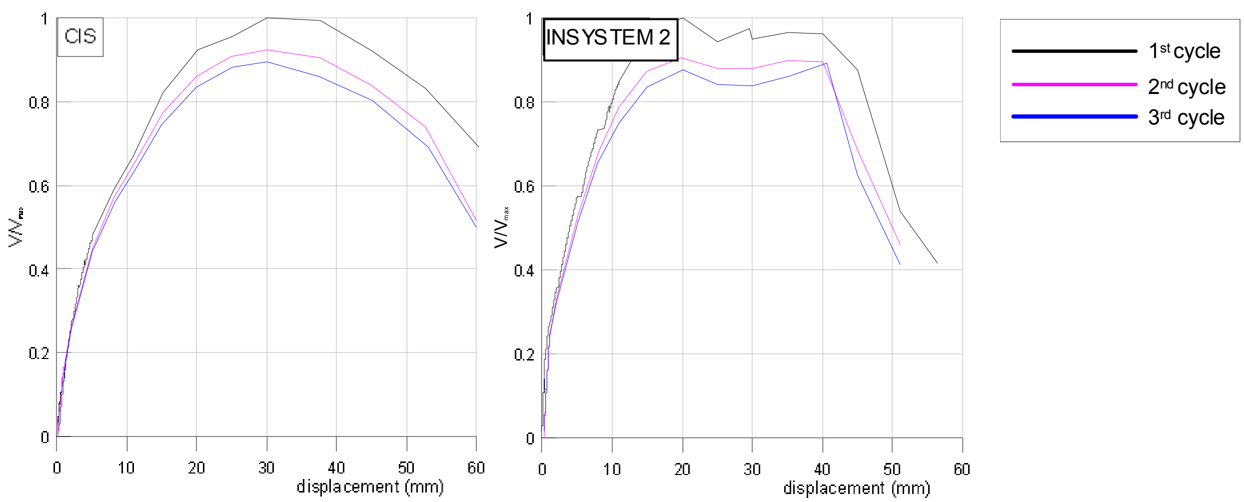
The maximum resistance of INSYSTEM 2 (equal to 359.0kN) was obtained at a deflection value (measured at the middle of the wall) equal to 20mm, whereas the maximum deflection applied to the infill was 55mm. The force-response degradation between the first and third cycle was almost equal to 15%. At a deflection value equal to 50mm, the force-response during the first cycle is almost 60% of the maximum force-response.

Regarding the crack pattern, the infill detaches from the RC columns at low values of deflection. Yield lines due to bending are formed. As the deflection increases, the cracks become more distributed. At the maximum applied deflection, crushing of the bricks occurs at the mid-height and the base of the infill.



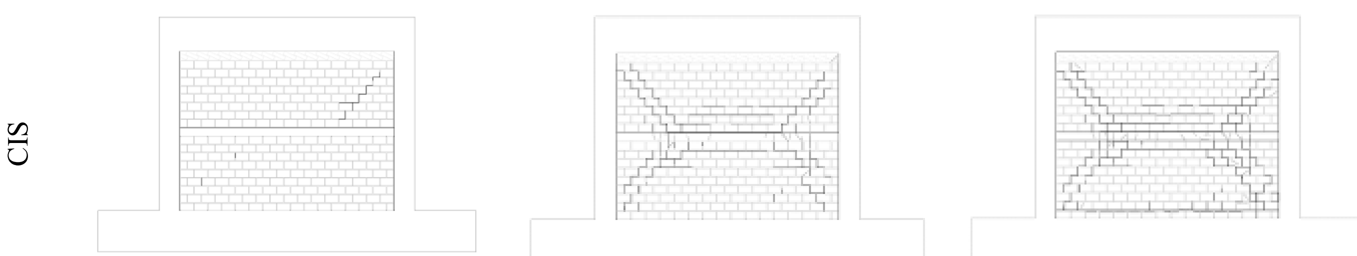
(a) (b)

Fig. 11 – Out-of-plane tests. Hysteresis loops for the (a) CIS and (b) INSYSTEM 2 specimens.

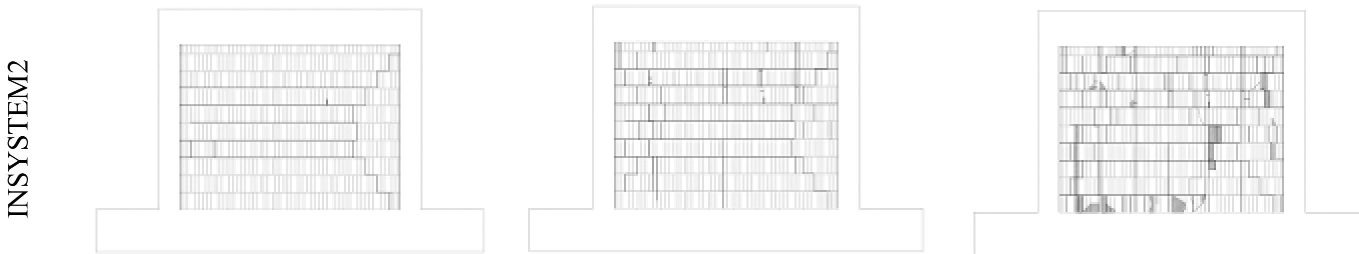


(a) (b)

Fig. 12 – Out-of-plane tests. Normalized resistance vs. displacement curves for the (a) CIS and (b) INSYSTEM2 specimens.



defl.=5mm defl.=30mm, at max. resistance defl.=60mm, max. imposed drift



defl.=5mm defl.=20mm, at max. resistance defl.=55mm, max. imposed drift

Fig. 13 – Out-of-plane tests. Crack pattern of the CIS and INSYSTEM 2 specimens at various drift values.

Fig. 14 – Out-of-plane tests. Cracking of the CIS and INSYSTEM 2 specimens at maximum deflection.

5. Conclusions

The paper presents the results of full scale testing an alternative solution of (horizontally and vertically) reinforced infill walls. The proposed system consists in a single leaf brick masonry wall, constructed with a new brick unit, which offers the possibility to place vertical reinforcement within the thickness of the infill wall. The tests results are compared with those obtained from testing the currently applied infills in Greece.

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

1) Under in-plane cyclic displacements, the proposed system was able to sustain as large as 2.58% in-plane drift without significant force-response degradation. The system proved to be quite stable, as it sustained drift values up to 3.5%, again, without significant force-response degradation. On the contrary,

2) The currently used system was less resilient. Actually, it underwent significant damages under lower drift values (1.10% and 1.57% respectively), whereas the force-response degradation was quite high. Therefore,

3) The proposed system may ensure an improved behaviour of infill walls under seismic events corresponding either to the design earthquake and to more frequent events, thus, limiting the safety issues and the economical losses.

4) The behaviour of the proposed system proved to be stable also under out-of-plane actions. It ensured significant resistance and energy absorption. The behaviour of the current infill system exhibited several times smaller resistance; it was, however, able to sustain large out-of-plane deformations.

5) It has to be admitted that further investigation is needed by simulating real conditions, i.e. by testing infilled frames under simultaneous in-plane and out-of-plane actions. Shaking table tests carried out to document the behaviour of the proposed system, to be presented elsewhere, have proven the stable and improved behaviour of the system: The occurrence of repairable damages at rather large imposed displacements ensures a satisfactory behaviour of the INSYSTEM2 infills. Although shaking table testing of the CIS is still to be performed,

inspection after numerous earthquakes (see www.insysme.eu) has put in evidence the poor behaviour of the system.

6. Acknowledgements

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