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OUT-OF-PLANE BEHAVIOR OF DECOUPLED MASONRY INFILLS UNDER SEISMIC LOADING

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Abstract

Masonry is used in many buildings not only for load-bearing walls, but also for non-load-bearing enclosure elements in the form of infill walls. Many studies confirmed that infill walls interact with the surrounding reinforced concrete frame, thus changing dynamic characteristics of the structure. Consequently, masonry infills cannot be neglected in the design process. However, although the relevant standards contain requirements for infill walls, they do not describe how these requirements are to be met concretely. This leads in practice to the fact that the infill walls are neither dimensioned nor constructed correctly. The evidence of this fact is confirmed by the recent earthquakes, which have led to enormous damages, sometimes followed by the total collapse of buildings and loss of human lives. Recently, the increasing effort has been dedicated to the approach of decoupling of masonry infills from the frame elements by introducing the gap in between. This helps in removing the interaction between infills and frame, but raises the question of out-of-plane stability of the panel. This paper presents the results of the experimental campaign showing the out-of-plane behavior of masonry infills decoupled with the system called INODIS (Innovative decoupled infill system), developed within the European project INSYSME (Innovative Systems for Earthquake Resistant Masonry Enclosures in Reinforced Concrete Buildings). Full scale specimens were subjected to the different loading conditions and combinations of in-plane and out-of-plane loading. Out-of-plane capacity of the masonry infills with the INODIS system is compared with traditionally constructed infills, showing that INODIS system provides reliable out-of-plane connection under various loading conditions. In contrast, traditional infills performed very poor in the case of combined and simultaneously applied in-plane and out-of-plane loading, experiencing brittle behavior under small in-plane drifts followed by high out-of-plane displacements. Decoupled infills with the INODIS system have remained stable under out-of-plane loads, even after reaching high in-plane drifts and being damaged.

Keywords: in-plane, out-of-plane; INODIS; earthquake; connection detail

1. Introduction

In almost every moderate to high intensity earthquake event RC frames with masonry infill walls suffered damage, in some cases even a total collapse. This is because of several reasons. First reason is common use of masonry infills in practice all over the world, and therefore in seismically active areas too. Additionally, interaction of infill walls with the frame leads to the change of dynamic characteristics of structure [1, 2, 3], which is usually neglected in the design practice leading to the wrong estimation of interstorey displacements. Furthermore, deflection of RC frame activates much stiffer infill walls that have a low drift capacity of 0.2–0.3% [4] and rather stiff and brittle in-plane response, infill panels achieve its maximum load capacity very fast which is followed by a sudden decrease of strength. Therefore, it can be concluded that infill wall increases the strength of infilled frame, but it highly decreases its ductility, which conflicts with ductile seismic design [4]. These problems are even more pronounced due to the fact that a large number of characteristics influences the behaviour of infilled frames and on top of that, their values differ in a high range [5]. Also, an insufficient infill/frame connection by mortar gets easily damaged under low levels of drift causing tilting of the infill wall and sometimes falling out of the plane of the frame [6]. This all lead to the both in-plane and out-of-plane damage of infill walls observed in many reports [6, 7]. Since the failure of infill walls, either in-plane or out-of-plane frequently occurs during earthquakes the limitation of damages in infill walls is a very important public safety issue. The failure to do so may cause injuries or even casualties, sometimes caused by an earthquake which may not be as strong as the design one. Also, the damage of infills may be significant from the economic point of view due to the repair or reconstruction of some infills, repair of damages to structural system, non-structural components, equipment, rental and relocation costs and general income losses.

This pushed the investigations and research in this field. The behavior of masonry infills under in-plane loading was studied by many researchers [8, 9, 10, 11, 12], amongst others. The behavior of infill walls under out-of-plane loads was first examined by McDowell et al. [13] who described the out-of-plane capacity based on the one-way arching mechanism, while Dawe an Seah [14] based on the investigation of the influence of the supports deformability and presence of openings, developed an empirical relationship for uniform lateral load capacity, with the assumption that the load resistance is based on the two-way arc. Asteris et al. [15] gave a comprehensive literature review of the capacity models developed for the prediction of the out-of-plane response of infilled frames. Recently several authors [15, 16] concluded that in-plane damage can reduce the out-of-plane capacity of infill panels leading to their collapse causing severe risk for life safety. Also, it is observed [17, 18] that the out-of-plane collapse of infills may occur even for moderate intensity earthquakes, concluding that it is mostly affected by the slenderness ratio, the aspect ratio (height/length ratio), the masonry compressive strength and, above all, the boundary conditions [19, 20] and the presence of an opening [21]. Furthermore, in the work [22, 23, 24, 25] effect of sequential in-plane and out-of-plane loading was examined resulting in significant decrease of capacity. Only few authors [20, 26, 27] conducted experimental tests combining at the same time the in-plane and out-of-plane actions on the wall, concluding that there is strong interaction between two directions and it has to be taken into account. Paulay and Priestley [28] concluded that due to the in-plane stresses arching effect presented by membrane action in out-of-plane direction will not develop.

Since the significance of the in-plane/out-of-plane interaction is realized, it pushed the research into the direction of developing the idea of decoupling the infill from the frame [29, 30] and in that way removing this interaction. The easiest way to do this is by introducing a gap between the frame and infill and filling it with the soft material. Additional reason that pushes a decoupling as an approach is that it eliminates the problem of a large set of situations for the mechanical characteristics of masonry and the boundary conditions between frames and infills. In this way, it is applicable to the great variability in the materials and construction techniques adopted in different countries. Furthermore, the above mentioned decrease of RC frame ductility due to the infills does not appear in a case of decoupled infills. Also, the wall/frame stiffness ratio that has an important effect on the cracking strength of the walls and the maximum shear strength of the system [31] is an issue solved with the decoupling. However, for this approach an appropriate out-of-plane connection for an infill wall should be provided. Kuang and Wang [32] inserted additional steel anchors in the bed joints of the masonry infill and connected them to the frame. Nevertheless, these anchors can get activated under in-plane loading, thus bringing stress concentration into the infills.

Although big effort has been spent on studying and trying to improve the behavior of masonry infills under earthquake loading, just recently the potential of decoupling infills from the surrounding frame has been recognized as an appropriate solution. However, there are just a few experimental and/or numerical studies about in-plane behavior and even less is done for testing out-of-plane behavior of decoupled masonry infill walls. Therefore, this article presents a novel contribution by presenting the results of experimentally tested infill walls with the newly proposed decoupling system, with the focus on the out-of-plane behavior.

2. Decoupling system

Within the European project INSYSME [33], funded under the 7th Framework Program by the European Commission and aimed at developing innovative systems for masonry enclosure walls, new innovative systems were developed and analyzed. Research presented in this paper is part of this project and its aim was developing a constructive measure that solves the above mentioned problems and provides its simple application in practice, thus enabling engineers to apply the system easily and without any complicated numerical models.

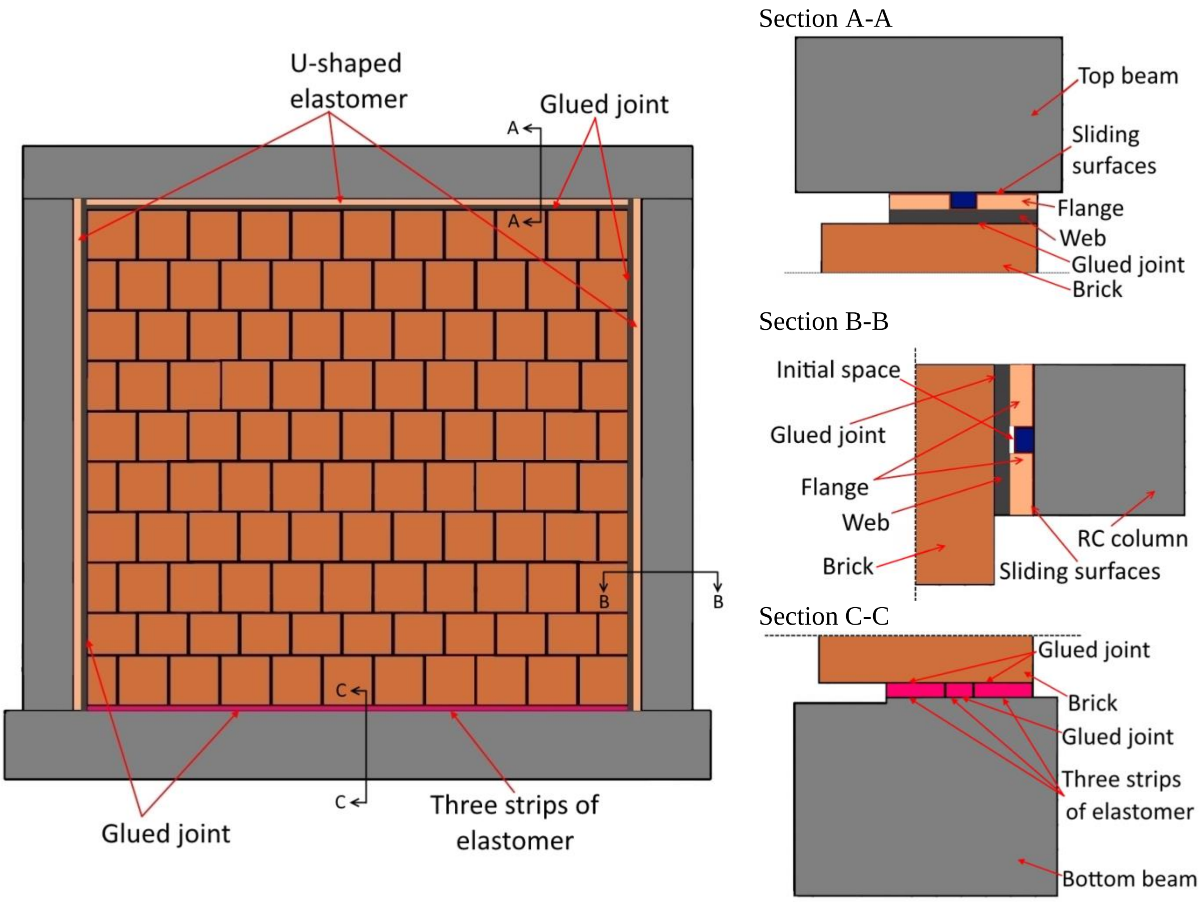


Fig. 1 – Details of the INODIS decoupling system [34]

During the INSYSME project, authors of this paper developed the INODIS system with the conceptual idea to decouple infill by applying elastomers between RC frame and infill panel such that the brittle behavior of the infill walls will be avoided. This way activation of infill walls due to RC frame in-plane deformations is postponed to higher drifts, thus disabling high stresses in both RC frame and infill wall. The elastomer bearings are designed to allow the design drift of the RC frame without inducing damages to the infill wall. At the same time the U-shaped elastomers that are glued to the bricks (Fig. 1), on one side, and are in contact to the plastic profiles, which are nailed to the frame, provide out-of-plane restrain for an infill wall. Further details of the INODIS system with the steps for its application can be found in Marinković and Butenweg [34] and Marinković [35].

3. Experimental campaign

In order to design and better understand the behavior of infilled RC frames under earthquake loading, it is required to have detailed knowledge about the material and mechanical properties of the different components used. These properties are helpful in describing the mechanical and deformation behavior of the infill masonry walls under in-plane, out-of-plane and vertical load, as well as combinations of these loads. Therefore, material and mechanical properties of masonry units, mortar, concrete, reinforcement, as well as elastomer are derived by conducting material tests and tests on small subassemblies. A detailed description of these tests is given in [34, 35].

Since experimental testing campaign includes both in-plane and out-of-plane loading, equipment and instrumentation had to be built to fulfill planned testing procedures. Therefore test setup has been specifically constructed for the tests within the INSYSME project. Vertical force of 200kN per column has been applied with the vertical hydraulic jacks and kept constant during all the tests. In-plane loading has been applied at the top beam through the horizontal increasing cyclic displacements by reaching each displacement amplitude three times. For out-of-plane loading, four airbags were placed between the stiff supporting panel and infill wall. In that way, all the deformation appears only in infill wall. Detailed description of the test setup can be found in [20, 35].

The reinforced concrete frames have been designed according to DIN EN 1992-1-1 (2011) [36] and DIN EN 1998-1 (2010) [37] considering the German national annexes for ductility class L. Furthermore, the capacity of the testing setup had to be considered such as capacity of the hydraulic actuators. Columns were designed to have 25/25 cm quadratic cross section with the 1.48% of longitudinal reinforcement and 0.63% and 0.42% of transverse reinforcement in corners and middle section respectively. Height of the beam is 25 cm and the width 45 cm with the 1.05% of longitudinal reinforcement and 0.35% and 0.23% of transverse reinforcement in corners and middle section respectively. Dimensions and arrangement of reinforcement can be found in [20, 35]. Traditionally infilled frames are constructed in a usual way of bricklaying, and it is just important to mention that for bed joints thin layer mortar was used, while head joints were made as dry joint connection without mortar, while the normal mortar has been placed on the lower beam and on the columns as a connection for the bricks at the bottom and sides. The layout of the RC frame with infill masonry and the integrated INODIS system is shown in Fig. 2 with the description and size of the elastomers applied.

The horizontal and vertical displacements of the RC frame are recorded by the inductive displacement transducers. Furthermore, the out-of-plane displacements are measured on the frame and in the center of the wall as well by using the inductive displacement transducers. The frame and infill displacements are both recorded by an independent optical measurement system using point markers attached to the test specimen. The optical system works with two cameras to record simultaneously in- and out-of-plane displacements. In order to allow crack visibility, the specimens were painted with a thin layer of white paint, which was the only surface finishing. In addition, the masonry infills are being protected from a sudden falling out by securing it with the four tension belts, which are being positioned at a distance of 5 cm from the exterior wall surface. The belts are attached to the columns of the frame.

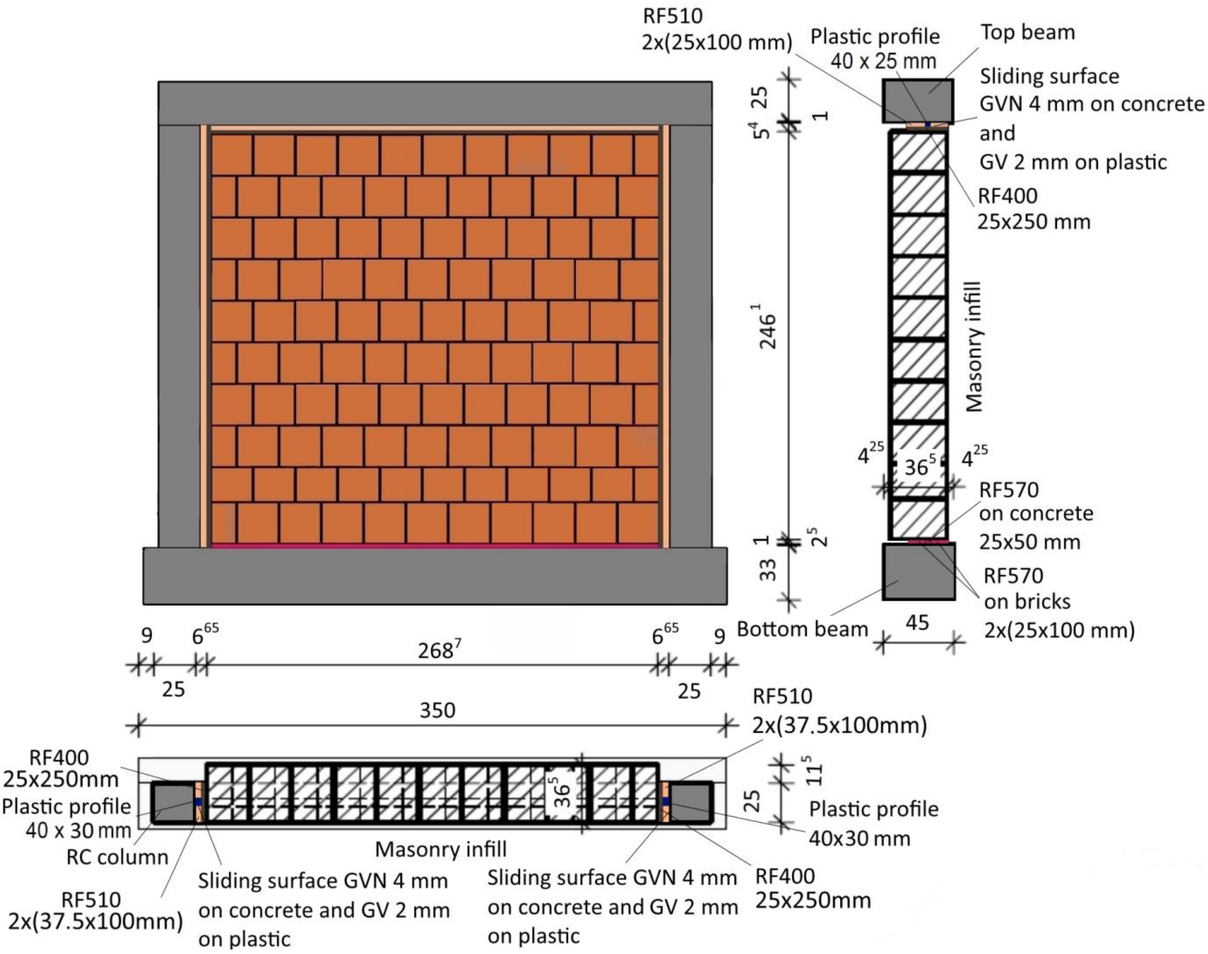


Fig. 2 – Test specimen for decoupled infilled frame [34]

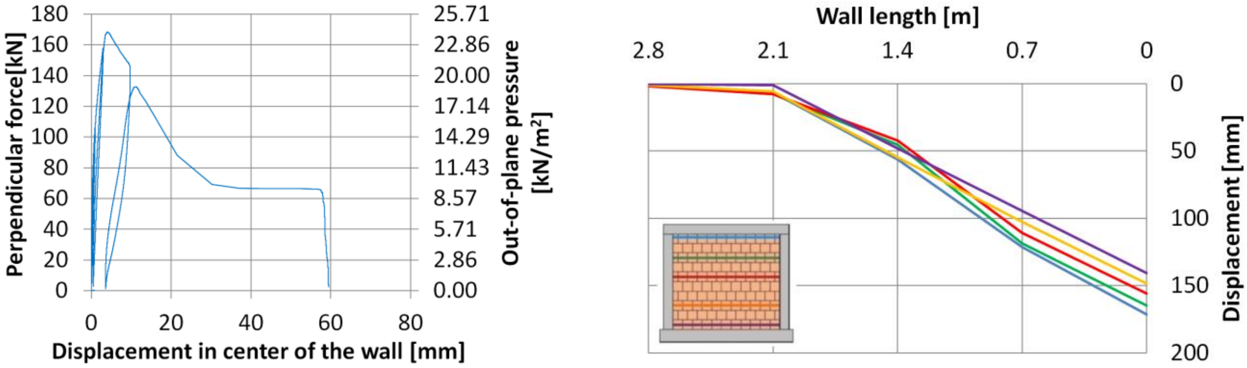
4. Experimental results

First the results of the experimental tests on traditional infills are presented. Then the testing outcomes on the decoupled infilled frame are shown, followed with the comparison of the results for traditional and decoupled solutions. Traditionally infilled frame specimens are tested under pure out-of-plane loading until failure (BO specimen), sequential in-plane and out-of-plane load (BI specimen) and under simultaneously applied in- and out-of-plane loading (BIO specimen). Decoupled infilled frame (DIO specimen) was tested with the comprehensive loading protocol covering pure in-plane, pure out-of-plane, sequential and simultaneous application of in- and out-of-plane loading.

4.1 BO specimen

Out-of-plane test on BO specimen was performed to investigate the behavior of the masonry infills under out-of-plane loading and to assess the load capacity as well as the capacity of the connection to the RC frame. However, in the case of BO specimen a gap of 5cm was present on one side of the wall, between the wall and frame. In this way, an unfavorable effect of the infill supported on three sides is tested.

As already described, application of the out-of-plane loads has been done by increasing the pressure in the air bags until failure of the wall. The masonry infill specimen BO was able to activate a maximum resistance of about 170 kN, corresponding to a uniformly distributed load of about 24 kN/m² (Fig. 3a). The resistance of the infill appears to be limited by sudden contact failure between RC frame and the uppermost and the lowest row of bricks. This results in a tilting of the wall as well as an overloading and splitting of the bricks in the top infill row (Fig. 4a). Due to the support on three sides, the free edge undergoes the largest deflections, especially at the top (Fig. 3b). As expected the gap on the right side influenced the failure mode of the wall, having high deformations of the right side of the wall while deformations of the left side stayed almost intact (Fig. 3b). Apparently, loss of connection/support at the top and bottom lead to the loss of capability to form arching mechanism, which further lead to the sudden and brittle failure of the right side of the wall (Fig. 4b). This kind of behavior shows that traditional connection of infill walls with the frame through the mortar presents a weak place for the infilled frames.



a) b)

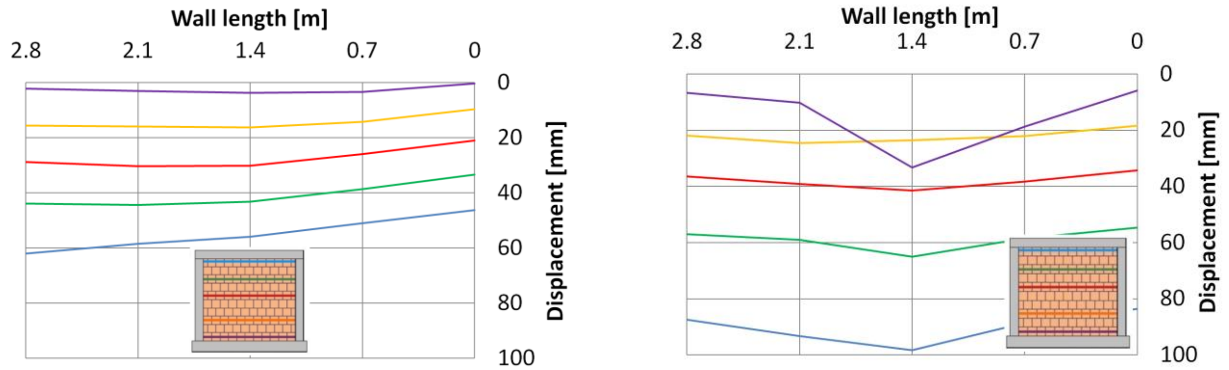
Fig. 3 – a) Force-displacement curve and b) top view of the wall deformation in the out-of-plane direction at the end of the test

a) b)

Fig. 4 – a) Damage of the bricks at the top row and b) failure of the BO specimen

4.2 BI specimen

BI specimen was loaded first with the in-plane displacement up to 1.25% of interstorey drift, which is equal to 34.38 mm. First cracks already appeared at 0.06% of drift while reaching 110 kN of in-plane force. Afterwards, with the reduced stiffness specimen activated the horizontal force of 225 kN at 1.25% of drift. At this stage specimen had notable cracks in the infill wall. This caused that just 3 kN/m² could be applied in the subsequent out-of-plane loading phase, producing 29 mm of deformation in the center of the wall (Fig. 5a). Then the out-of-plane load was removed and in-plane displacement was applied up to 2.1% of in-plane drift. However, each in-plane amplitude was followed with the increase of out-of-plane displacement causing infill wall movement and failure perpendicular to the wall (Fig. 5b).

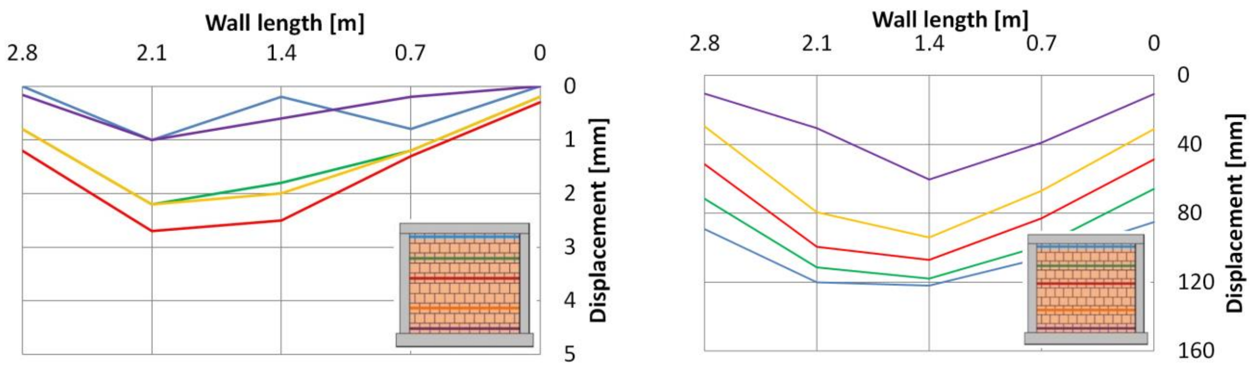


a) b)

Fig. 5 – Top view of the wall deformation in the out-of-plane direction a) under maximum out-of-plane load of 3 kN/m^2 and b) at the end of the test

4.3 BIO specimen

BIO specimen was first loaded with the 5 kN/m² of pressure perpendicular to the wall. The pressure in the airbags has been kept constant during the application of in-plane displacement in sinusoidal cycles. First cracks appeared already at 0.05% of in-plane drift, when significant decrease in stiffness is observed. Maximum in-plane force of 225 kN was reached at 0.65% of drift and then started to decreased rapidly. At 0.3% of in-plane drift notable out-of-plane displacements started to appear (Fig. 6a). For small applied interstorey drifts, it can clearly be seen that the deformations correspond to the bending line of an arching effect. In the following load cycles, the arching effect is substantially decreased due to the loss of the support boundary conditions and the infill reacts with sudden and rapidly increasing out-of-plane deformations. The bending line now corresponds to a tilting movement of the infill superimposed on a rigid body movement caused by the loss of the boundary conditions on both the top as well as the base of the wall. The out-of-plane deformations at a drift of 0.8% already measure 8.5 cm. At the 1% of in-plane drift out-of-plane displacements were quite high and in order to continue with the testing, the out-of-plane pressure was reduced to 2.5 kN/m². However, just one more cycle of in-plane displacement was able to be applied and the wall completely failed by moving in out-of-plane direction (Fig. 6b). The test had to be aborted as the wall deformations uncontrollably increased. The reasons for such high out-of-plane displacements at the top and bottom of the infill wall are the loss of the arching mechanism because of the loss of the wall supports due to the in-plane frame deformation. Also, in-plane cyclic loading damages the mortar connection between the upper brick and the frame which caused the out-of-plane movement to start at the top.

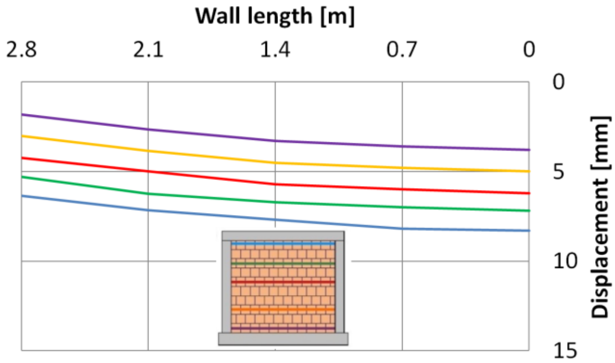


a) b)

Fig. 6 – Top view of the wall deformation in the out-of-plane direction under maximum out-of-plane load a) at 0.3% of in-plane drift and b) at the end of the test (1.0% of in-plane drift)

4.4 DIO specimen

In contrast to the above-mentioned tests, for the INODIS system all three load types (in-plane, out-of-plane and simultaneous in- and out-of-plane) are investigated on one specimen (DIO). First, a pure in-plane loading up to the drift of 1.25 % caused no damage and cracks, leaving the infill wall completely intact. In the second phase, subsequently out-of-plane load has been applied until reaching 5 kN/m². This caused small deformations (Fig. 7a) that disappeared when the load was removed leaving negligible deformations (Fig. 7b).



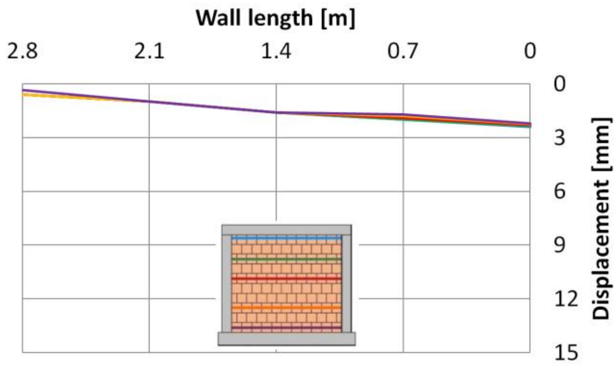


Fig. 7 – Top view of the wall deformation in the out-of-plane direction a) at the 5 kN/m^2 of out-of-plane load and b) at the end of the phase 2 of the DIO test

In the next testing phases until the end of the test, simultaneous application of in- and out-of-plane loading has been performed in a way that the out-of-plane load was ranging from 2.5 kN/m² to 5 kN/m², while in-plane cyclic displacement was increasing gradually. Decoupled infilled frame specimen was able to reach 1.8% of in-plane drift under 5 kN/m² of out-of-plane pressure before first crack in the specimen appeared. Until this point displacements of the wall were less than 10 mm. After the load is removed, some of the deformations caused by the formation of cracks remained in the wall, but the deformations in the hyperelastic elastomers reverse for the most of the wall (Fig. 8a). Damage pattern at the end of the loading after 1.8% of in-plane drift is shown in Fig. 8b. Formation of these cracks is caused by the combined stress and strain of in-plane and out-of-plane loading. This leads to an increase in the bending stresses from out-of-plane load until the flexural strength of the masonry is exceeded. In the next load cycle, the vertical crack in wall appears because the clamping effect is reduced in the unloaded upper right corner of the frame and again the bending stresses due to the out-of-plane load exceeds the flexural strength of the masonry. The wall does not move out-of-plane due to the circumferential support provided by the elastomers. In spite of the crack formation, the wall stays stable in the frame. Therefore, increase of in-plane displacements was continued up to 3.25%, which is the limit of the testing equipment. At this stage in plane force resistance started to slowly reduce, while out-of-plane displacements increased up to 5cm in the center of the wall. Even the wall at this stage was damaged with the several bricks cracked, it remained stable in the frame due to the glued connection to the elastomeric U-profiles.

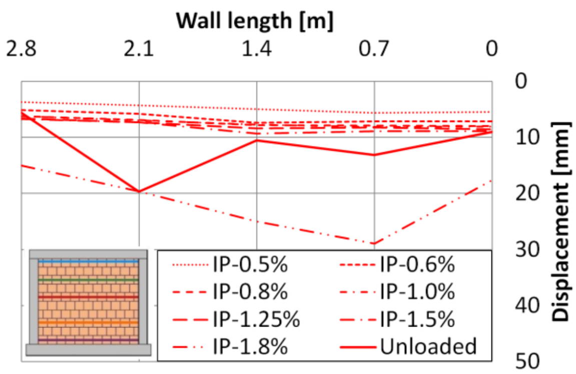


Fig. 8 – a) Top view of the wall deformation in the out-of-plane direction for the horizontal section in the middle height of the wall for different in-plane drifts and b) cracks in the wall at the 1.8% of in-plane drift

4.5 Comparison

The comparison of the out-of-plane force-deformation curves for traditional infills in Fig. 9a shows significant decrease of out-of-plane force resistance in a case of sequentially and simultaneously applied in- and out-of-plane loading. The BO specimen exhibits an extremely high load capacity of 24 kN/m^2. In contrast, the load capacity drops to 3–5 kN/m^2 when the in- and out-of-plane loads are applied sequentially (BI specimen) or simultaneously (BIO specimen). This corresponds to a reduction of 5–8 times although the infill panels in the BI and BIO tests were supported on four sides. In contrast, for the case of decoupled infilled frame (DIO specimen) the out-of-plane force was able to be kept at the same level (Fig. 9b), even after sequential and simultaneous application of in-plane and out-of-plane load, without experiencing a failure.

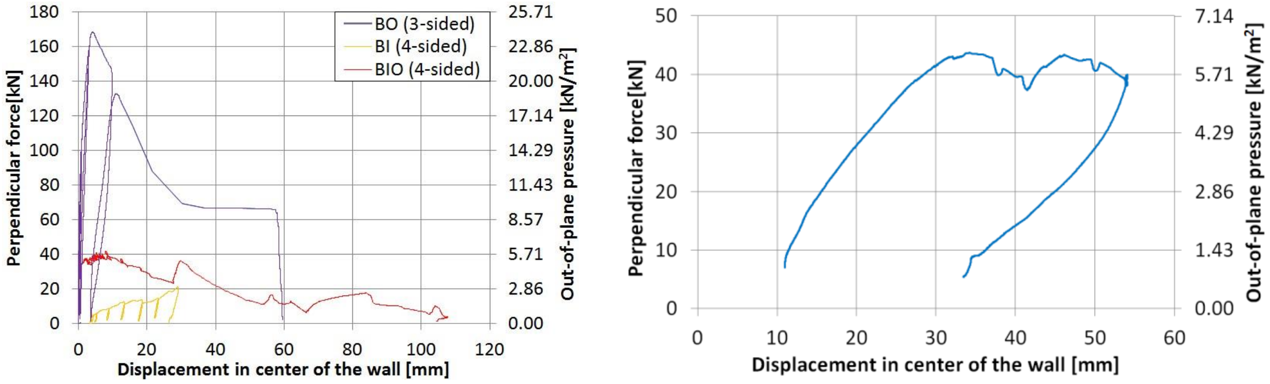


Fig. 9 – a) Comparison of out-of-plane force-displacement curves for the traditional specimens and b) force-displacement out-of-plane curve for DIO specimen in the last phase of the test

Fig. 10 shows the force-displacement curves of the out-of-plane deformations at the center of the wall for the second loading phase, where out-of-plane load was applied after 1.25% of in-plane drift, for the BI and DIO specimens. Decoupled infill wall easily reached 5 kN/m^2, without any crack in contrast to the traditional specimen who was able to take just 3kN/m^2 of out-of-plane pressure. Important to notice is that all the deformations in the case of decoupled infill were reversible, due to the elastomeric connection at the boundaries. Furthermore, traditional infill developed only residual deformations from the very start of out-of-plane load application. This shows the significant influence of previous in-plane loading on the out-of-plane behavior, which is not present in the case of decoupled infills. Furthermore, tilting of the traditional specimen BI due to the loss of connection caused by previous in-plane loading is also not experienced for decoupled specimen DIO (Fig. 10b), because of the presence of elastomeric U-profile that provides constant out-of-plane connection at the top.

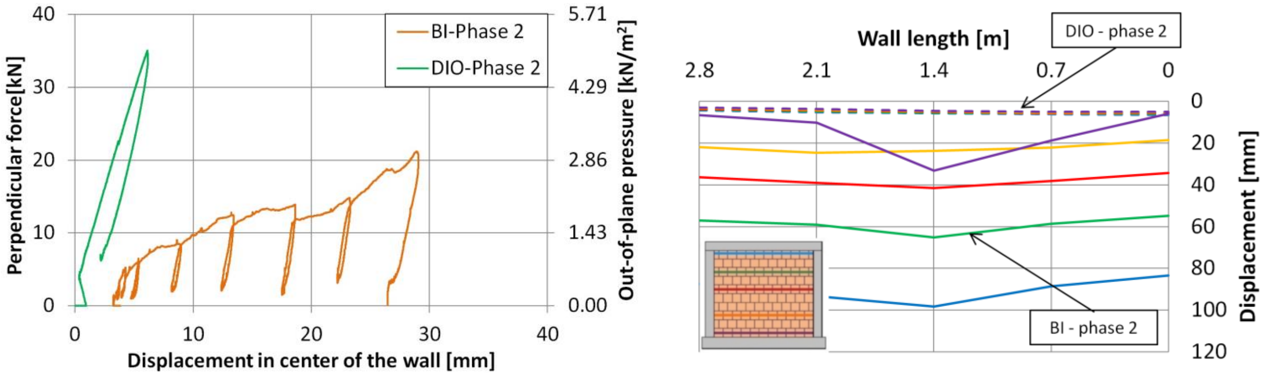


Fig. 10 – a) Comparison of out-of-plane force-displacement curves and b) top view of the out-of-plane deformations for the maximum loads for the second loading phase of the BI and DIO specimen

Fig. 11a shows the force-displacement curves for the BIO and the third and fourth loading phases of the DIO test for the out-of-plane deformations at the center of the wall. In the BIO test, a constant out-of-plane load of 5 kN/m^2 is applied in combination with an increasing sinusoidal in-plane load just up to interstorey drift of 1.0%. In the DIO test, the out-of-plane load is varied between 2.5 and 5.0 kN/m^2, whereby the maximum interstorey drift for the third and fourth phase is 1.8%. A comparison of the results shows that the deformations for the decuopled infill are 3-5 times smaller and even more important the infill stays stable in the frame, while the traditional infill wall moves out of the frame (Fig. 11b). In the case of BIO specimen damage started already at small drifts (0.3-0.4%) and at the drift of 1.0% the wall was completely destroyed. In contrast, specimen DIO experienced first crack at the 1.8% of drift.

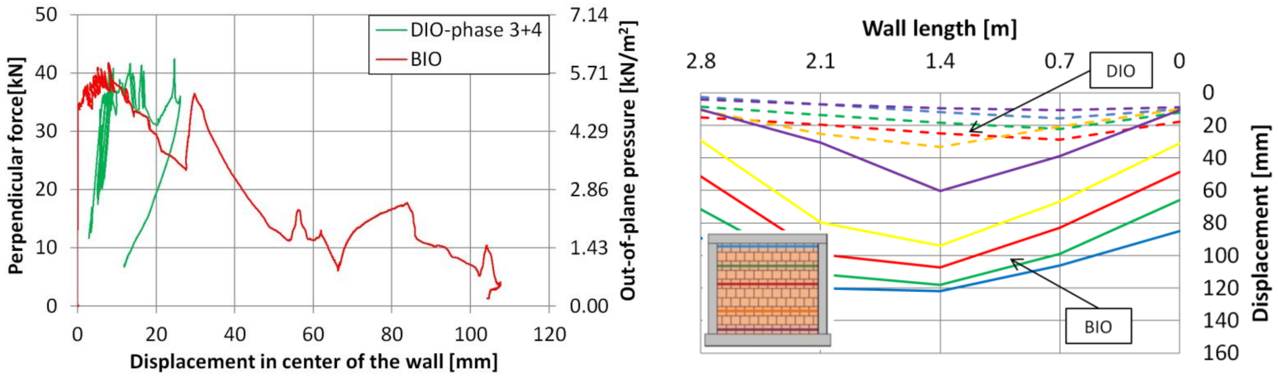


Fig. 11 – a) Comparison of out-of-plane force-displacement curves for the test BIO and third and fourth loading phase of the test DIO and b) top view of the out-of-plane displacements for 5 kN/m2 out-of-plane surface load and interstory drifts of 1.0% (BIO) and 1.8% (DIO)

5. Summary

The article presents the results of the experimental study on the decoupled masonry infill walls. The critical issue of out-of-plane behavior of decoupled infills is studied by applying pure out-of-plane loading as well as combination of in-plane and out-of-plane loads. Results of the experimental campaign on the full scale masonry infilled RC frames are presented. Even the out-of-plane behavior of decoupled infills is a critical issue to be solved, the results show that the applied system INODIS is capable to provide adequate out-of-plane restrain and at the same time to prevent in-plane damage of the wall.

Experimental results show that traditional infill wall can take huge out-of-plane loads due to the activation of arching effect. However, in a case of earthquake, combination of in-plane and out-of-plane loading is always present, and experimental tests showed that in this loading situation we cannot rely anymore on arching effect and therefore both in-plane and out-of-plane resistance of infills is drastically lower. In a case of sequential loading (application of out-of-plane pressure after in-plane displacements) out-of-plane capacity is reduced 8 times. And this is logical because the mortar connection between infill wall and the frame is damaged and the wall has lost its out-of-plane restrain causing tilting of the wall. This is also drastic in a case of simultaneous application of in- and out-of-plane loading, where the out-of-plane resistance is reduced 5 times and in-plane displacement capacity 3 times. This is all followed by high out-of-plane displacements and movement of the wall out of the frame.

The results of the experimental tests show that these negative effects are avoided in the case of decoupled infill wall. In the tests it was possible to reach high in-plane drifts (3 times higher than in a case of traditional infills) without having any crack in the wall, under all loading conditions, even simultaneous application of in- and out-of-plane loading. This is due to the fact that elastomeric U-profile provides continuous connection of an infill wall to the frame and thus prevents infill failure perpendicular to the wall. This is even possible under combined in- and out-of-plane loading, because of the in-plane decoupling, which disables damage of the infill wall that highly reduces the out-of-plane capacity in a case of traditional infills. Additional advantage of decoupling that INODIS system provides is elimination of stress concentrations in both frame and bricks. This is achieved because of the use of elastomeric material that is much softer than surrounding concrete and masonry. Providing reliable and constant out-of-plane restrain and at the same time decoupling infill wall from the frame in in-plane direction is the crucial benefit that is provided with the application of the INODIS system. Development of the practical design concept of the INODIS system and its application in the practice is on the way. Furthermore, an experimental campaign for testing the effectiveness of the system on the infills with the openings is currently under preparation.

6. Acknowledgements

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