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Strengthening of hollow brick infill walls with perforated steel plates

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Abstract. The infill walls, whose contribution to the earthquake resistance of a structure is generally ignored due to their limited lateral rigidities, constitute a part of the lateral load bearing system of an RC frame structure. A common method for improving the earthquake behavior of RC frame structures is increasing the contribution of the infill walls to the overall lateral rigidity by strengthening them through different techniques. The present study investigates the influence of externally bonded perforated steel plates on the load capacities, rigidities, and ductilities of hollow brick infill walls. For this purpose, a reference (unstrengthened) and twelve strengthened specimens were subjected to monotonic diagonal compression. The experiments indicated that the spacing of the bolts, connecting the plates to the wall, have a more profound effect on the behavior of a brick wall compared to the thickness of the strengthening plates. Furthermore, an increase in the plate thickness was shown to result in a considerable improvement in the behavior of the wall only if the plates are connected to the wall with closely-spaced bolts. This strengthening technique was found to increase the energy absorption capacities of the walls between 4 and 14 times the capacity of the reference wall. The strengthened walls reached ultimate loads 30-160% greater than the reference wall and all strengthened walls remained intact till the end of the test.

Keywords: perforated steel plate; hollow brick infill wall; structural strengthening; earthquake behavior; reinforced concrete frame

1. Introduction

Strengthening of existing structures might be needed due to several reasons, including but not limited to the design and construction errors, changes in the intended use of the structure, compliance with the new structural codes, and additional service loads expected. Inadequate resistance of structures to earthquake forces stemming from inadequate design or deterioration is one of the most significant reasons urging engineers to strengthen the old structures. The main purpose behind the existing techniques for strengthening RC structures against earthquakes is to increase the overall lateral rigidity of the structure by adding new components to the lateral

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bearing system or strengthening the existing members by using different materials. In this way, the lateral drift of a structure during an earthquake can be reduced to meet the drift requirements of the codes. These strengthening techniques also aim at providing the structural system with components where the earthquake-induced energy can be absorbed so that the other structural members are not damaged seriously, preventing the total collapse of the structure.

The contribution of infill walls to the earthquake resistance is usually neglected in the structural design and analysis. Nonetheless, several studies in the literature (Marjani and Ersoy 2002, Xingke 2008) indicated that these walls have a limited but non-negligible contribution to the earthquake behavior of RC structures. Strengthening the infill walls offers an effective solution for improving the earthquake behavior of structures since it increases the overall lateral rigidity by increasing this limited contribution. Furthermore, this strengthening technique helps the walls to absorb the earthquake energy so that the load bearing elements of the frame are subjected to minimum damage during earthquakes.

Various strengthening techniques for infill walls have been offered and implemented in the literature. FRP sheets are commonly used for strengthening the infill walls due to their easy and quick application to the walls, the high strength-to-weight ratio of these materials, and the resistance of the polymers to harsh environmental conditions. Triantafillou (1998) experimentally found out that the CFRP sheets improve the shear and out-of-plane bending behavior of brick walls to a major extent. Nonetheless, the success of this strengthening technique in brick walls subjected to axial forces and in-plane bending moments was shown to depend on the adequacy of the anchorage of the sheets to the wall. Vandergrift *et al.* (2002) showed that the CFRP laminates have a significant contribution to the in-plane shear and out-of-plane bending capacities of masonry walls. The final failure of the strengthened specimens was caused by the separation of the composite sheets from the wall caused by the shear cracks, which initiated in the walls and later propagated to the FRP-wall interfaces. Ozcebe *et al.* (2003) tested one-bay two-storey frames, whose infill walls were strengthened with diagonal CFRP strips. The experiments indicated that this strengthening technique has a great contribution to the lateral rigidity and energy absorption capacity of an RC frame with nonbearing walls. Erdem *et al.* (2006) experimentally found out that strengthening masonry walls with CFRP strips help the walls to resist a major portion of the lateral forces in an earthquake similar to the role of RC infill walls in an RC frame building. The efficiency of strengthening masonry walls with FRP strips was found to mainly depend on the number and characteristics of the FRP anchors between the strips and the wall. El-Dakhakhni *et al.* (2006) conducted an extensive experimental study on unreinforced masonry (URM) assemblages strengthened with GFRP laminates and indicated that the laminates increased the axial, diagonal compression, and shear strengths of the assemblages by keeping them intact throughout loading. The diagonal compression tests on steel frames with masonry walls showed that these frames did not fail until corner crushing of the infill walls in the presence of GFRP laminates. The tests of Altin *et al.* (2008) on one-bay one-storey frames showed that symmetrical strengthening of hollow brick walls with CFRP strips on both interior and exterior faces significantly increases the lateral load and energy absorption capacities of the walls while decreasing their drift ratios at ultimate load. This study also pointed out the major influence of the type and number of FRP anchors on the behavior of strengthened walls.

The studies on strengthening masonry walls with FRP composites indicated that the efficiency of this method depends on the efficiency of the anchors between the FRP laminates and the wall. The high costs of the FRP materials, the skilled labor needed for this process, the difficulties in anchoring the sheets to the wall, the low fire resistances of the epoxy adhesives needed to bond

FRP sheets to the wall are among the reasons for this technique not to become common in daily applications, considering that the process needs to be applied to several walls in the structure.

To overcome the low resistance of epoxy to fire particularly in historical structures, textile reinforced mortar (TRM) was proposed to be used for strengthening stone and brick walls. The experimental and analytical studies conducted by Triantafillou and Papanicolaou (2006), Triantafillou *et al.* (2006), Prota *et al.* (2006), and Papanicolaou *et al.* (2007, 2008, 2011) showed that the use of basalt and glass fiber reinforced mortars effectively increases the in-plane and out-of-plane bending capacities and ductilities of stone and masonry walls and this positive influence increases with increasing layers of FRP textile. Kahn (1984), Alcocer *et al.* (1996), and ElGawady *et al.* (2006) investigated the influence of the use of steel reinforced shotcrete on the behavior of brick walls. Kahn (1984) found that the presence of anchor dowels between the shotcrete layer and the wall and coating the surfaces of the wall with epoxy before the application of shotcrete do not significantly influence the effect of this strengthening process. ElGawady *et al.* (2006) showed that this technique greatly contributes to the load capacities and ductilities of brick walls if the reinforcement and shotcrete are applied on both faces of the wall. Sevil *et al.* (2011) experimentally showed that strengthening the brick walls of an RC frame with a mortar of 2 % steel fiber content doubles its lateral load and energy absorption capacities compared to a frame with unstrengthened infills. Frosch (1996) and Frosch *et al.* (1996) conducted experiments on seismic strengthening of RC frames by connecting precast concrete panels to the infill walls of the frames having poor seismic detailing. The experiments indicated that the infill walls can have a considerable contribution to the lateral stiffness and strength of the frame similar to the role of shear walls in a real structure, if the concrete panels are connected to the existing infill walls and the frame with satisfactory anchorage details. Baran and Tankut (2011), who tested one-bay two-storey RC frames, found that bonding the precast concrete panels to the infill walls by only using epoxy mortar and to the surrounding frame by using dowel anchors provides satisfactory improvement in the performance of the frames, eliminating the need for any additional anchorage details. Acun and Sucuoglu (2005) used mortar reinforced with welded wire mesh for strengthening the infill walls of one-bay two-storey RC frames and found out that the strength of the mortar and the number of wire mesh layers influence the increase in the lateral rigidity and strength of the frame. Similarly, Korkmaz *et al.* (2010) showed that the thickness of the plaster layer has an important effect on the lateral load and energy absorption capacities of an RC frame when strengthening the infill walls of the frame with mesh reinforcement covered with plaster. Topcu *et al.* (2005) found that ferrocement coating of masonry walls increases the load capacities of the walls and the number of diagonal cracks on the walls while decreasing the crack widths. Based on the test of a repaired RC frame with a masonry infill, Amanat *et al.* (2007) concluded that coating the infill walls of RC frames with ferrocement layers can effectively increase the lateral load capacities of the frames.

Using mortar or shotcrete reinforced with steel or FRP bars is a promising strengthening technique for brick infill walls. Nevertheless, the application of these methods for several infill walls of a structure is rather cumbersome if not impossible since they include various stages, such as anchorage of the wire mesh or textile to the wall, covering the mesh with shotcrete or mortar, and plastering the wall. Due to the difficulties involved in these techniques and the high costs of the FRP materials, several researchers (Taghdi *et al.* 2000a, b, Farooq *et al.* 2006, Ozbek and Can 2012, etc.) investigated the use of mild steel strips or steel profiles for strengthening brick walls. The studies of Taghdi *et al.* (2000a, b) indicated that strengthening brick walls with diagonal steel strips provides significant improvements in the lateral load-deflection behavior of these members by reducing the crack widths in the wall until the slip of the anchor bolts. Farooq *et al.* (2006) found that the use of steel strips on both faces of the wall results in considerable increase in the lateral and diagonal compression capacities of the wall due to the confinement effect of the strips. Finally, Ozbek and Can (2012) verified the considerable positive effect of the flag plates in the corners of the wall on the behavior of masonry walls strengthened with diagonal steel angles.

Considering the significant improvements in the capacities and ductilities of infill walls achieved by the use of steel plates and angles, a new strengthening technique was offered in the present study. The use of perforated steel plates covering the entire face of the wall and connected to the wall through anchor bolts was investigated. This strengthening technique offered an economical and feasible alternative to the existing strengthening techniques in the literature. The use of the less costly and easily applicable perforated steel plates constituted a promising strengthening method due to the ease and speed of the process, which does not impair the use of the structure by the inhabitants, as well as the following advantages:

- The ductility of mild steel and the higher deformabilities of the perforated plates via the holes compared to the solid ones increase the ductilities and energy absorption capacities of the strengthened walls.
- The plates are anchored to the wall only with the help of bolts. The lack of epoxy speeds up the strengthening process and decreases the cost and amount of labor needed.
- The bolt holes can be drilled in the wall more easily due to the presence of perforations in the plate. Installation and removal of the plates are easy and the plates can be installed without damaging the water and power fixtures in the wall, whose locations are marked on the wall before installation of the plates.
- Mild steel plates are cheaper and more available compared to other strengthening materials, particularly FRP materials. Therefore, this strengthening technique is less costly and easier to implement. Furthermore, the fire resistant, recyclable, and non-cancerogenic nature of steel is also an advantage.
- The strengthening plates can be easily covered with plaster not to impair the aesthetic appearance of the walls.

The present paper summarizes the first stage of a research program aimed at investigating the contribution of strengthening the infill walls with perforated steel plates on the strength, rigidity, and ductility of brick-infilled RC frames. Within this stage, a reference unstrengthened and twelve strengthened hollow brick infill wall specimens were subjected to diagonal compression loading to evaluate the contribution of this technique to the individual behavior of the infill walls without RC frame. The load was conveyed to the wall specimens through a steel test frame, which simulated the loading conditions of infill walls in a real structure and enabled the researchers to investigate the behavior of the isolated infill walls under earthquake loading. Perforated plates, used on both faces of the wall, were connected to the wall and to each other by means of post-tensioned anchor bolts, extending through the wall thickness. The post-tensioning forces in the anchor bolts contributed to the shear resistances of the interface planes between the plates and the wall, and therefore, increased the composite action of the wall and the plates. The main test parameters of the present study were the anchor bolt spacing and the plate thickness. Large plates covering the entire face of the wall were adopted instead of diagonal steel strips 1) to resist the tensile stresses particularly after the formation of diagonal tension cracks in the wall, 2) to increase the compressive strength of the wall thanks to the confinement provided by the plates on both sides of the wall and the post-tensioning forces in the bolts. The strengths, ductilities, initial rigidities, and energy absorption capacities of the strengthened specimens were compared to each other and to the unstrengthened specimen. Finally, the experimental results were compared to estimates obtained from the analytical solutions developed for estimating the diagonal load capacities of the walls based on the FEMA 306 (FEMA 1998) approach and important conclusions were drawn.

2. Experimental study

2.1 Specimen details

The experimental part of the present study aimed at investigating the effects of the use of perforated steel plates with varying thickness and bolt spacing on the diagonal compressive strength, ductility, energy absorption capacity, and initial stiffness of hollow brick infill walls. A total of 13 specimens were tested. The specimens had a height of 1000 mm, a width of 1000 mm, and a thickness of 125 mm (85 mm brick+40 mm plaster). Each specimen was strengthened on both faces with steel plates of four different thickness values (0.5, 1.0, 1.5, and 2.0 mm), having the perforation pattern illustrated in Fig. 1. The strengthened specimens were composed of four different groups with regard to the plate thickness and the three specimens in each group differed in the spacing of the bolts connecting the plates to the wall (Table 1). The M6 bolts, used in the

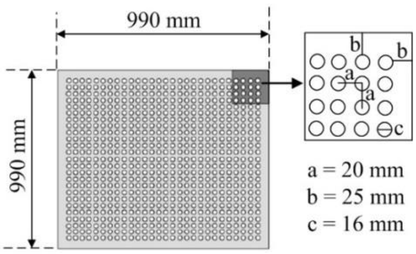


Fig. 1 Perforation pattern of the plates

Table 1 Specimen details

Specimen	Plate Thickness (mm)	Bolt Spacing (mm)
R	-	-
S0.5-100	0.5	100
S0.5-150	0.5	150
S0.5-200	0.5	200
S1.0-100	1.0	100
S1.0-150	1.0	150
S1.0-200	1.0	200
S1.5-100	1.5	100
S1.5-150	1.5	150
S1.5-200	1.5	200
S2.0-100	2.0	100
S2.0-150	2.0	150
S2.0-200	2.0	200

specimens, were post-tensioned with a torque value of 3.5 N.m. This torque value was adapted to create the largest post-tensioning forces possible in the bolts (about 70% of the axial capacity of the bolts) by also preventing the rupture of the bolts during the lateral expansion of the walls in the test due to the Poisson's effect.

The reference specimen was denoted with the capital letter "R" and the strengthened specimens with the capital letter "S". The first and second numbers in the notations of the strengthened specimens correspond to the plate thickness and anchor spacing in mm, respectively. For instance, S0.5-100 denotes the wall strengthened with 0.5-mm-thick plates, anchored to the wall with bolts spaced at 100 mm center-to-center.

2.2 Material properties

The specimens were composed of 85x190x190 mm hollow bricks with a measured compressive strength of 13.0 MPa parallel to the channels of the brick, 2.8 MPa and 3.2 MPa in short and long directions, respectively, perpendicular to the channels. Steel plates from the same batch, having approximately equal yield and ultimate strengths of about 280 MPa, were used for strengthening. For bonding the bricks and plastering, a cement-lime-sand mixture with a ratio of 1:1.5:5.5 by weight was used. This mixture had a water/cement ratio of 0.6 by weight. The compressive strength of the mortar and plaster used in each specimen was measured as 42 MPa, based on 100x200 mm cylinder tests.

2.3 Test setup and test procedure

Infill walls act as diagonal compression struts when the load-bearing system of a structure is subjected to lateral earthquake forces (Sayin and Kaplan 2005). Therefore, the specimens of the present study were tested under monotonic diagonal compression. Each specimen was placed in a steel frame before the test (Fig. 2). This steel frame was composed of four members connected to each other with hinges. Each member of the frame was made up of two hot-rolled NPU160 channels, welded tip-to-tip, so that the members were sufficiently rigid not to undergo significant deformations between the hinge locations. The rigid members and hinged connections between the members created an unstable mechanism around the wall specimen with a negligible diagonal resistance and stiffness. In this way, the steel frame did not restrain the diagonal deformations in the wall and did not contribute to the load capacity of the test specimen.

In the present study, testing the wall in an unstable steel frame was adopted instead of the standard test method given in ASTM E519 (ASTM 2010). According to this standard, the test specimens should be loaded with the help of two loading shoes, confining the two loading corners of the wall (Fig. 3). However, the contact surface between the confining plates of the loading shoes and the sides of the wall are pre-imposed in this technique and this contact surface does not change throughout the test, which does not simulate the conditions in an actual structure. The contact surface of the corners of the wall with the surrounding frame, through which the lateral loads are conveyed to the wall, varies with the load in a real structure. The present experiments indicated that the length of the contact surface on each side of the wall varied from 20% to 40% of the side length throughout the test as opposed to the ASTM E519 (ASTM 2010) method, which limits this length to 12% of side length all along the test. Thanks to the unstable steel frame free to deform in diagonal direction, the present setup allowed these contact surfaces to change during the test.

The steel frame (Fig. 3) surrounding the wall deformed with the wall and allowed the contact surface between the frame and the wall to change in accordance with the load level and the damage condition of the wall, similar to the conditions in a real structure.

The infill walls were tested in a universal testing frame with a capacity of 4000 kN (Fig. 2). The lower hinge of the frame was seated on a hydraulic jack with a capacity of 2000 kN and the upper hinge was connected to a load cell with a capacity of 1000 kN with the help of rigid steel plates. The diagonal wall deformations were measured by two LVDT's connected to the bottom plate located between the specimen and the hydraulic cylinder. The diagonal deflections of the specimens were obtained by averaging the measurements of the two transducers to cancel the effects of any possible rotations in the bottom plate due to accidental eccentricities in the load or imperfections in the test setup. The measurements of the LVDT's located beneath the specimen were assumed to differ only marginally from the measurements of an LVDT installed along the compression diagonal of the wall thanks to the negligible diagonal resistance and stiffness of the steel test frame surrounding the specimen. The load cell and LVDT's were connected to a computerized DAQ system through which the load-deflection curves of the specimens could be observed during the test (Fig. 4). The LVDT's had a precision of 0.01 mm. Finally, a lateral bracing system (Fig. 4) was used for preventing the out-of-plane deformations of the assembly.

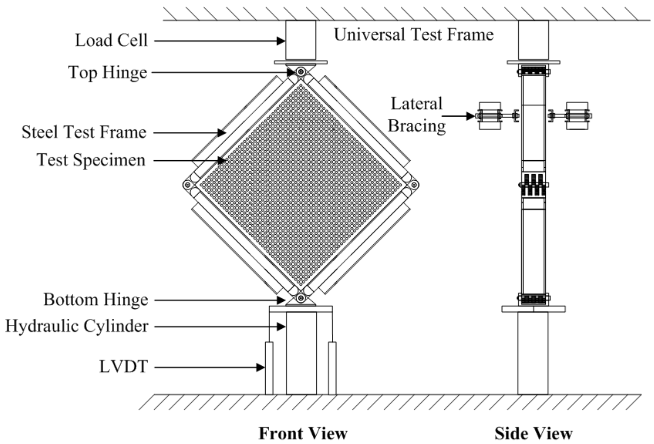


Fig. 2 Test setup

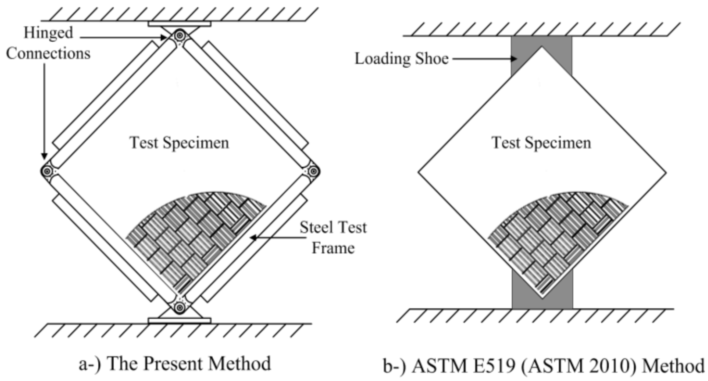


Fig. 3 Comparison of the present and ASTM E519 (ASTM 2010) methods

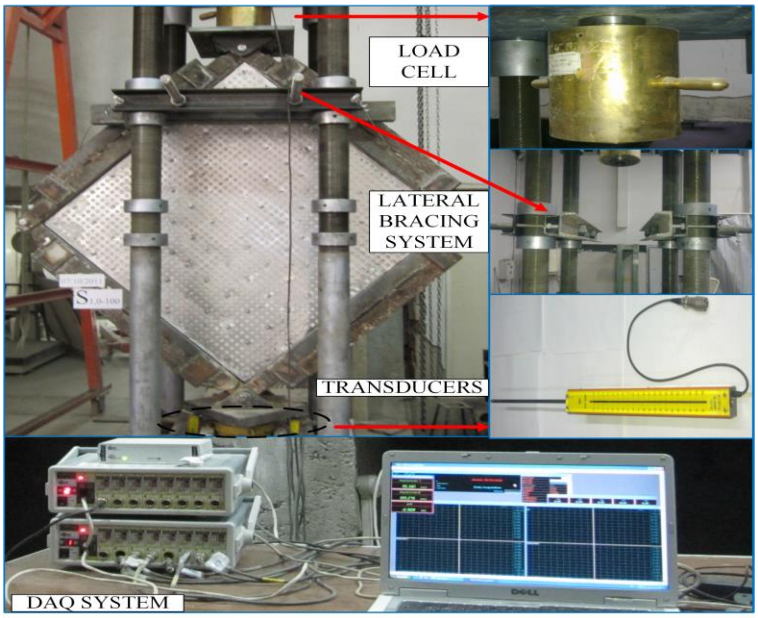


Fig. 4 Components of the test setup

Before the actual test, the gaps in the frame-wall assembly and between the connection plates and the frame were ensured to be closed by applying a limited load. Next, the specimens were loaded continuously until failure and the deflections and the load measured throughout the test.

2.4 Failure modes of the specimens and experimental observations

The reference wall (R) failed in a brittle manner due to the formation of several vertical cracks in the direction of the applied load and due to crushing of the loaded corners of the wall. The vertical cracks, which represent the diagonal tension cracks in an infill wall subjected to lateral loads, first developed around midheight of the wall and later propagated towards the loaded corners. The failure was very sudden and brittle, resulting in falling of several bricks from the wall (Fig. 5(a)).

The strengthened walls (S) exhibited a significantly more ductile behavior than the reference wall. The failure of the strengthened specimens was caused by out-of-plane buckling of the plates and crushing of the wall, which initiated in the loaded corners and spread towards the midheight of the specimen as the test proceeded (Fig. 5(b)). Buckling of the plate between successive anchors resulted in a wavy plate pattern at the end of the test. Furthermore, overstressing of the anchors in the loaded corners caused the bolts to tear the plate at high load levels, particularly in the specimens with a bolt spacing of 20 cm. Despite the distortions in the plate (shape changes due to out-of-plane buckling) and crushing of the wall, the strengthened specimens remained intact and wall pieces did not separate from the wall, which is crucial for the safety of the inhabitants of a structure during an earthquake. The additional tensile strength provided by the plate and the increase in the compressive strength of the wall due to the confining effect of the plate resulted in the strengthened walls to undergo major plastic deformations without a significant loss in the load

(a) Reference wall (b) Strengthened walls

Fig. 5 Failure modes of the specimens

capacity after reaching the ultimate load. These plastic deformations are important particularly in the energy absorption point of view. The increasing energy absorption capacities of the infill walls help the earthquake-induced energy to be redeemed in the walls so that the load bearing members of the structure are liable to less damage.

Specimen S2.0-100 could not be loaded until complete failure due to the limits of the test setup. Therefore, the measured load and ductility values do not represent the full capacities of this wall.

3. Evaluation of the test results

Table 2 presents the ultimate loads (P_{ult}), deformation ductility indices (μ), and energy absorption capacities of the specimens. The modulus of toughness value of each specimen was calculated from the entire area under the load-deflection curve of the respective specimen and this value indicates the total amount of energy absorbed by the specimen until complete failure. In addition to the absolute values of the ultimate load and modulus of toughness, the ratio of the ultimate load and modulus of toughness of each specimen to the respective values of the reference wall are also presented in the table as the relative values.

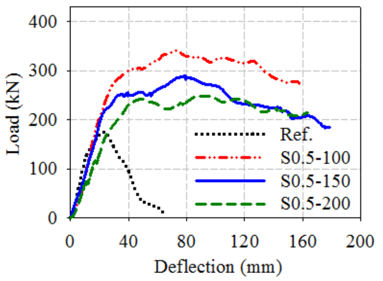
The deformation ductility index is the ratio of the ultimate deformation of a specimen at the instant of failure to the yielding deformation. Since the reference wall failed suddenly after reaching the ultimate load and did not undergo noteworthy plastic deformations, the ductility index of the reference wall was taken as unity. Therefore, the ductility index of each strengthened wall also indicates the ratio of the ductility of the respective specimen to the ductility of the reference wall. The ultimate deformation in the strengthened walls is the deformation value at which the load in the wall dropped to 85% of the ultimate load capacity in the descending branch of the load-deflection curve, based on the ductility factor definition of Eurocode 8 (CEN 2003). The deformations beyond this limit were ignored due to the significant decrease in the load capacity.

The yielding deformation in the strengthened specimens, on the other hand, corresponds to the deformation value at which the linear elastic portion of the curve ends.

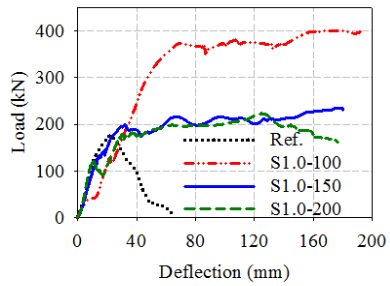
Figs. 6 and 7 illustrate the experimental load-deflection curves of specimens with regard to the plate thickness and bolt spacing, respectively.

Table 2 Test results

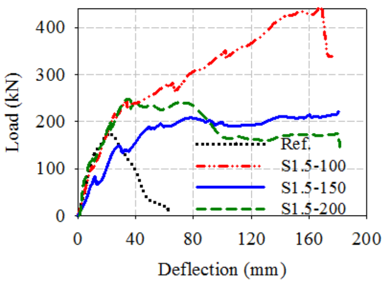
Specimen	Ultimate Load		Yielding Deformation (mm)	Ultimate Deformation (mm)	Deformation Ductility Index	Modulus of Toughness	
	Absolute (kN)	Relative				Absolute (Joule)	Relative
R	180	1.00	-	-	1.00	3950	1.00
S0.5-100	350	1.94	25.78	133.58	5.18	45830	11.58
S0.5-150	285	1.58	21.14	108.57	5.13	25920	6.55
S0.5-200	250	1.39	31.00	158.00	5.09	33940	8.58
S1.0-100	400	2.22	30.29	169.29	5.58	59520	15.04
S1.0-150	240	1.33	29.15	160.15	5.49	36980	9.35
S1.0-200	237	1.32	30.28	157.43	5.20	30640	7.75
S1.5-100	466	2.59	24.00	165.15	6.88	53470	13.52
S1.5-150	240	1.33	46.00	185.00	4.02	32220	8.15
S1.5-200	244	1.36	16.54	90.00	5.44	18270	4.62
S2.0-100	360	2.00	29.14	161.00	5.53	40980	10.36
S2.0-150	310	1.72	25.71	150.49	5.85	42250	10.68
S2.0-200	260	1.44	14.14	80.57	5.70	19300	4.88



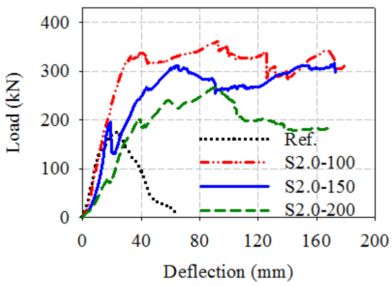
(a) plate with a thickness of 0.5 mm



(b) plate with a thickness of 1.0 mm

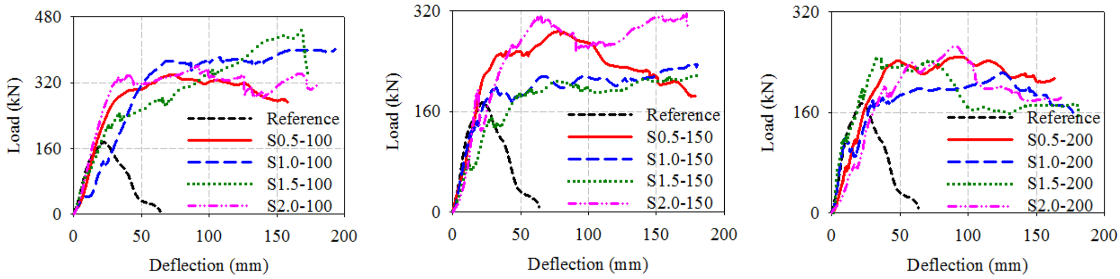


(c) plate with a thickness of 1.5 mm



(d) plate with a thickness of 2.0 mm

Fig. 6 Load-deflection curves of the specimens with identical plate thickness



(a) a bolt spacing of 100 mm (b) a bolt spacing of 150 mm (c) a bolt spacing of 200 mm

Fig. 7 Load-deflection curves of the specimens with identical bolt spacing

The deflection values in the plots correspond to the diagonal deflections of the wall, i.e. deformations in the diagonal compression strut. Furthermore, the total amounts of energy absorbed by each specimen up to different deflection values are illustrated in Figs. 8 and 9 with regard to the plate thickness and bolt spacing, respectively.

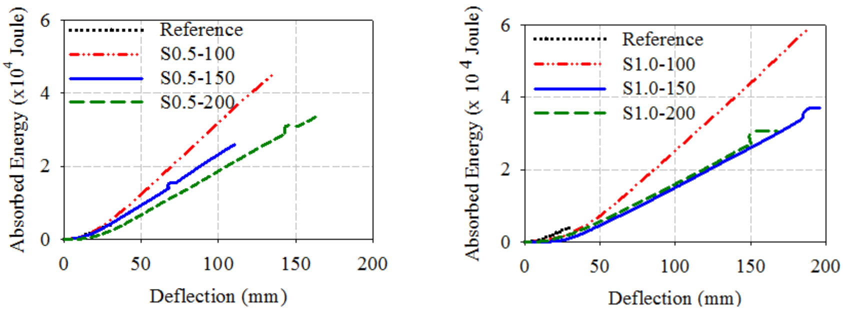
The values in Table 2 indicate that this strengthening technique has a major contribution to the load capacity, ductility, and energy absorption capacity of a brick wall, no matter what the thickness of the strengthening plate and spacing of the anchor bolts are. In the present study, this method provided a 30-160% increase in the load capacity, a 3-6 times increase in the ductility index, and a 4-14 times increase in the energy absorption capacity of the wall compared to the unstrengthened reference wall. Differently, this strengthening technique has no major contribution to the initial stiffness of the wall. As can be noticed in Figs. 6-7, the slopes of the initial portions of the load-deflection curves of the strengthened specimens are quite close to the respective slope of the reference specimen. Despite the expected contribution of the plates to the stiffness of the wall, the weak areas created by the holes of the anchor bolts in the wall might have caused the initial stiffness values of the strengthened walls to be very close to or even sometimes slightly smaller than the reference wall.

3.1 Comparison of the specimens with identical plate thickness

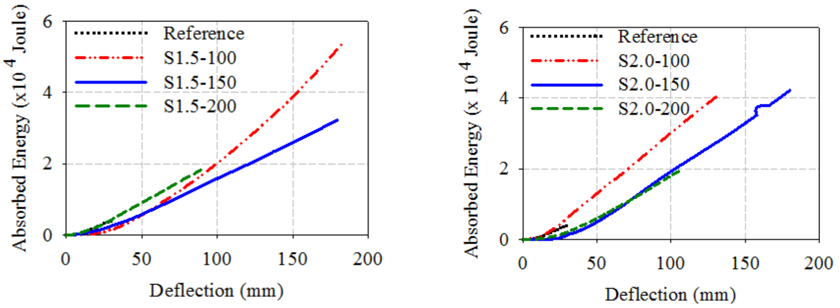
The results of the present study indicated that the bolt spacing has a major influence on the ductilities and load-carrying capacities of brick walls strengthened with perforated steel plates. Among the specimens with identical plate thickness, the reduction in the bolt spacing from 20 cm to 10 cm resulted in a 40-90% increase in the ultimate load, a 2-7% increase in the ductility index, and a 40-190% increase in the modulus of toughness. The values tabulated in Table 2 also indicate that the bolt spacing had a greater influence on the energy absorption capacities of the walls strengthened with thick plates (1.5 and 2.0 mm) compared to the walls strengthened with thin plates (1.0 mm).

Another important effect of bolt spacing on the wall behavior can be noticed in Fig. 6. The specimens with a bolt spacing of 15 and 20 cm underwent sudden reductions in the load in the elastic portion of the load-deflection curve. The sudden drops in the load capacities of S2.0-150 and S2.0-200 (Fig. 6(d)) within the elastic limits are quite noticeable. These reductions were caused by crushing of the wall and formation of diagonal tension cracks in the wall. In specimens with a bolt spacing of 10 cm, the adequate confining effect provided by the plates and closely-spaced bolts prevented the wall crushing and crack formation from causing a sudden drop in the load capacity. Whereas, the confining effect provided by the bolts with a spacing of 15-20 cm was not adequate to prevent this sudden drop. Similarly, the specimens with a bolt spacing of 10 cm exhibited a steadier load-deflection behavior in the plastic region of the load-deflection curve, unlike the walls with a bolt spacing of 15-20 cm, which experienced fluctuations in the load-deflection curve up to failure due to the inadequate confining effect and composite action of the plates.

Fig. 8 indicates that the increase in bolt spacing also decreased the amount of energy absorbed by a wall up to a certain deflection. The increase in the confining effect and composite action of the plate provided by more closely-spaced bolts increased the rate of energy absorption within the elastic and plastic limits in all of the four specimen groups with identical plate thickness. The only

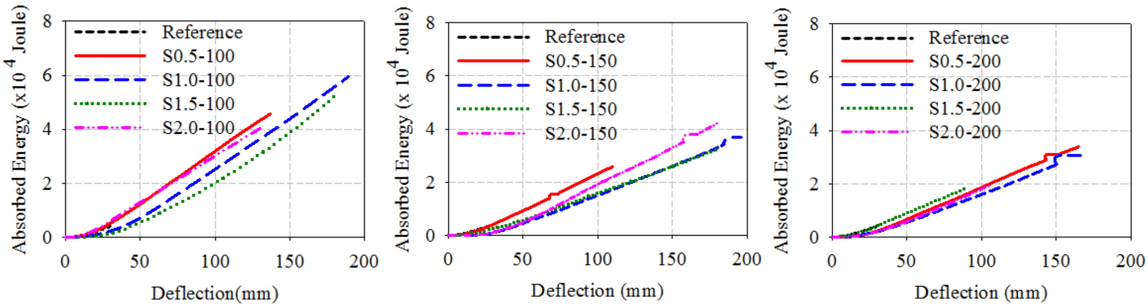


(a) plate with a thickness of 0.5 mm (b) plate with a thickness of 1.0 mm



(c) plate with a thickness of 1.5 mm (d) plate with a thickness of 2.0 mm

Fig. 8 Energy-deflection curves of the specimens with identical plate thickness



(a) a bolt spacing of 100 mm (b) a bolt spacing of 150 mm (c) a bolt spacing of 200 mm

Fig. 9 Energy-deflection curves of the specimens with identical bolt spacing exception for this conclusion is Specimen S1.5-100 (Fig. 8(c)), whose energy absorption rate remained below the rates of S1.5-150 and S1.5-200. This might be caused by the accidental experimental errors or initial geometric imperfections of S1.5-100. Later, the energy absorption rate of S1.5-100 exceeded the rates of S1.5-150 and S1.5-200 within the plastic limits. In general, the energy absorption rates of the specimens with a bolt spacing of 10 cm significantly exceeded the ones with a bolt spacing value of 15 cm or 20 cm for identical plate thickness. The specimens with a bolt spacing value of 20 cm had energy absorption rates in close agreement with the ones of specimens with a bolt spacing value of 15 cm.

3.2 Comparison of the specimens with identical bolt spacing

The tests conducted within the scope of the present study indicated that the plate thickness has a smaller influence on the behavior of infill walls compared to bolt spacing. Among the specimens with identical bolt spacing, increasing the plate thickness from 0.5 mm to 2.0 mm resulted in a 3-8% increase in the load capacity, and a 7-15% increase in the ductility index. On the contrary, the energy absorption capacity slightly increased or even sometimes decreased with increasing plate thickness among specimens with identical bolt spacing. Fig. 9(a) and 9(b) indicate that the energy absorption rate of a strengthened wall decreases, as the plate thickness increases since the deformability of the plate decreases with increasing thickness. Nevertheless, Fig. 9(c) shows a different trend. This figure indicates that the specimens with a bolt spacing of 20 cm had similar energy absorption rates within the elastic and inelastic limits of deformation. In other words, the plate thickness has a lesser influence on the energy absorption rate when the plates are poorly anchored to the wall.

The ultimate loads of the walls with a bolt spacing of 20 cm did not differ from each other significantly, while increasing the plate thickness resulted in greater increases in the load capacity among the specimens with a bolt spacing of 10 cm. The load capacity of S1.5-100 was about 35% greater than the load capacity of S0.5-100. Accordingly, increasing the plate thickness provides considerable increase in the load capacity of a wall, only if the plates are anchored to the wall with closely-spaced bolts.

Increasing the plate thickness provided considerable increases in the ductility indices of the walls no matter what the bolt spacing was. The ductility index of S1.5-100 was about 33% greater than the index of S0.5-100, while the ductility index of S2.0-200 was about 12% greater than the index of S0.5-200. Accordingly, the contribution of increasing the plate thickness to the ductility of the wall increases with decreasing bolt spacing.

4. Analytical study

The diagonal compressive force that causes the diagonal tension failure of an unstrengthened hollow brick infill wall can be calculated by using the analytical formulation given by FEMA 306 Manual (FEMA 1998). According to this approach, which is based on the study of Saneinejad and Hobbs (1995), the cracking shear (V_{cr}) of the infill is calculated from

$$V_{cr} = \frac{2\sqrt{2} \cdot t_{inf} \cdot L_{\inf} \cdot \sigma_{cr}}{\left(\frac{L_{\inf}}{h_{\inf}} + \frac{h_{\inf}}{L_{\inf}} \right)} \tag{1}$$

where t_{inf}, L_{inf}, and h_{inf} are the thickness, length, and height of the infill wall, respectively; and σ_{cr} the cracking strength of masonry, calculated from the following equation according to FEMA 306 (FEMA 1998)

$$\sigma_{cr} = \frac{f'_{me90}}{20} \tag{2}$$

where f'_{me90} is the compressive strength of masonry in the horizontal direction, i.e. parallel to the channels of the brick.
The reference unstrengthened wall failed in diagonal tension soon after the initiation of diagonal cracking in the wall. The analytical ultimate load (P_{an}) of the wall calculated from the cracking shear (Eq. (1)) is in a close agreement with the experimental ultimate load (P_{ult}) of the wall (Table 3), indicating that the wall failed in diagonal tension. A masonry wall ceases to carry diagonal loads once diagonal cracking initiates, since the diagonal crack, which initiates around the midheight of the wall, propagates rapidly and extends from one loaded corner to the other soon after its initiation. Due to this cracking, the tensile stresses carried by the wall up to cracking are transferred to the strengthening plates in a strengthened wall. This transfer prevents a sudden and abrupt change in the load at the initiation of cracking. The experiments of the present study indicated that the strengthened walls failed at loads well above the values at which diagonal tension cracking initiates. Therefore, the contribution of the wall itself to the diagonal load capacity of a strengthened wall was ignored.

Estimating the failure load of a strengthened wall is quite cumbersome if not impossible, since this load is closely related to the interface shear between the plates and the wall. In the present study, an equation was developed for estimating the shear capacities (V_p) of strengthened walls by assuming that a strengthened wall reaches its full capacity when yielding takes place across the entire length of the diagonal struts in the plates if adequate interface shear strength between the plates and the wall is provided. By modifying Eq. (1) for the case of strengthened walls, the following equation was obtained

Table 3 Comparison of the analytical and experimental results

Specimen	Ultimate Load (kN)		P_{ult}/P_{an}
	Experimental (P_{ult})	Analytical (P_{an})	
R	180	171	1.05
S0.5-100	350	367	0.95
S0.5-150	285	367	0.78
S0.5-200	250	367	0.68
S1.0-100	400	392	1.02
S1.0-150	240	392	0.61
S1.0-200	237	392	0.60
S1.5-100	466	587	0.79
S1.5-150	240	587	0.41
S1.5-200	244	587	0.42
S2.0-100	360	783	0.46
S2.0-150	310	783	0.40
S2.0-200	260	783	0.33

$$V_p = \frac{2\sqrt{2}\cdot\left[2t_p\cdot\left(L_p - L_h\right)\right]\cdot f_y}{\left(\dfrac{L_{\inf}}{h_{\inf}} + \dfrac{h_{\inf}}{L_{\inf}}\right)} \tag{3}$$

where t_p and L_p are the thickness and length of each strengthening plate, respectively; L_h the summation of the diameters of the holes along the length of the plate; and f_y the yield strength of the plates.

The analytical load values of the strengthened walls (P_{an}) obtained from the shear capacity values (V_p) are tabulated in Table 3 together with the experimental failure loads (P_{ult}). These values indicate that the specimens S0.5-100 and S1.0-100 failed at diagonal loads in close agreement with the values estimated by Eq. (3). As the spacing of the bolts increase for the same plate thickness, the difference between the analytical and experimental ultimate loads increases. The negative influence of increasing the bolt spacing on the load capacity of the strengthened wall is primarily related to the decrease in the friction stresses between the plate and the wall. As the number of bolts decrease, the total friction force in the plate-wall interface decreases. This causes the full capacity of the plate not to be developed in the lack of an adequate number of anchor bolts. For instance, almost the full capacity of the plate was developed in S0.5-100 and S1.0-100, while only 68% and 60% of the capacities of the plates were attained in S0.5-200 and S1.0-200 due to the lack of adequate interface shear in these specimens. In S0.5-200 and S1.0-200, the diagonal struts in the strengthening plates could not yield completely due to inadequate interface shear strength and the plates could not develop their full capacities.

The tabulated values also indicate that the differences between the analytical and experimental load values increase with increasing plate thickness. The composite action of the plate and the wall becomes more difficult to attain and the tendencies of the plate and the wall to behave separately increase as the plate thickness increases. The P_{ult}/P_{an} ratio decreased about 35-50% as the plate thickness increased from 0.5 mm to 2.0 mm for the same bolt spacing. In general, it can be said that the best composite action can be attained and the full capacity of the strengthening plates can be reached in walls strengthened with thin plates, which are anchored to the wall with closely-spaced bolts.

5. Conclusions

The present paper summarizes the analytical and experimental studies conducted as the first stage of a research program, aimed at investigating the contribution of strengthening the infill walls of RC frames with perforated steel plates to the lateral strength, stiffness, and ductility of infilled RC frames. In this stage, an unstrengthened reference and twelve strengthened hollow brick infill walls were subjected to monotonic diagonal compression, using a special loading frame that does not pre-impose the contact surface between the wall and the surrounding frame. Perforated steel plates were used for strengthening due to several advantages, including the low costs, wide availability, easy and quick installation and removal of these plates thanks to perforations, and the elimination of the need for epoxy in this technique. The effects of the use of perforated steel plates on the wall behavior were examined for different plate thickness and anchor bolt spacing values. The experimental ultimate loads of the strengthened walls were compared to the estimates obtained from an analytical formula, which ignores the contribution of the masonry wall itself due to diagonal tension cracking and considers that the diagonal load capacity of a strengthened infill wall is obtained from the load value reached when yielding takes place across the entire diagonal strut in the plate under diagonal compression. The following conclusions were drawn from these experimental and analytical studies:

- Strengthening with perforated steel plates greatly contributes to the strength, stiffness, and ductility values of hollow brick infill walls. The use of steel plates in the present experiments resulted in a 30-160 % increase in the load capacity, a 3-6 times increase in the ductility index, and a 4-14 times increase in the energy absorption capacity of the wall over the reference wall.
- Unlike bare brick walls, which fail suddenly and in a brittle manner due to the formation of diagonal tension cracks and crushing of the loaded corners, brick walls strengthened with perforated steel plates exhibit a ductile behavior and remain intact up to failure. This intact behavior is crucial for the safety of the inhabitants during an earthquake. The failure of the strengthened walls of the present study was caused by the out-of-plane buckling of the strengthening plates and crushing of the loaded corners.
- Spacing of the bolts, anchoring the plates to the wall, is more influential on the behavior of strengthened walls compared to the plate thickness. The decrease in the confining effect of the plates due to inadequate number of anchors results in the plates not to be able to develop their load capacities and to increase the deformation capacities of the strengthened walls to a major extent. Accordingly, the increase in the strength, stiffness, and ductility of the wall due to the use of plates reduces with increasing bolt spacing.
- When the plates are not anchored to the wall with closely-spaced bolts, the load capacity of the wall undergoes significant fluctuations within the elastic and inelastic deformation limits of the load-deflection curve. These fluctuations, which are caused by crushing of the wall and out-of-plane buckling of the plates, can be prevented by attaining sufficient composite action between the wall and the plates by adequate anchorage of the plates (closely-spaced bolts).
- Increasing the plate thickness results in a considerable improvement in the wall behavior only if the anchor bolts are closely-spaced. Although an increase in the plate thickness generally results in an increase in the strength and ductility of the wall, the energy absorption capacity of the wall does not necessarily increase. As the plate thickness increases, the deformation capacity of the plate decreases, generally resulting in a reduction in the energy absorption capacity of the wall.
- The amount of energy absorbed by a wall up to a certain displacement and the energy absorption rates in the elastic and inelastic portions of the load-deflection curve increase significantly as the spacing of the anchor bolts decreases. Nonetheless, the energy absorption rates decrease with increasing plate thickness, which is caused by the decreasing deformation capacities of the plates with increasing thickness.
- Strengthening with perforated steel plates does not affect the initial stiffness of a brick wall, significantly. The positive influence of the plates on stiffness is encountered by the negative influence of the bolt holes in the wall.
- The ultimate load capacity of a strengthened wall is solely provided by the strengthening plates. When the cracking shear of the wall is exceeded, the wall ceases to contribute to

the load-carrying capacity as a result of the diagonal tension cracks extending between the two loaded corners of the wall.

- The length of the contact surface between the loading frame and a wall assemblage changes in accordance with the load and damage level of the assemblage when testing an assemblage in diagonal tension. The present experiments indicated that the length of the contact surface varied from 20% to 40% of the side length of the assemblage during the test. The loading method proposed in this study offers advantages over the existing ASTM E519 (ASTM 2010) method by allowing the contact surface to change during the test instead of pre-imposing a constant contact surface.

The present study investigated the effects of the use of perforated steel plates on the individual behavior of the hollow brick infill walls of an RC frame. The findings of the present study were obtained from the limited number of tests, which mainly focused on the influence of bolt spacing and plate thickness on the wall behavior. More experiments with various test parameters, such as mortar strength, perforation pattern, etc., will be needed to validate the experimental findings of the present study and to reach more comprehensive conclusions about this strengthening technique. The influence of this strengthening technique on the overall behavior of the infilled RC frames will be investigated in the following stages of this research program.

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