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Strengthening of hollow brick infill walls with expanded steel plates

Alper Cumhur[*1], Adil Altundal[1a], Sabahattin Aykac[2b] and Bengi Aykac[2c]

[1]*Civil Engineering Department, Sakarya Üniversity, 54187 Sakarya, Turkey*
[2]*Civil Engineering Department, Gazi University, 06500 Ankara, Turkey*

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Abstract. An efficient, economical and practical strengthening method for hollow brick infill walls was proposed and investigated in the present study, experimentally and numerically. This method aims at increasing the overall lateral strength and stiffness of the structure by increasing the contribution of the infill walls and providing the non-bearing components of the structure with the capability of absorbing earthquake-induced energy to minimize structural damage during seismic excitations. A total of eleven full-scale infill walls strengthened with expanded mild steel plates were tested under diagonal monotonic loading to simulate the loading condition of the non-bearing walls during an earthquake. The contact surface between the plates and the wall was increased with the help of plaster. Thickness of the plates bonded to both faces of the wall and the spacing of the bolts were adopted as test parameters. The experiments indicated that the plates were able to carry a major portion of the tensile stresses induced by the diagonal loads and provided the walls walls with a considerable confining effect. The composite action attained by the plates and the wall until yielding of the bolts increased the load capacities, rigidities, ductilities and energy-absorption capacities of the walls, considerably.

Keywords: expanded steel plate; brick infill wall; structural strengthening; diagonal compression; seismic behavior; reinforced concrete frame

1. Introduction

Failure of structures as a result of severe earthquakes in different parts of the globe necessitate the implementation of efficient, economical and easily applicable structural strengthening methods. Structural strengthening applications primarily aim at preventing causalties by providing the structures with the capability of withstanding major earthquakes.

Hollow brick infill walls are only considered in the estimation of dead loads in a structure and their contribution to the vertical and lateral strength of the structural system is usually ignored. The studies carried out by Marjani and Ersoy (2002) and Xingke (2008) pointed out the considerable contribution

*Corresponding author, Assistant Professor, E-mail: alpercumhur@hitit.edu.tr
[a]Professor, E-mail: altundal@sakarya.edu.tr
[b]Associate Professor, E-mail: saykac@gazi.edu.tr
[c]Associate Professor, E-mail: baykac@gazi.edu.tr

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of these walls to the earthquake resistance of RC structures. Baran (2012) found out that hollow bricks and plaster significantly improve the lateral strength and stiffness of RC frames. Considering the fact that the earthquake-resistant structural design codes in different parts of the globe suggest the inclusion of infill walls in seismic analyses (Baran *et al*. 2014), various studies in the literature focused on strengthening the infill walls rather than the structural frame for improving the seismic behavior of structures. The use of different materials including FRP, shotcrete, steel fiber-reinforced mortar, steel strips, steel profiles, precast high-strength concrete panels, perforated mild steel plates, concrete/RC strips, ferrocement and epoxy in strengthening hollow brick infill walls was investigated in various studies in the literature.

Triantafillou (1998) found that the FRP laminates are prone to separation from the wall, subjected to compression and in-plane bending, if adequate bonding is not provided between the laminate and the wall. The tests also indicated the significant contribution of CFRP laminates to the shear and out-of-plane bending moment capacities of brick walls. The experiments conducted by Vandergrift *et al*. (2002) showed that CFRP strips improve the ductilities and energy absorption capacities of the walls yet cannot provide the walls with the capability of remaining intact at large deformations. Ozcebe *et al*. (2003) established the significant contribution of diagonal CFRP strips on both faces of brick walls to the overall lateral strength and rigidity of RC frame. El-Dakhakhni *et al*. (2006) found that FRP laminates prevent disintegration of URM walls even at high deformation levels. The experiments of Erdem *et al*. (2006) pointed out the significance of the connections between CFRP strips and the wall in the efficiency of the strengthening procedure. Altin *et al*. (2008) established that symmetrical strengthening on both faces of the walls with diagonal CFRP strips provides significant increases in the load-carrying capacity and rigidity of an infill wall while reducing the lateral displacement at ultimate load. In seeking for an alternative strengthening method for historical structures, the use of fiber-reinforced mortar (FRM) was investigated in several studies (Triantafillou and Papanicolaou 2006, Triantafillou *et al*. 2006, Prota *et al*. 2006, Papanicolaou *et al*. 2007, Papanicolaou *et al*. 2008) due to the higher fire resistance of this strengthening material. Papanicolaou *et al*. (2011) experimentally found out that strengthening with the help of basalt and glass fiber reinforced mortar is quite efficient in increasing the ductilities of stone walls. Kahn (1984) showed that the anchor nails connecting the shotcrete layer to the wall and covering the wall faces with epoxy have little influence on the monotonic diagonal behavior of brick walls strengthened with reinforced shotcrete. The tests of Acun and Sucuoglu (2005) on one-bay two-storey RC frames indicated that strengthening the brick walls with welded wire mesh covered with plaster improves the lateral strength and rigidity of the frame, significantly. ElGawady *et al*. (2006) found that strengthening the both faces of an infill wall with shotcrete reinforced with wire mesh improves the behavior of the wall under both axial and lateral loads. The tests conducted by Sevil *et al*. (2011) on one-bay two-storey RC frames exhibited that retrofitting the infill walls with mortar containing plasticizers and steel fibers results in tremendous increases in the lateral strength, stiffness and energy absorption capacity values of the frame.

Baran and Tankut (2011) found that precast concrete panels provide major improvements to the earthquake behavior of one-bay two-storey RC frames and decrease the shear deformations in the infill walls if adequately anchored to the frame. Baran *et al*. (2014) used concrete/RC strips for strengthening brick walls and this strengthening method efficiently improved the behavior of the walls under lateral loads. Topcu *et al*. (2005) proposed and investigated the use of ferrocement in strengthening the brick walls due to the several advantages of this method including its ease of application and economy. Araki *et al*. (2011) and Bu *et al*. (2011) experimentally exhibited the efficiency of epoxy injection to the joint regions between the bricks in improving the shear and bending strenghs and ductilities of infill walls.

Different from the abovementioned studies, Taghdi *et al*. (2000a) proposed the use of diagonal and vertical mild steel strips in strengthening brick and concrete walls. The tests carried out in this study proved the efficiency of the use of steel strips in wall strengthening applications. Later, Taghdi *et al*. (2000b) developed analytical formulations for estimating the load capacities of walls strengthened with steel strips. Farooq *et al*. (2006) established that the major contribution of steel strips bonded to both faces of a wall to the compressive and shear capacities of brick walls stems from the confining effect provided by these strips. Ozbek and Can (2012) used steel angles and steel flag plates in strengthening brick walls and found that providing flag plates on all corners of a brick wall prevents major damage in the corners and improves the behavior of the walls, considerably. Aykac *et al*. (2014) investigated the influence of strengthening brick infill walls with perforated steel plates, which proved to be efficient in providing the brick walls with significant ductilities and energy absorption capacities. Hamidreza and Soodeh (2014) conducted nonlinear static analyses on infilled RC frames under different lateral loading patterns and recommended design guides to prevent progressive failure of RC frames during earthquakes.

The strengthening methods proposed by the previous researchers aimed at improving the behavior of infill walls under reversed cyclic lateral loads in order to provide the structural frame with non-bearing elements which can absorb a major portion of the free earthquake-induced energy. In this way, the bearing elements of the structural frame are prone to less damage during seismic excitations. The strengthening techniques also aimed at providing the walls with greater lateral strength and stiffness to increase the overall lateral load capacity and rigidity of the structure. Due to their lower prices, ductile nature and easy applicability, mild steel elements proved to be efficient in strengthening the infill walls as suggested by the experiments of Taghdi *et al*. (2000a, b), Ozbek and Can (2012) and Aykac *et al*. (2014). The present study focused on the use of expanded steel plates in strengthening brick walls owing to their several advantages, including but not limited to the following ones:

• The staggered openings of the expanded steel plates ensure a perfect bond between the plate and the plaster. This bond contributes to the composite action between the wall, plates and plaster.

• The staggered pattern of openings increases the ductility of the plates. This pattern and the ductile nature of mild steel provide the plates with high deformability, which in turn increases the ductility and energy absorption capacity of the strengthened wall.

• These plates are light and less costly compared to the majority of the strengthening materials and they provide the wall with aesthetic view.

• Thanks to the openings in the plates, the plates can be easily fixed to the wall with the help of bolts. This easy application reduces the cost and workmanship required for the strengthening process which is crucial in large structures where many walls need to be strengthened.

• The plates provide confining effect to the brick wall, which increase the compressive strength of the wall. Furthermore, the tensile stresses in the wall are carried by the steel plates after the formation of diagonal cracks in the wall. This two-fold effect of the plates contributes to the diagonal load capacity of a brick wall, significantly.

• The strengthening procedure can be conducted without damaging the water and sanitary fixtures in the wall if the locations of these fixtures are marked on the wall. These marks remain visible during the process thanks to the large openings in the plates.

In the present study, 11 brick infill wall specimens, including a reference unstrengthened and ten strengthened, were tested under monotonic diagonal loading. Thickness of the expanded plates and spacing of the bolts connecting the plates to the wall were chosen as test parameters. The test results were compared in terms of load capacities, rigidities, ductilities and energy absorption capacities of the walls. Finally, the experimental load values were compared to analytical estimates obtained from a formula developed by Aykac *et al*. (2014).

2. Experimental study

2.1 Test specimens

In the experimental phase of the study, brick infill wall panels with a height of 1000 mm and a width of 1000 mm were tested. The specimens composed of 85×190×190 mm bricks and the bricks were laid in a way that their channels were oriented horizontally. Both faces of the unstrengthened reference specimen were plastered. In strengthened specimens, the expanded steel plates were directly applied on both faces of the wall (Fig. 1) and later covered with plaster. Thickness of the plates used in strengthening and spacing of the anchor bolts in each specimen are tabulated in Table 1. The openings in the plates were 20 mm wide and 50 mm long and the strips had a width of 3 or 4.5 mm (Fig. 2).

The specimens were denoted with a capital letter and two numbers following the letter. The capital letter “R” denotes the reference specimen, while the letter “B” corresponds to the strengthened specimens. The first number following the letter (1.5, 2.0 and 3.0) corresponds to the thickness of the expanded plate, while the second number (100, 150 and 200) corresponds to the spacing of the M6 bolts fixing the plates to the wall.

2.2 Material properties

The bricks had a compressive strength of 6.3 MPa parallel to the horizontal channels and 3.2 and 3.1 MPa perpendicular to the channels in short and long directions, respectively. To determine the material properties of the mortar and plaster used in the specimens, three cylinders were taken from each cast. The tests on these cylinders showed that the mortar and plaster had an average

Table 1 Test specimens

Specimen	Plate Thickness (mm)	Bolt Spacing (mm)	Number of M6 Bolts
R	-	-	-
B1.5-100	1.5	100	100
B1.5-150	1.5	150	49
B1.5-200	1.5	200	25
B1.5-500	1.5	200	25
B2.0-100	2.0	100	100
B2.0-150	2.0	150	49
B2.0-200	2.0	200	25
B3.0-100	3.0	100	100
S3.0-150	3.0	150	49
S3.0-200	3.0	200	25

Fig. 1 Expanded steel plate application

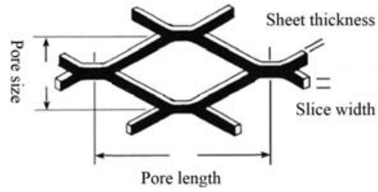


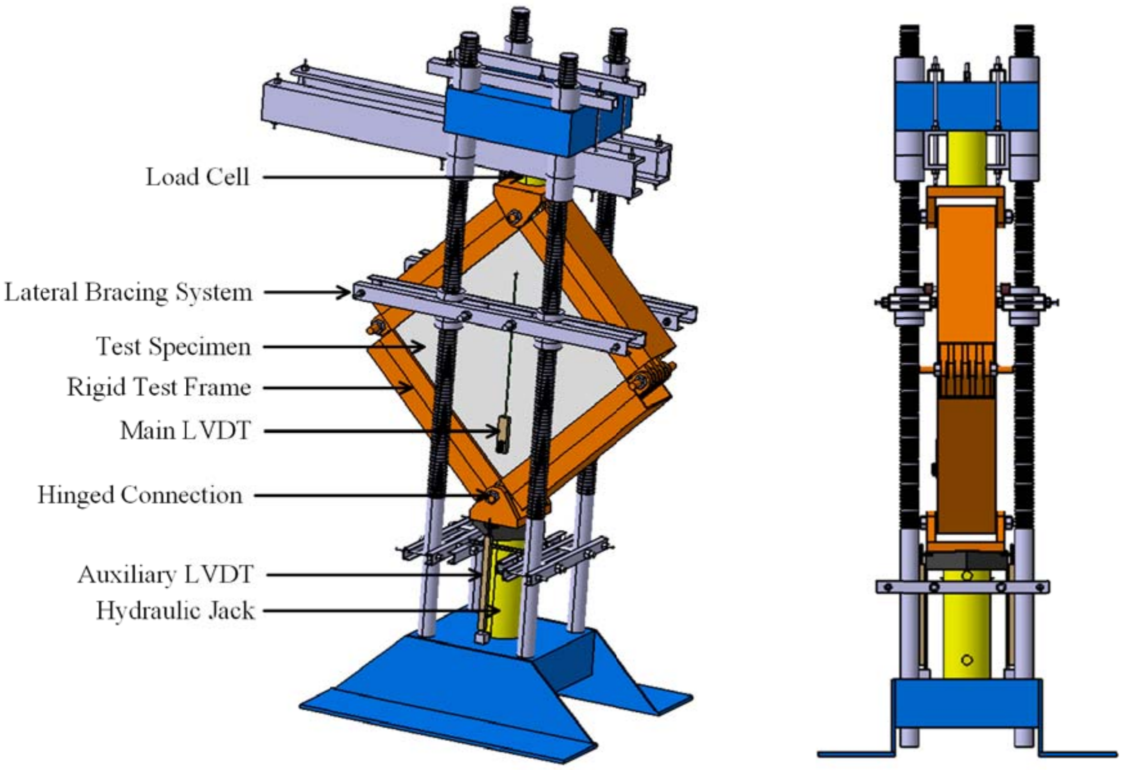
Fig. 2 Pattern of the expanded steel plate

compressive strength of 10 and 9 MPa, respectively. The M6 bolts connecting the expanded plates to the wall were post-tensioned with a torque of 3 N.m. The plates were of Grade 280.

2.3 Loading and measurement system

Sayin and Kaplan (2005) found out that infill walls carry diagonal forces in the presence of lateral earthquake loads in the structural frame. To simulate this loading scenario, the specimens were tested under diagonal loading in the present tests. For this purpose, the rigid frame illustrated in Fig. 3 was constructed. This frame consisted of four rigid legs connected to each other with hinges. The four hinged connections at four corners caused the frame to be unstable so that the frame around the specimens did not provide any resistance to the diagonal loads except the negligible friction forces at connections. The load was applied by a single action hydraulic jack, placed underneath the rigid frame, and measured by a load cell above the rigid frame (Fig. 3).

The present test frame allowed the contact surface between the wall and frame to change in the tests with increasing wall deformations, similar to the loading condition between the wall and RC frame in an actual structure. In ASTM E519 method (ASTM 2010), which is commonly used in diagonal compression loading of brick wall samples, the masonry specimens are tested with the help of two loading shoes, confining the two loading corners of the wall. The ASTM test method has a major disadvantage, which causes the testing conditions to be significantly different from the real conditions of an infill wall in an RC frame. In this method, the contact surface between the confining plates of the loading shoes and the sides of a wall are pre-imposed and this contact surface (12% of the side surface) does not change throughout the test, unlike the contact surface of a real infill wall with the surrounding frame. The equivalent width of the diagonal compression strut in the wall depends on the contact surface between the wall and surrounding frame. Consequently, the equivalent width of the diagonal compression strut in the wall is constant up to failure in the ASTM approach. The constant contact surface is not a cause of concern in plain brick walls, since these walls are subjected to limited deformations up to failure. The strengthened walls, on the other hand, undergo much greater deformations compared to plain walls up to failure. Consequently, the contact surface between the loading mechanism and the strengthened wall should not be limited to allow the width of the diagonal compression strut to change in the test, similar to the conditions in an actual frame. The present and previous experiments conducted by the authors (Aykac *et al*. 2014) indicated that the length of the contact surface on each side of a strengthened wall varied from 20% to 40% of the side length throughout the test and the



(a) Elevation view (b) Side view

Fig. 3 The test frame

strengthened walls reached their ultimate loads after excessive deformations. For this reason, limiting the contact surface, through which the load is conveyed to the wall, and the width of the compression strut will definitely reduce the load capacity and the deformations of a strengthened wall. In other words, the efficiency of the strengthening method and its contribution to the load-deflection behavior of an infill wall could not be fully determined in the ASTM test method.

Each wall specimen was placed in the rigid frame and tested under monotonic diagonal loads continuously up to failure. The loading speed was increased with increasing wall deformations. The diagonal deformations in the wall were measured with the help of LVDT's with a precision of 0.01 mm. Two LVDT's were installed directly on the two faces of the specimen, while additional two transducers were installed between the lower base of the test frame and the rigid test frame (Fig. 3). The additional two LVDT's were used for ensuring continuous deformation measurement even if the two LVDT's on the specimen cease to measure accurate deformation values due to possible damage in the specimen. The LVDT on the front face of the specimen measured the shortening of the specimen in the direction of the applied load (vertical direction), while the LVDT on the rear face of the specimen measured the elongation in the perpendicular (horizontal) direction. The load and deformation measurements, acquired by a high resolution load acquisition system (Fig. 4), were recorded and monitored by a computer continuously during the test. Finally, the test videos were also recorded (Fig. 4).

(a) Video recording of the tests

(b) Data acquisition system

Fig. 4 Measurement and recording system in the tests

3. Failure modes of specimens and discussion of test results

Unlike the unstrengthened reference specimen, which failed with very limited ductility, the strengthened specimens exhibited ductile behavior up to failure. Despite reaching different ductility and load capacity levels, all strengthened specimens underwent significant diagonal deformations and remained intact up to failure. The strengthening plates on both faces of the brick wall resisted the tensile stresses after cracking and prevented the diagonal tension cracks in the wall to propagate and widen with increasing applied load. The plaster on the plates increased the bonding between the plates and wall, improving the composite action. The wall deformations at failure are illustrated in Fig. 5. The load-deformation curves of the specimens, shown in Fig. 6, indicate the significant contribution of the expanded steel plates to the load capacity, ductility, energy absorption capacity and initial rigidity values of the strengthened specimens.

Table 2 presents the yielding and ultimate load values of the specimens. The yielding load corresponds to the load value at which yielding of the strengthening plate initiated and the load-deflection curve deviated from the initial linear segment. The ultimate load corresponds to the maximum load value reached by each specimen during the test. The ratio of the ultimate load of each specimen to the ultimate load of the reference specimen is illustrated in Table 3 as well as the deformation ductility index, initial rigidity and modulus of toughness values of the specimens.

The load values tabulated in Table 2 and Table 3 indicate that the strengthened specimens reached ultimate load values in the range of 1.0-3.0 times the ultimate load capacity of the bare reference specimen. The specimen B1.5-500, which had the greatest bolt spacing and the lowest plate thickness among the strengthened specimens, reached an ultimate load in the order of the load capacity of the reference specimen. Nonetheless, Fig. 6(a) indicates that B1.5-500 was able to undergo significant deformations without excessive reductions in its load-carrying capacity unlike the reference specimen, which failed suddenly and in a very ductile manner immediately after reaching its ultimate load. Specimen B3.0-100, which had the greatest plate thickness and the most closely-spaced bolts among the specimens, had an ultimate load about 200 % higher than the capacity of the reference specimen. In general, the load capacity can be seen to increase with increasing plate thickness and decreasing bolt spacing.

The initial rigidities of the specimens are also tabulated in Table 3. The initial rigidity values were obtained from the ratio of yielding load to the deformation at yielding load. The ratio of the initial rigidity of each specimen to the initial rigidity of the reference specimen is also shown in the table together with the absolute values (kN/mm). The tabulated values indicate that the strengthening method resulted in 20-220% increase in the initial rigidity of the wall. According to these values, the bolt spacing does not have a noticeable influence on the initial rigidity of the wall, while the rigidity generally increases with increasing plate thickness.

The structures are designed to undergo elastic deformations and return to their original undeformed state when exposed to earthqukes of low magnitude. Nevertheless, in the case of heavy earthquakes, designing a very rigid structural system, not prone to permanent deformations, is not economical. Therefore, structures are expected to undergo permanent deformations and absorb earthquake-induced energy in the plastic ranges of deformation without collapse when subjected to severe earthquakes. Modulus of toughness indicates the total amount of energy transmitted to a structural member or a structure up to failure. This modulus includes the recovered energy (energy transmitted to a structure in the elastic range of deformation) and the dissipated energy (energy transmitted to a structure in the plastic range of deformation). In the present study, the modulus of toughness (MOT) values of the test specimens are examined since MOT indicates the deformability of a structure before permanent collapse. The MOT values reported in Table 3 are the values including the area under the load-deflection curve up to a deflection value of 250 mm, the maximum deformation limit allowed by the test setup. Furthermore, the energy absorption rates of the specimens with increasing deflection are illustrated in Fig. 7.

The relative MOT values given in Table 3 indicate that this strengthening procedure provided the brick walls with energy capacities between 6-18 times the capacity of the reference unstrengthened wall. Even the wall B1.5-500, having the gretest bolt spacing and the smallest plate thickness among the specimens, reached a MOT value about 6 times the value of the bare wall, implying the efficiency of this technique on the energy capacity of the wall. The energy capacity can be seen to generally increase with decreasing bolt spacing and increasing plate thickness. In Specimen B3.0-100, which had the smallest bolt spacing and greatest plate thickness among the specimens, the increase in the capacity reached 17 times the capacity of the bare wall.

The strengthening methods also aim at providing the brick walls with ductile behavior so that the walls remain intact and preserve a major portion of their load capacities till the end of an earthquake. According to Eurocode 8 (CEN 2003), the deformation ductility index (DDI) of a structural member is the ratio of deflection at 85% of the ultimate load in the tail of the load-deflection curve to the deformation at initiation of yielding. Nevertheless, this definition of DDI was not applicable to the specimens of the present study.

The tests on the specimens were pursued up to a deflection value of 250 mm due to the limitations of the test setup. The load capacities of majority of the specimens at ultimate deformation (250 mm) were greater than 85% of the ultimate load. Consequently, the DDI definition of Eurocode 8 (CEN 2003) could not be used in the present study. Instead, a load value denoted as the average load (P_{ave}) was calculated for each specimen. P_{ave} is the arithmetic average of the load values along the load-deflection curve. P_{ave} values of the test specimens are tabulated in Table 2. In the present study, the ratio of the deflection at 85% of the average load to the deflection at yielding was adopted as DDI. If the load at ultimate deflection (250 mm) remained above 85% of the average load, DDI was calculated by dividing the ultimate deflection to the yielding deflection. The DDI values calculated accordingly are shown in Table 3. Since yielding of the strengthening plate does not take place in the reference specimen and this specimen fails suddenly in a brittle manner, the DDI value of the reference specimen was taken 1. Therefore, the DDI values of the strengthened specimens also correspond to the ratio of the ductility of a strengthened wall to the ductility of the bare wall.

(a) Specimen R

(b) Specimen B1.5-100

(c) Specimen B1.5-150

(d) Specimen B1.5-200

(e) Specimen B1.5-500

(f) Specimen B2.0-100

(g) Specimen B2.0-150

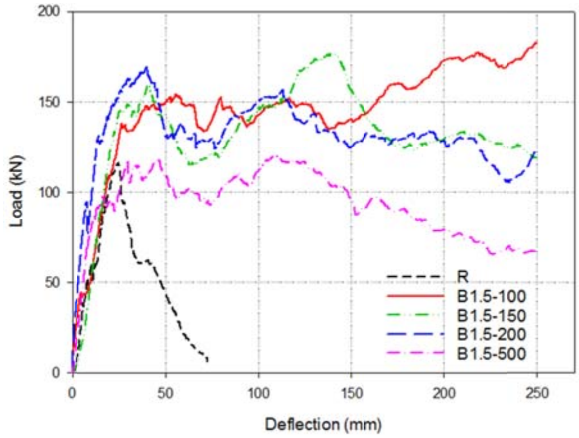
(h) Specimen B2.0-200

(i) Specimen B3.0-100

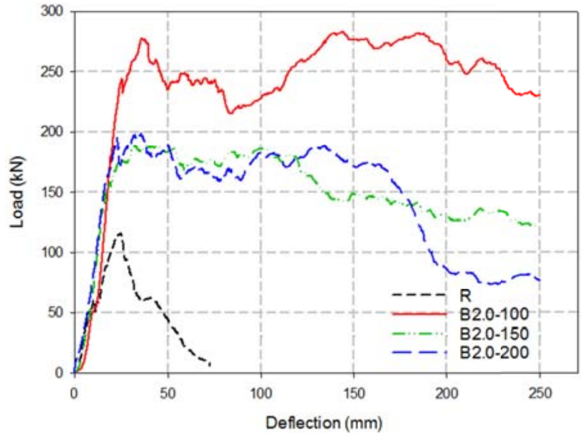
(j) Specimen B3.0-150

(k) Specimen B3.0-200

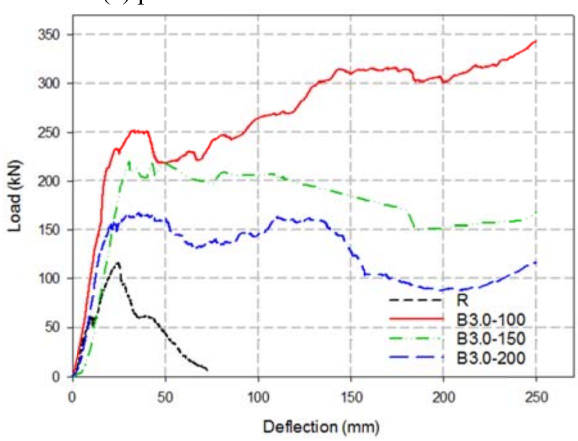
Fig. 5. Deformations in the specimens at failure



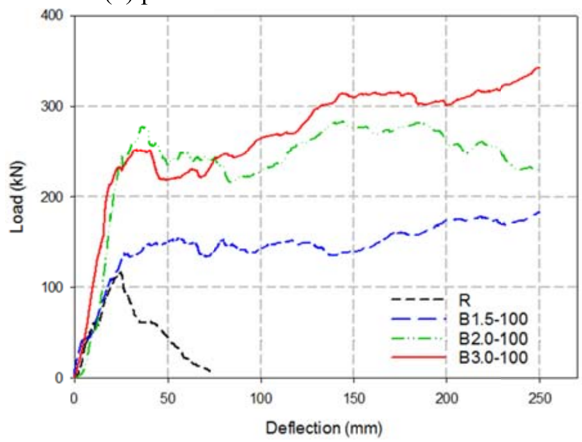
(a) plate with a thickness of 1.5 mm



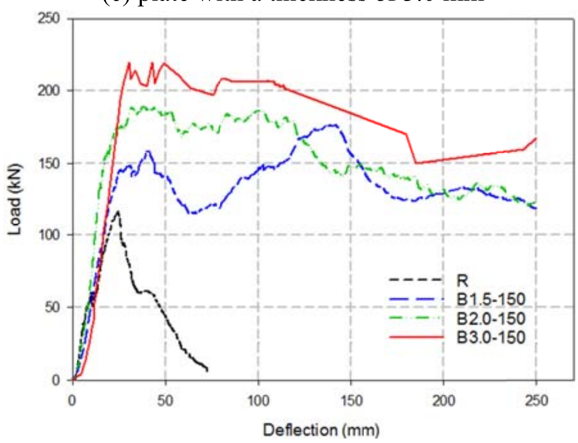
(b) plate with a thickness of 2.0 mm



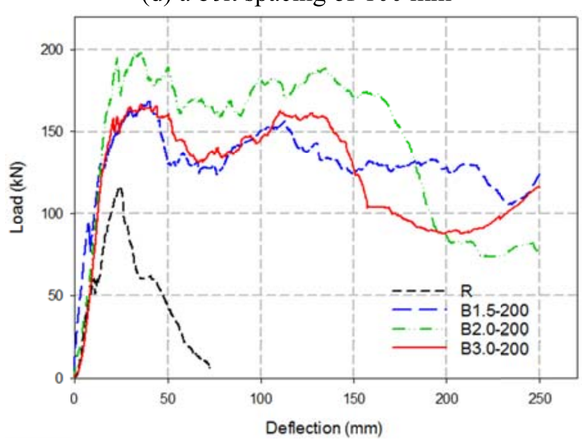
(c) plate with a thickness of 3.0 mm



(d) a bolt spacing of 100 mm

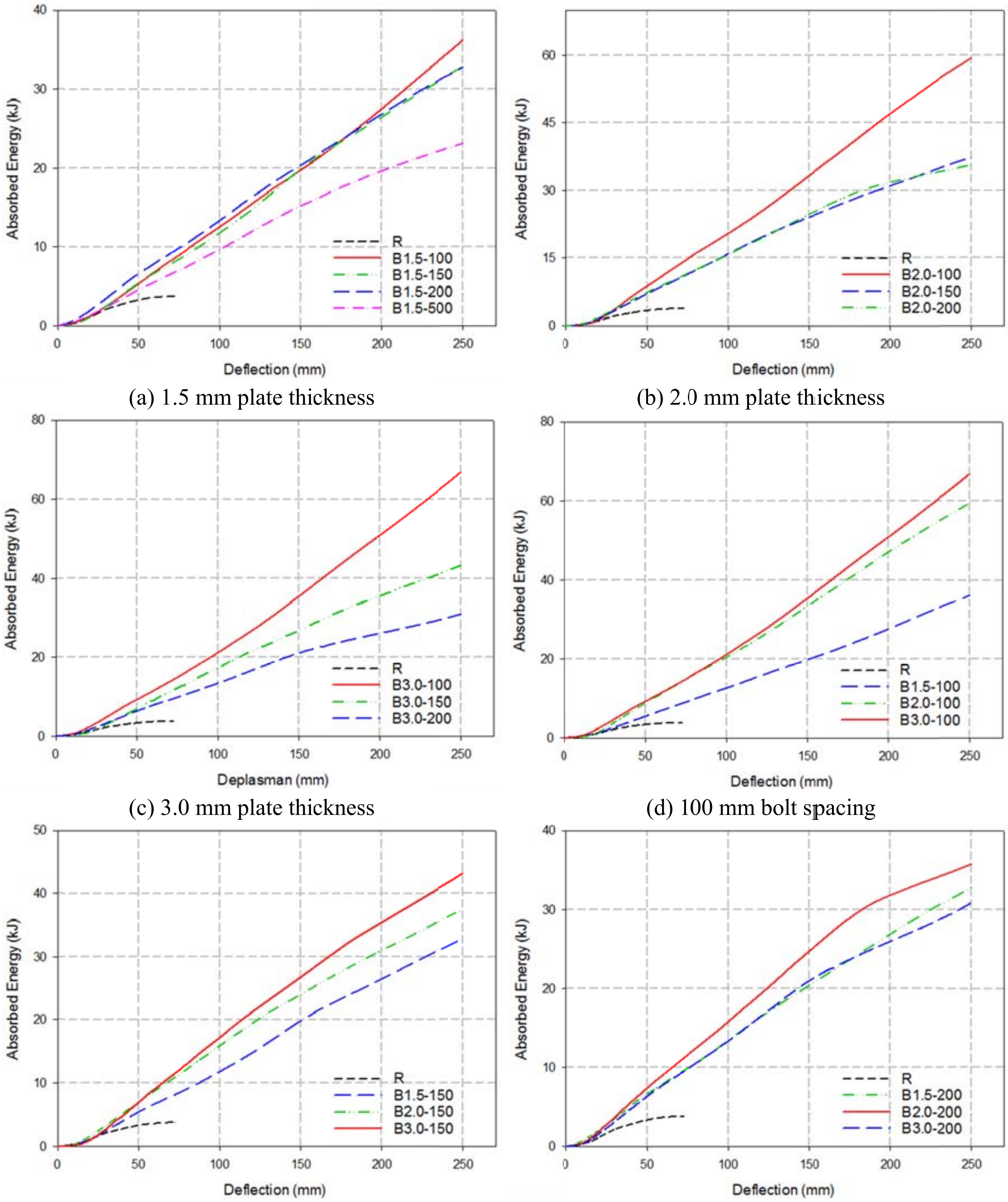


(e) a bolt spacing of 150 mm



(f) a bolt spacing of 200 mm

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



(a) 1.5 mm plate thickness (b) 2.0 mm plate thickness

(c) 3.0 mm plate thickness (d) 100 mm bolt spacing

(e) 150 mm bolt spacing (f) 200 mm bolt spacing

Fig. 7 Absorbed energy-deflection curves of the specimens

Table 2 The yielding, ultimate and average load values of the specimens

Numune	P_y (kN)	P_{max} (kN)	P_{ave} (kN)
R	110	117	117
B1.5-100	135	183	148
B1.5-150	141	176	141
B1.5-200	130	170	141
B1.5-500	90	120	120
B2.0-100	240	283	252
B2.0-150	153	189	165
B2.0-200	170	199	164
B3.0-100	214	343	268
B3.0-150	207	220	205
B3.0-200	148	167	139

Table 3 Comparison of the test results

Specimen	Ultimate Load		Initial Rigidity		Deformation Ductility Index (DDI)	Modulus of Toughness	
	Absolute (kN)	Relative	Absolute (kN/mm)	Relative		Absolute (kJ)	Relative
R	117	1.00	5.0	1.0	1.0	3.74	1.0
B1.5-100	183	1.56	6.1	1.2	9.2	36.20	9.7
B1.5-150	176	1.50	7.1	1.4	9.9	32.85	8.8
B1.5-200	170	1.45	10.8	2.2	16.8	32.77	8.8
B1.5-500	120	1.03	9.0	1.8	15.0	23.14	6.2
B2.0-100	283	2.42	16.0	3.2	11.8	59.37	15.9
B2.0-150	189	1.62	12.8	2.6	12.1	37.44	10.0
B2.0-200	199	1.70	12.1	2.4	10.3	35.71	9.5
B3.0-100	343	2.93	12.6	2.4	11.8	66.83	17.9
B3.0-150	220	1.88	10.4	2.1	9.8	43.27	11.6
B3.0-200	167	1.43	11.4	2.3	9.4	30.81	8.2

The DDI values of the strengthened walls vary between 9-17 times the DDI value of the reference specimen, indicating the significant contribution of the strengthening method on the ductility of the wall. Specimen B1.5-200 had a ductility index about 16 times greater than the ductility of the bare wall.

For identical plate thickness, the bolt spacing proved to be quite influential in improving the monotonic diagonal behavior of the strengthened wall. As the bolt spacing increases, the unsupported lengths of the plates, i.e., the lengths of the plate segments between two adjacent bolts, increase. Consequently, the buckling loads of the plates decrease with increasing bolt spacing and the strengthening plates cease to contribute to the load capacity of the strengthened wall at lower load levels. As the bolt spacing increases, the composite action in the wall and the confining effect of the plates on the wall are lost at earlier stages of loading and the full capacity of the composite wall could not be developed. Therefore, the load capacity of the strengthened wall decreases with increasing bolt spacing. Similarly, the reduction in the confining effect of the plates with increasing bolt spacing results in reductions in the initial rigidity of the wall. Increasing the bolt spacing from 100 mm to 200 mm can be seen to decrease the relative initial rigidity of the wall from 3.2 to 2.4, when the test results of specimens B2.0-100, B2.0-150 and B2.0-200 are considered (Table 3).

The DDI values of the specimens can be seen not be influenced significantly from the bolt spacing (Table 3). The modulus of toughness values, on the other hand, decreased considerably with increasing bolt spacing in all specimen groups with identical plate thickness. In strengthened walls with a plate thickness of 3.0 mm, for instance, increasing the bolt spacing from 100 mm to 200 mm caused the MOT value to decrease from 18 to 8 times the MOT value of the bare wall. Fig. 7(a)-7(c) indicate that the energy absorption rates throughout the course of loading also increase with decreasing bolt spacing.

The plate thickness does not affect the behavior of the strengthened wall as much as the bolt spacing. In all specimen groups with identical bolt spacing (100, 150 and 200 mm), the load capacity generally increased with increasing plate thickness (Table 3). The increase in the load capacity with increasing plate thickness is more considerable in specimens with a bolt spacing of 100 and 150 mm. This implies that the increase in the plate thickness is more influential on the wall behavior when a higher degree of composite action is attained with the help of closely-spaced bolts. The initial rigidity of the strengthened wall increased for different bolt spacing values when the plate thickness increased from 1.5 mm to 2.0 mm. The strengthened walls with a plate thickness of 3.0 mm, however, had initial rigidities slightly greater or smaller than the rigidities of the specimens with a plate thickness of 2.0 mm for identical bolt spacing. This might stem from the difficulty of attaining composite action in the case of thicker strengthening plates. Increasing the plate thickness for the same value of bolt spacing does not have a definite positive influence on the DDI value of the strengthened wall, as derived from the values tabulated in Table 3. Finally, the MOT value can be seen to generally increase with increasing plate thickness. This increase is more pronounced in specimens with a bolt spacing of 100 mm thanks to the greater confining effect of the plates. Fig. 7(d)-7(f) illustrate that the energy absorption rate throughout the course of loading also increases with increasing plate thickness.

4. Analytical study

The FEMA 306 Manual (FEMA 1998) gives the following analytical expression, which is originally developed by Saneinejad and Hobbs (1995), for the calculation of the cracking shear force (V_{cr}) of an infill wall

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

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, obtained from the following formula

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

where f'_{me90} is the compressive strength of masonry in the horizontal direction. Previously, Aykac *et al*. (2014) proposed the following formula for estimating the ultimate lateral load capacities (V_p) of the strengthened brick walls

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

where t_p and L_p are the thickness and length of the strengthening plate on each side of the wall and 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. Eq. (3) is based on the observations of Aykac *et al*. (2014), who found out that the brick wall itself has no contribution to the ultimate load capacity of a strengthened wall since it is in a completely cracked state at ultimate load levels. So, the analytical value calculated from Eq. (3) represents the capacity provided by the strengthening plates if the plates are bonded to the wall, perfectly.

Table 4 presents the analytical load estimates from Eq. (3) together with ratio of the experimental ultimate load of each specimen to the analytical value. The tabulated values indicate that the difference between the experimental and analytical values increases as the plate thickness and the bolt spacing increase. The greater differences with increasing plate thickness and bolt spacing stem from the fact that Eq. (3) estimates the diagonal load capacity of a strengthened wall when the plates are perfectly bonded to the wall and there is a perfect composite action between the plates and the wall. As a matter of fact, the experimental ultimate load values of Specimens B1.5-100 and B1.5-150 are in close agreement with the analytical values, implying the accuracy of the load estimates in the case of good bonding between the plates and the wall. The composite action decreases with increasing bolt spacing and increasing plate thickness and the deviation of the analytical estimates from the experimental values increase. The experimental ultimate load of Specimen B3.0-200 was only 30 % of the analytical estimate, caused by the low degree of composite action in this specimen. Finally, the specimen B1.5-500, which had the greatest bolt spacing among all specimens, was able to reach 60 % of the analytical estimate, representing the

Table 4 Comparison of the analytical and experimental results

Specimen	Ultimate Load (kN)		P_{ult}/P_{an}
	Experimental (P_{ult})	Analytical (P_{an})	
B1.5-100	183	191	0.96
B1.5-150	176	191	0.92
B1.5-200	170	191	0.89
B1.5-500	120	191	0.63
B2.0-100	283	381	0.74
B2.0-150	189	381	0.50
B2.0-200	199	381	0.52
B3.0-100	343	572	0.60
B3.0-150	220	572	0.38
B3.0-200	167	572	0.30

capacity in the presence of full composite action between the plates and the wall. This result implies that the brick walls strengthened with thin plates are able to approach their full capacities (composite action) even in the presence of rather widely-spaced bolts. The brick walls strengthened with thin plates can reach the full composite action much more easily than the wall strengthened with thick plates.

5. Conclusions

Strengthening hollow brick infill walls with expanded mild steel plates was investigated. A total of 11 test specimens, including a reference unstrengthened specimen, were tested under monotonic diagonal loading. The expanded steel plates were installed on both faces of the wall, covered with plaster and connected to the wall and to each other with the help of post-tensioned M6 bolts. The expanded steel plates were used in strengthening owing to their several advantages, including but not limited to easy installation, the lack of need for chemical adhesives, low costs and higher availability of the plates and higher deformation capacities of the plates thanks to the ductile nature of mild steel and the perforations on the plates. Thickness of the strengthening plates and spacing of the bolts were adopted as the test parameters. The test results were evaluated based on the load and energy capacities, initial rigidities and ductilities of the specimens. Finally, the ultimate load values of the specimens were compared to analytical estimates from an equation, originally developed by Aykac *et al*. (2014). The analytical and experimental studies conducted within the study yielded to following conclusions:

- • The proposed strengthening method proved to be quite effective in improving the monotonic diagonal behavior of the brick infill walls. The method was found to provide the brick walls with an increase of 0-200 % in the ultimate load capacity, an increase of 20-220 % in the initial rigidity, a 8-16 times increase in the deformation ductility index and a 5-17 times increase in the modulus of toughness. Even the specimen B1.5-500, which had the smallest plate thickness and greatest bolt spacing among the strengthened specimens, was able to reach ductility and energy capacity values substantially beyond the respective values of the bare reference wall.

• Unlike the bare reference specimen, which exhibited a brittle behavior and failed immediately after the formation of diagonal tension cracks, the walls strengthened with expanded steel plates underwent excessive diagonal deformations before failure. The strengthened walls remained intact and no significant disintegration took place in the walls till the end of the tests, implying the significance of the proposed method for prevention of the casualties during earthquakes. The plaster on the expanded steel plates, which is necessary for aesthetic appereance and hiding the diagonal tension cracks in the wall, was found to contribute to the bonding between the plates and the wall.

• The expanded steel plates on both sides of the wall was found to have a two-fold contribution to the behavior of the infill wall. First, the plates on both sides increased the compressive strength of the wall thanks to the confining effect. Secondly, the expanded steel plates were able to resist the tensile stresses in the wall after the formation of diagonal tension cracks. Consequently, the load capacities of the strengthened walls continued to increase after the formation of diagonal tension cracks.

• Decreasing the bolt spacing results in considerable improvements in the ultimate load capacity, initial rigidity and modulus of toughness values and energy absorption rates of the brick walls. These improvements stem from the fact that the buckling loads of the strengthening plate increase with decreasing bolt spacing since the unsupported lengths of the plate segments between the adjacent bolts decrease. As the bolt spacing increases, the strengthening plates cease to contribute to the behavior and the load capacity of the wall starts decreasing at earlier stages of loading before the full capacity of the composite body can be developed. Furthermore, more closely-spaced bolts provide better confining effect to the bricks, resulting in an increase in the compressive load capacity of the brick wall, itself.

• The experiments indicated that the plate thickness does not have as pronounced influence on the monotonic diagonal behavior of the infill walls as the bolt spacing. The positive influence of increasing the plate thickness on the load and energy capacity and initial rigidity of the strengthened wall was found to increase with decreasing bolt spacing. This implies that increasing the plate thickness is only beneficial if the plates are connected to each other and to the wall with closely-spaced bolts. Otherwise, higher degrees of composite action cannot be attained between the plates and the wall by increasing the thickness of the plates.

• The analytical equation developed by Aykac *et al*. (2014) for strengthened infill walls accurately estimates the ultimate load capacities of the walls if adequate bonding between the plates and the wall is attained. The accuracy of the estimates decreases with increasing bolt spacing and increasing plate thickness as a result of the decreasing composite action between the plates and the wall.

In the present study, the bare and strengthened brick walls were tested under monotonic compressive loading to investigate the contribution of the expanded steel plates on the diagonal load capacities of the infill walls. In the further stages of the present research, strengthened and bare brick walls are going to be tested under reversed cyclic lateral loading for a better understanding of the influence of the present technique on the earthquake behavior of the brick walls. Furthermore, the strengthening plates were applied directly on the wall in the present study and the coarse and fine plaster layers were then applied on the plates. In the forthcoming stages of the research, the influence of the application of the plates on the coarse and fine plaster layers of the wall are going to be investigated to increase the effieciency of the strengthening technique in the presence of diagonal compression and reversed cyclic lateral loading.

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