Influence of Strengthening the Infill Walls with Perforated Steel Plates on the Behavior of RC Frames

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The Strengthening of the non-bearing elements of a structure not only increases the overall lateral strength and stiffness of the structure, but also causes a major amount of the earthquake energy to be absorbed by the nonbearing members and therefore reduces the risk of damage in the structural components. The present paper focuses on a number of experiments carried out within an extensive research program, investigating the influence of strengthening the brick infill walls of an RC frame with perforated steel plates on the seismic behavior of the frame. Perforated steel plates are adopted in strengthening due to their several advantages including the great ductilities and deformation capacities of these plates, the fire resistant, recyclable and non-cancerogenic nature of steel and the ease of application of this technique. A total of 14 half-scale specimens, each composed of a strong foundation, two columns, a beam, and a brick wall, were tested. Plate thickness, bolt spacing and plate-column connection were chosen as the test parameters. The observations from previous experiments conducted on individual brick wall specimens were used for detailing the strengthening plates and the plate-wall connections. Additional column and joint strengthening applications provided significant improvements in the seismic behavior of the specimens.

Keywords: *Brick Wall, Earthquake Behavior, Steel Plate, Structural Strengthening*

Introduction

A significant number of structures around the globe needs seismic strengthening due to improper design and construction practices and noncompliance with the structural design codes, standards and regulations. Strengthening and repair applications on existing structures have two main

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purposes. First, the lateral rigidity and strength of the structure is aimed to be increased to enhance the ability of the structure to withstand greater lateral loads with limited displacement. Secondly, the earthquake-induced energy is desired to result in minimal damage in components of the gravity and lateral load-resisting system of the structure. To achieve these goals, two main types of structural retrofit techniques have been implemented in the past, namely strengthening the lateral load-resisting system by adding new members or fortifying the existing ones and strengthening the non-structural elements, i.e. the infill walls. Strengthening the infill walls has been and is the subject of several studies in the literature due to two main reasons:

1. The infill walls have a very small or no contribution to the overall lateral strength and rigidity of a structure since they fail in a quite brittle manner as soon as the diagonal tension capacity of the wall is exceeded. The infill walls strengthening applications aim at increasing the overall lateral strength and rigidity of the structure by providing the infill walls with greater diagonal load capacity and rigidity.
2. These applications also aim at providing the infill walls with ductile load-deflection behavior so that a major portion of the earthquake-induced energy is absorbed by the infill walls and the gravity and the lateral-load bearing system of the structure is liable to less damage.

The CFRP sheets and GFRP laminates (Triantafillou, 1998; Erdem et al., 2006; El-Dakhakhni et al., 2006; Ozcebe et al., 2003); FRP textile reinforced mortar (TRM) (Triantafillou and Papanicolaou, 2006; Triantafillou et al., 2006; Prota et al., 2006; Papanicolaou et al., 2011); shotcrete reinforced with steel mesh (Kahn, 1984; ElGawady et al., 2006); fiber-reinforced mortar (Sevil et al., 2011); precast concrete and precast reinforced concrete panels (Frosch et al., 1996; Baran and Tankut, 2011); and ferrocement layers (Topcu et al., 2005; Amanat et al., 2007) are among the materials used for strengthening infill walls by previous researchers. The use of FRP reinforcement, sheets and laminates has been widely adopted by previous researchers due to their high strength and good bonding performance with concrete. Nonetheless, several shortcomings of this method, including the high cost, low fire resistance, need for skilled labor and the problems related to bonding FRP composites to the wall surface caused FRP strengthening to not become common in practice. Furthermore, the use of epoxy adhesives as the bonding agent also reduces the practicality, effectiveness and economy of the method and increases the vulnerability of the strengthening layers to fire, which is crucial in fire protection of historical structures. Despite being effective in improving the seismic performances of the infill walls, the aforementioned strengthening methods are not easily applicable to real structures, in which a great number of infill walls need to be strengthened.

In search for an economical, easy-to-apply and convenient method, steel strips, profiles and plates were utilized in a number of studies (Taghdi et al., 2000; Farooq, Ilyas and Ghaffar, 2006; Ozbek and Can, 2012; Aykac et al., 2014; Kalkan et al., 2013; Ozbek et al., 2014) for strengthening infill walls. Aykac and his companions (Aykac et al., 2014; Kalkan et al., 2013; Ozbek et al., 2014) proposed the use of perforated steel plates for strengthening hollow brick infill walls and conducted a series of tests on the wall specimens. Perforated steel plates were adopted due to their following advantages and superiorities over the existing strengthening materials and methods:

i. The ductile stress-strain properties of mild steel and the additional ductility provided by the perforations improve the ductility and energy absorption capacity of the strengthened wall.
ii. Perforated steel plates on both faces of the wall have a two-fold effect on the strength of the wall. First, the tensile stresses are resisted by the plates after the formation of diagonal tension cracks in the wall. Secondly, the confining effect of the plates increases the compressive strength of the wall itself.
iii. The perforated steel plates can be covered with plaster to improve the aesthetic quality of the structure
iv. The perforations increase the bonding surface area between the wall and the plaster and improve composite behavior in the plated wall
v. The plates are connected to the wall only with the help of steel bolts. The lack of epoxy adhesives in strengthening contributes to the ease of application and economy of the method.
vi. The method is also applicable to structures with a high risk of fire or which need to be protected against fire (historical structures) thanks to the higher fire resistance of steel compared to the composites and the lack of chemical adhesives in the method.
vii. The recyclable and non-cancerogenic nature of steel can also be counted among the superiorities of the method over the existing methods.
viii. The presence of perforations in the plates facilitates the installation, removal and replacement of the strengthening plates and drilling of the holes for bolts in the wall. These perforations also avoid any possible damage for the water and sanitary fixtures in the wall if the locations of these fixtures are marked on the wall before drilling the holes

The present paper summarizes 14 experiments conducted within the third stage of an experimental program (Ozbek et al., 2014). In the first stage of the program, individual brick wall specimens were tested under monotonic diagonal loading (Aykac et al., 2014), similar to the loading condition of infill walls in the case of lateral seismic loading. Based upon the promising results obtained in the first stage, individual wall specimens were tested under reversed cyclic lateral loading in the second stage (Kalkan et al., 2013). The first and second stages of the program indicated that the perforated steel plates are quite effective in improving the behavior of brick infill walls. In the third stage, on the other hand, the influence of this wall strengthening technique on the overall performance of an RC frame was investigated. The findings and observations from the first and second stages enabled the authors to design the details of the strengthening procedure.

Experimental Study

A total of 14 RC frame specimens, tabulated in Table 1, were tested. Specimen R1 is the reference bare frame and specimen R2 is the RC frame with an unstrengthened infill wall. The strengthened specimens were denoted with the capital letter "S"; a number corresponding to the thickness of the strengthening plate (1, 1.5, 2 mm); the capital letter "Z", indicating that no axial load was applied to the columns; a capital letter representing the connection of the strengthening plates to the surrounding columns ("Y" for connected plates and "N" for plates with no column connection); and a final number corresponding to the spacing of the bolts.

The RC frames were intentionally designed to be non-compliant with the structural design codes so that they do not have adequate earthquake resistance. In this way, the influence of wall strengthening on the overall performance of the poorly-designed structural frame could be investigated. Concrete with quite low compressive strength (10 MPa) was used in the frame and the stirrup spacing was not reduced in the beam-column connection regions. Furthermore, the beams with a cross-section of 150x250 mm had greater in-plane flexural rigidities compared to the columns, having a cross-section of 100x200 mm. In this way, plastic hinges were forced to form in the columns rather than the beams.

Table 1. *Test Specimens*

Specimen	Plate Thickness (mm)	Bolt Spacing (mm)	Connection to Columns
R1	-	-	-
R2	-	-	-
S1ZY150	1.0	150	Yes
S1ZN150	1.0	150	No
S1ZY200	1.0	200	Yes
S1ZN200	1.0	200	No
S1.5ZY150	1.5	150	Yes
S1.5ZN150	1.5	150	No
S1.5ZY200	1.5	200	Yes
S1.5ZN200	1.5	200	No
S2ZY150	2.0	150	Yes
S2ZN150	2.0	150	No
S2ZY200	2.0	200	Yes
S2ZN200	2.0	200	No

In all strengthened specimens, additional measures were taken in the vicinity of the wall corners to avoid premature failure of the walls due to crushing of these regions. The corners of the wall were strengthened with L-shaped steel plates (Figure 1) and the bolt spacing was reduced to 100 mm in the corner regions.

In the test of Specimen S1ZN200, the effect of using perforated steel plates for strengthening the infill wall could not be fully understood since this specimen failed prematurely due to the shear failure of the columns (Figure 2). The infill wall did not undergo significant damage till the end of the test with the exception of limited crushing in the corners (Figure 2). To avoid the premature failure of the weak columns and to allow the strengthened wall to contribute to the frame behavior, the columns and the beam-column joints in the remaining specimens, were strengthened, in addition to the infill wall. Accordingly, the following additional strengthening measures were undertaken in the remaining strengthened specimens:

1. A steel jacket made up of longitudinal and transverse steel strips (Figure 1) was built around each column to increase the shear strength of the weak columns. The gaps between the jacket and the column were filled with epoxy adhesives to increase the confining effect of the jacket on the column.
2. In real frames, an additional confining effect is provided to the beam-column joint by the out-of-plane beams projecting from the joint. To simulate the confining effect of out-of-plane beams, the beam-column joints were strengthened with steel plates on both sides of the joint, connected to each other with post-tensioned steel bolts (Figure 1).

Figure 1. *Strengthening Details and Test Setup*

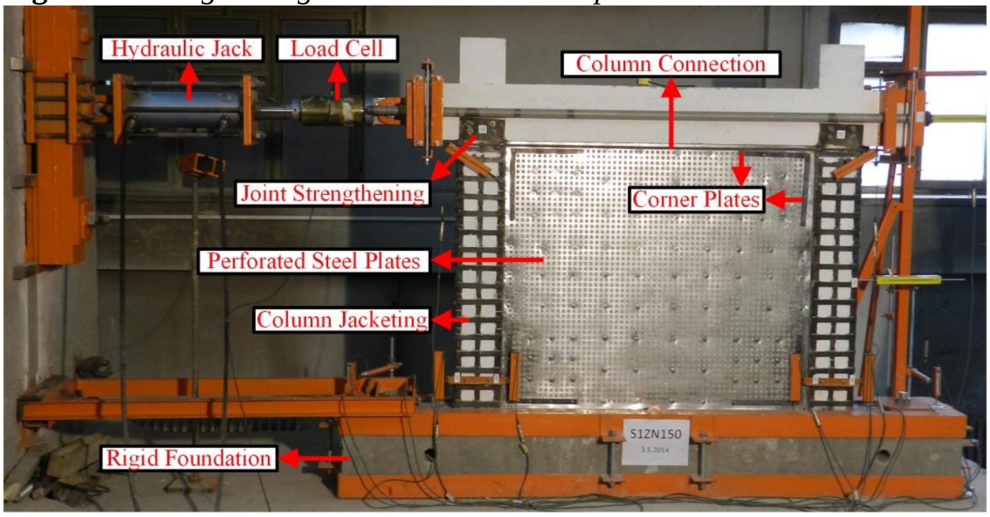


Figure 2. *Shear Failure of the Columns in Specimen S1ZN200*

3. In real frames, the slab and the surrounding frame members facilitate the transmission of the lateral loads between the columns. To simulate the contribution of the slab and surrounding frame members to the load

transfer, the upper ends of the columns were connected to each other with the help of steel bars, denoted as “Column Connection” in Figure 1.

Each test specimen was composed of a rigid foundation (Figure 1), two columns, a beam and an infill wall. The lateral load was applied by a double-action hydraulic jack, connected to a strong wall. In the tests of S1.5ZY150, S2ZN150, S2ZN200, S2ZY150 and S2ZY200, the out-of-plane motion of the hydraulic jack was prevented by steel cables connected to the strong wall (Figure 3). The lateral displacements of the frame at the center of the beam (floor level) and at mid-height of the column were measured with the help of LVDT’s. An additional potentiometer was used for measuring any possible lateral displacement at the lower end of the column, indicating the separation between the column and the rigid foundation (Figure 4). Two LVDT’s aligned along the wall diagonally measured the diagonal deformations in the wall. Finally, the rotations at the lower end of each column were measured by two LVDT’s connected by a rigid link, oriented horizontally at the initiation of the test (Figure 5).

Figure 3. *Steel Cables Preventing the Out-of-Plane Motion of the Jack*

Figure 4. *Lateral Displacement Measurement at the Lower End of the Column*


Figure 5. *Rotation Measurement at the Lower End of the Column*


The experiments discussed in this paper aimed at investigating the influence of the following test parameters on the overall performance of an infilled RC frame:

- Thickness of the strengthening plates
- Spacing of the bolts connecting the plates to the wall
- Presence of connections between the strengthening plates and the surrounding columns

Evaluation of the Test Results

The bare frame without infill wall (R1) failed due to plastic hinging at the ends of the columns (Figure 6). Furthermore, debonding cracking was observed in the beam and columns as a result of the low compressive strength of concrete. The longitudinal reinforcing bars buckled and concrete crushing took place in the plastic hinging regions. The reference frame with an unstrengthened infill wall

(R2) failed in a brittle manner due to the shear failure of the upper portions of the columns and the crushing of the corners of the wall (Figure 7). The upper portion of each column behaved as a short column after the crushing of the wall corners. The wide spacing of the stirrups at the column ends and the low compressive strength of concrete resulted in low shear strength of the columns and premature failure of these members under the lateral loads transferred by the wall diagonally. After the shear failure of the columns, the beam translated freely in forward and backward directions with the upper portions of the columns (Figure 7). The contact length between the infill and the column decreased to 40 % of the initial contact length at the end of the test.

Specimen S1ZN200 behaved similar to the reference R2 specimen and the influence of wall strengthening on the overall frame behavior could not be observed due to the premature shear failure of the weak columns (Figure 8). The infill wall did not experience significant damage except the limited crushing in the corners. The shear cracks in the upper portions of the columns controlled the frame behavior throughout the test and the load capacity of the frame slightly exceeded the load capacity of the reference frame R2 (Table 2). The ultimate load values of S1ZN200 was about 28 % and 38 % higher than the ultimate load values of R2 in the forward and backward directions.

Due to the shear failure of the weak columns of S1ZN200, the additional strengthening measures summarized in the previous section were realized in the remaining tests. As a result of this strengthening, all of the remaining specimens exhibited a quite ductile behavior (Figures 9-19).

Figure 6. *Failure Mode of Specimen R1*

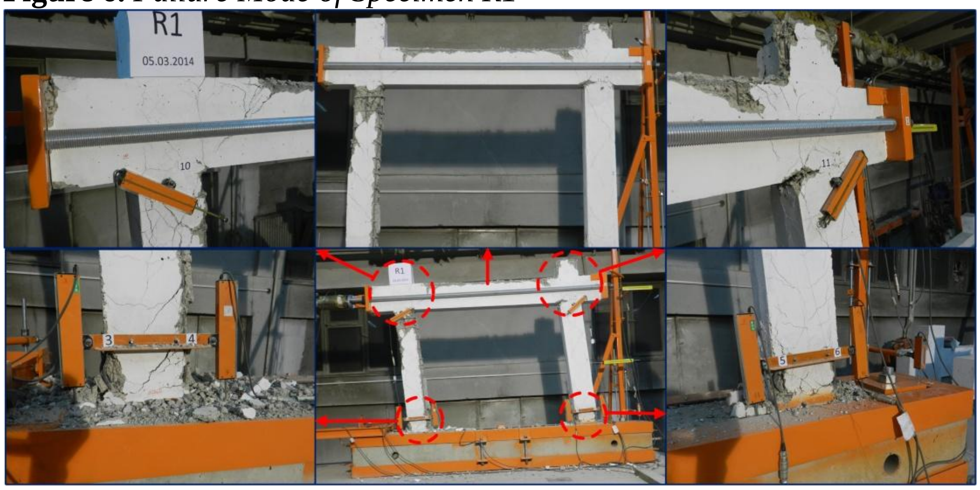


Figure 7. *Failure Mode of Specimen R1*

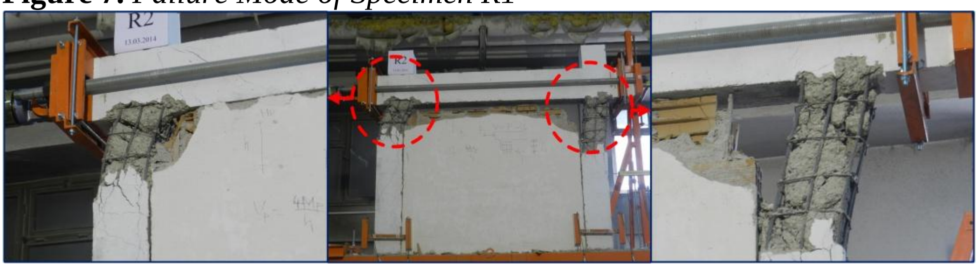


Figure 8. *Failure Mode of Specimen S1ZN200*

Figure 9. *Failure Mode of Specimen S1ZN150*

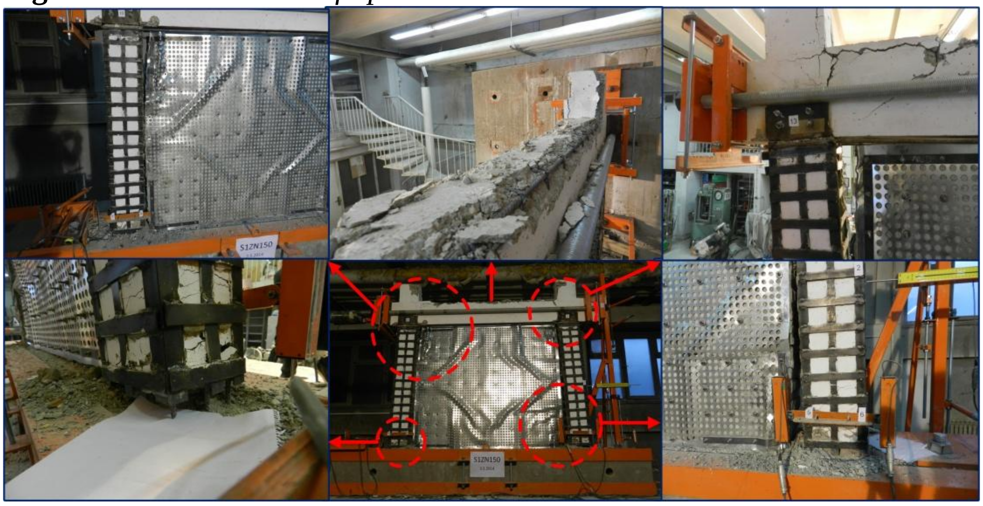


Table 2. *Test Results*

Specimen	Ultimate Load (kN)		% Ultimate Deflection	
	Forward Cycle	Backward Cycle	Forward Cycle	Backward Cycle
R1	50	47	6.0	5.6
R2	120	120	1.8	1.8
S1ZY150	235	231	6.2	> 6.0
S1ZN150	194	204	> 7.5	6.6
S1ZY200	230	234	7.2	>7.5
S1ZN200	153	165	3.0	4.0
S1.5ZY150	236	230	5.6	5.8
S1.5ZN150	225	238	> 7.5	6.0
S1.5ZY200	238	244	* 4.5	> 6.0
S1.5ZN200	229	227	> 7.5	> 7.5
S2ZY150	215	216	> 7.5	> 7.5
S2ZN150	200	216	> 7.5	> 7.5
S2ZY200	215	223	> 7.5	> 7.5
S2ZN200	185	185	7.1	> 7.5
* Out-of-plane translation of the frame				

Table 3. *Ultimate Load and Deflection Values of the Strengthened Specimens with Respect to the Unstrengthened Reference R2 Specimen*

Specimen	Ultimate Load Ratio		Ultimate Deflection Ratio	
	Forward Cycle	Backward Cycle	Forward Cycle	Backward Cycle
R2	1.00	1.00	1.00	1.00
S1ZY150	1.96	1.93	3.44	3.33
S1ZN150	1.62	1.70	> 4.17	3.67
S1ZY200	1.92	1.95	4.00	> 4.17
S1ZN200	1.28	1.38	1.67	2.22
S1.5ZY150	1.97	1.92	3.11	3.22
S1.5ZN150	1.88	1.98	> 4.17	3.33
S1.5ZY200	1.98	2.03	2.50	3.33
S1.5ZN200	1.91	1.89	> 4.17	> 4.17
S2ZY150	1.79	1.80	> 4.17	> 4.17
S2ZN150	1.67	1.80	> 4.17	> 4.17
S2ZY200	1.79	1.86	> 4.17	> 4.17
S2ZN200	1.54	1.54	3.94	> 4.17

Figure 10. *Failure Mode of Specimen S1ZY200*

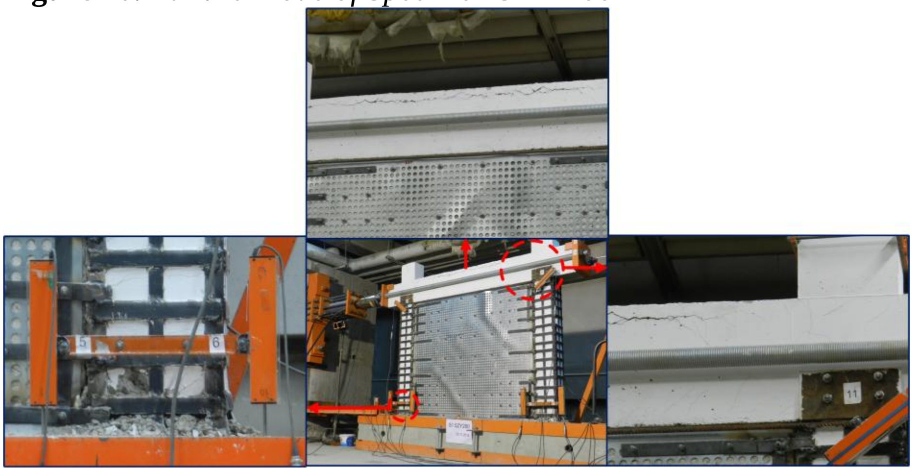


Figure 11. *Failure Mode of Specimen S1ZY150*

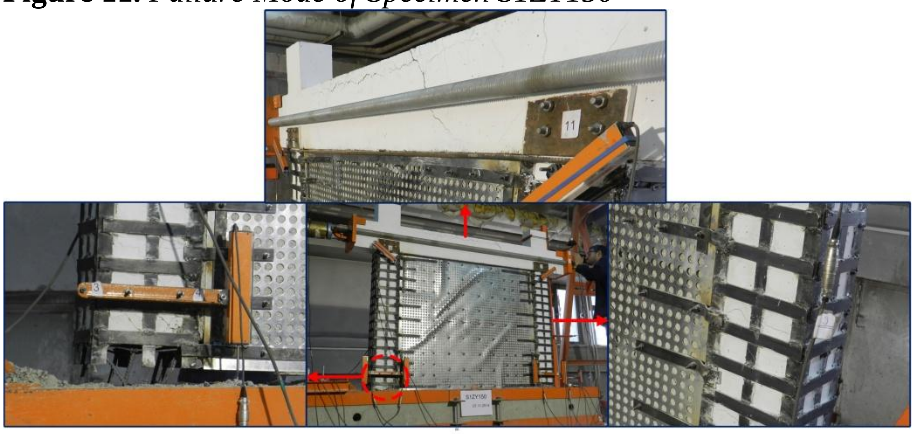


Figure 12. *Failure Mode of Specimen S1.5ZN200*

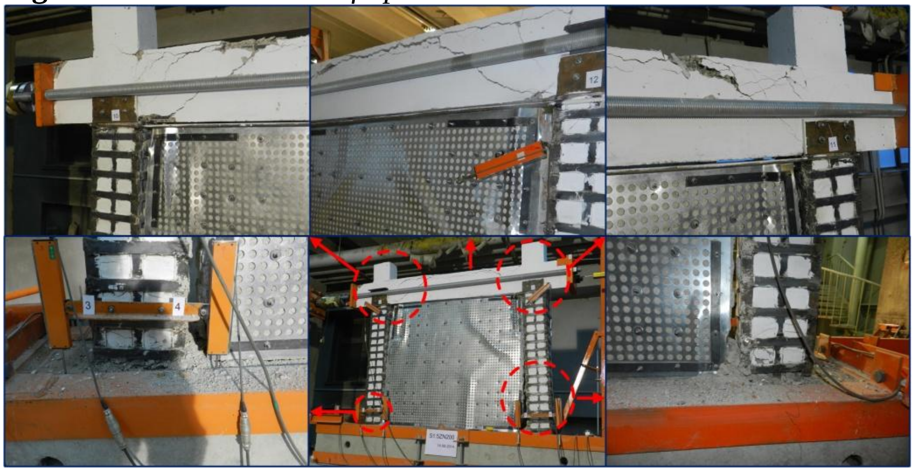


Figure 13. *Failure Mode of Specimen S1.5ZN150*

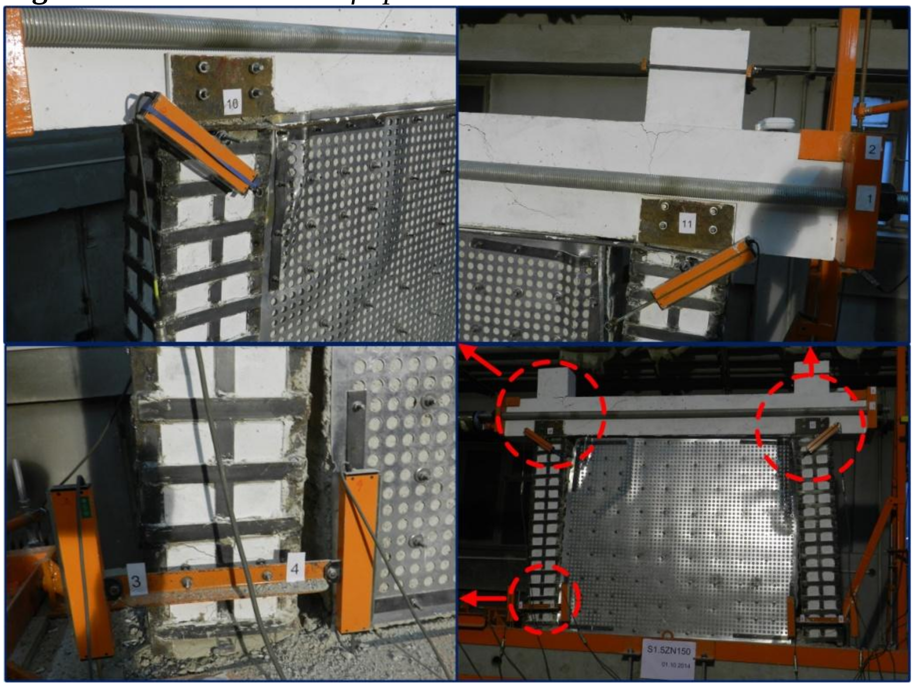


Figure 14. *Failure Mode of Specimen S1.5ZY200*

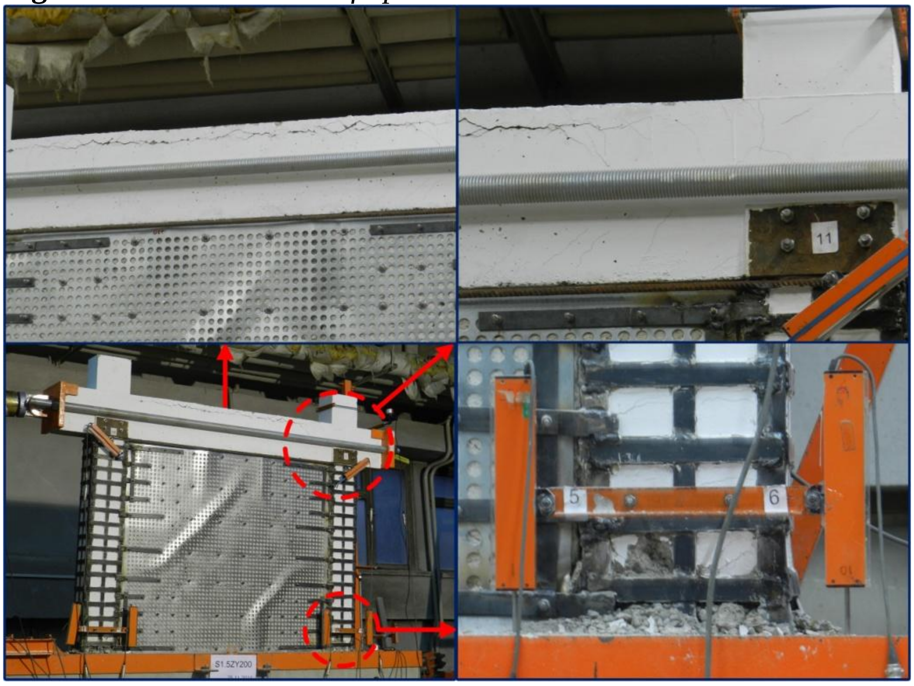


Figure 15. *Failure Mode of Specimen S1.5ZY150*

Figure 16. *Failure Mode of Specimen S2ZN200*

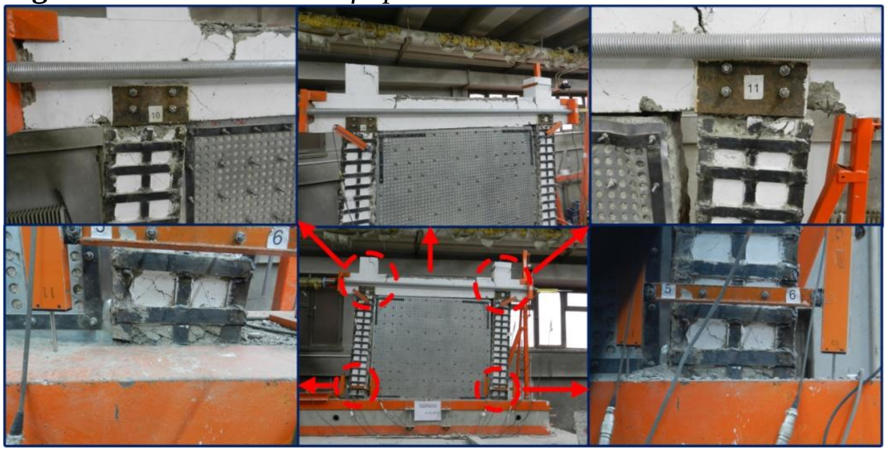


Figure 17. *Failure Mode of Specimen S2ZN150*

Figure 18. *Failure Mode of Specimen S2ZY200*

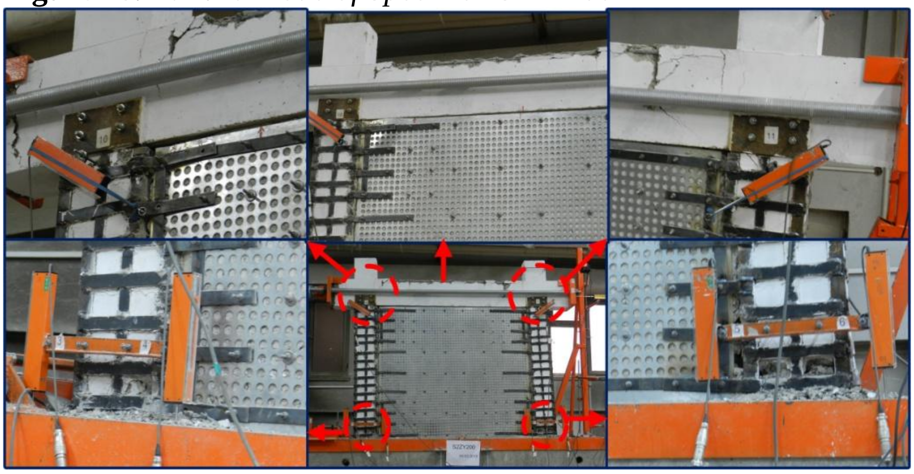
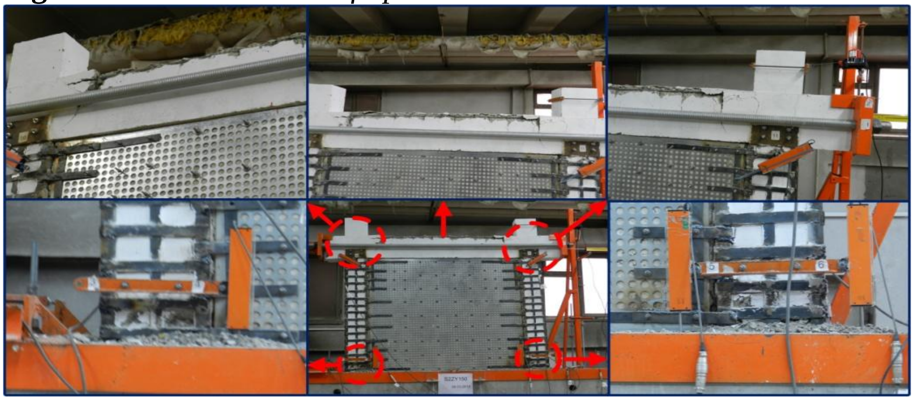


Figure 19. *Failure Mode of Specimen S2ZY150*



In all strengthened specimens, the following modes of damage took place before the complete failure of the specimen:

- Four plastic hinges at the upper and lower ends of the columns and two plastic hinges at the ends of the beam formed.
- At the level of the top longitudinal reinforcing bar of the beam, significant debonding cracks formed as a result of the low compressive strength of concrete. These cracks are not considered worrisome since the slab projecting from the beam in real frames prevents debonding cracks to form at the top of the beam.
- Diagonal tension cracks developed along the wall (Figure 20). However, the perforated steel plates prevented disintegration of the wall and provided the frame with ductile behavior. Consequently, the diagonal tension cracking along the diagonals and crushing in the corners remained rather limited.
- In specimens S1ZN150, S1ZN200, S1.5ZN150, S1.5ZN200, S2ZN150 and S2ZN200, significant separation at the wall-column interfaces took place (Figure 21).

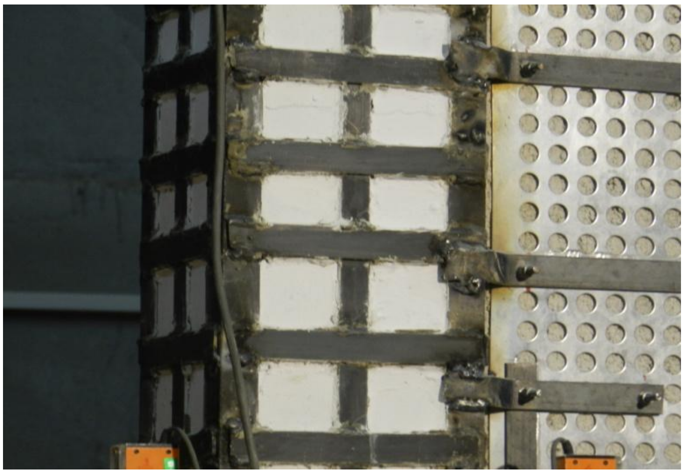
Figure 20. *Diagonal Tension Cracking in the Walls*

Figure 21. *Separation at the Wall-Column Interface in Specimen S1ZN150*

In the remaining specimens, the connections of the perforated steel plates to the surrounding columns (Figure 22) prevented this separation till the end of the test.

- The separation between the lower ends of the columns and the rigid foundation caused rupture of the longitudinal bars of the columns (Figure 15), upon which the tests were generally terminated.
- Diagonal shear cracks formed in the columns due to the low compressive strength of concrete. However, the steel jacket around the columns prevented these shear cracks to control the behavior of the frame and the premature shear failure of the columns.
- The diagonal compression forces in the wall resulted in buckling of the perforated steel plate segments between successive anchors (Figure 14). Nevertheless, the strengthening plates continued contributing to the ductility of the frame and prevented the disintegration of the wall despite these distortions.

Figure 22. *Connections of the Perforated Steel Plates to the Surrounding Columns*

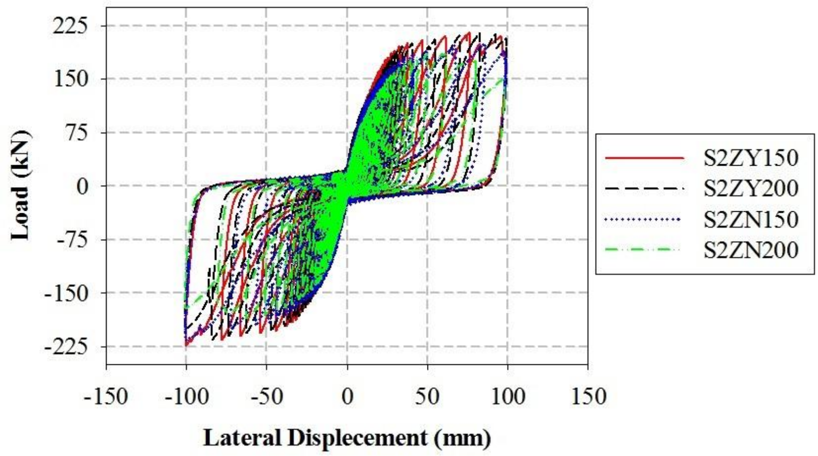


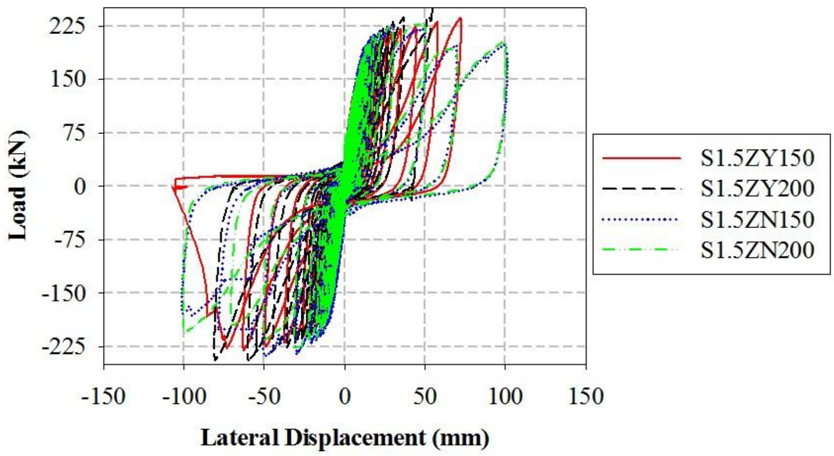
The ultimate load and deflection values of the specimens for forward and backward directions of loading are presented in Table 2. The ultimate deflection corresponds to the lateral top deflection at 85 % of the ultimate load in the descending branch of the envelope load-deflection curve. The relative values of these measures, corresponding to the ratio of a measure to the value of the reference R2 specimen, are tabulated in Table 3.

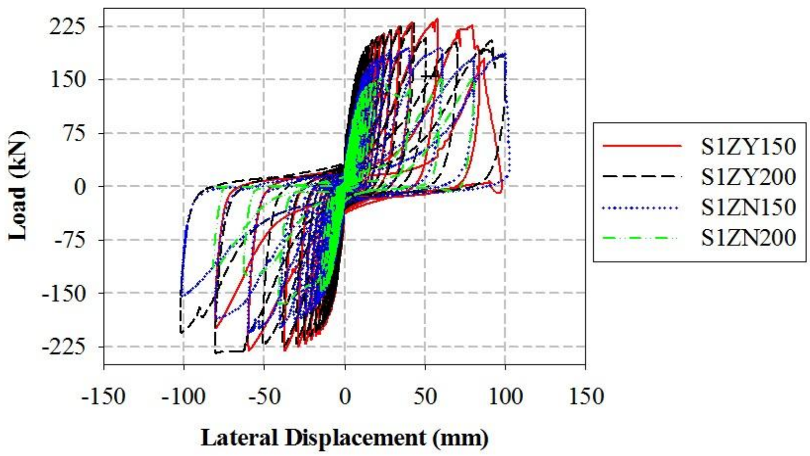
Different from the remaining specimens, the additional strengthening applications (column and joint strengthening) were not implemented in Specimen S1ZN200. Therefore, the test results of this specimen are significantly lower than the remaining strengthened specimens. In the following discussion, the test results of S1ZN200 are disregarded for this reason. The relative values in Table 3 indicate that this strengthening method resulted in an increase of 50-100 % and 50-105 % in the ultimate load capacity of the frame in the forward and backward directions of loading, respectively. Furthermore, the ultimate deflection values of the specimens increased to 2.5-4.2 times and 3.2-4.2 times the ultimate deflection value of specimen R2 in the forward and backward directions of loading, respectively. For specimens with the same plate thickness, the spacing of the bolts had a slight influence on the ultimate load value, while the connection of the strengthening plates to the surrounding columns resulted in a considerable increase in the load capacity. For identical plate thickness and bolt spacing, connecting the strengthening plates to the columns increased the lateral strength of the specimen between 10-30 %. This increase is more pronounced in the forward direction of loading compared to the backward direction. The test results indicate that there is no direct relationship between the ultimate load and the plate thickness for identical bolt spacing and column connection.

Figure 23 illustrates the influence of bolt spacing and column connection on the frame behavior for identical plate thickness. The load-deflection curves indicate that the frame behavior improves with decreasing bolt spacing and when the plates are connected to the surrounding columns. In other words, the energy absorption capacity and ductility of the frame increases with decreasing bolt spacing and in the presence of plate-column connections. The ultimate deflection values in Tables 2 and 3 do not yield to significant conclusions since the ultimate displacements of most of the specimens could not be accurately determined due to the limitations of the experimental setup.

Figure 23. *Load-Deflection Curves of the Specimens*







Conclusions

A total of 14 infilled RC frame specimens were tested to investigate the influence of strengthening the infill wall with perforated steel plates on the overall frame behavior. The thickness of the strengthening plates, spacing of the bolts and connections between the perforated steel plates and the columns were adopted as test parameters. By comparing the test results of the specimens with strengthened infill wall to the results of the bare reference frame and the reference frame with an unstrengthened infill wall, the following conclusions were drawn:

- The proposed method considerably increases the lateral strength and ultimate deformation values of infilled RC frames. The influence of this strengthening method on the overall lateral strength and the deformation capacity of the frame is rather limited if the columns of the frame with inadequate earthquake resistance are not strengthened. The present experiments indicated that the contribution of the perforated steel plates of the infill wall on the overall behavior of the frame can be increased by strengthening the columns and the beam-column connections of the frame against shear. Otherwise, the shear failure of the columns prevent the strengthened infill wall to fully develop its lateral capacity.
- Among the investigated test parameters, connecting the perforated steel plates to the surrounding columns was found to have the most considerable positive influence on the lateral strength of the infilled RC frame.
- Connecting the strengthening plates to the surrounding columns and decreasing the bolt spacing contribute to the deformation capacity, ductility and energy absorption capacity of an infilled RC frame significantly.
- Connecting the strengthening plates to the surrounding columns is an effective measure for limiting the separation at the wall-column interfaces during seismic excitations.

The present paper summarizes 14 experiments carried out within the final stage of a research program. In the remaining experiments of this stage, the frame specimens subjected to axial column loading as well as lateral seismic loads will be tested.

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