KSCE Journal of Civil Engineering (2016) 20(6):2439-2446

DOI 10.1007/s12205-016-0188-z

Structural Engineering

pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

A Study on Strengthening of Reinforced Concrete Frames using Precast Concrete Panels

Arife Akin* and Rifat Sezer**

Received March 7, 2015/Accepted October 11, 2015/Published Online January 22, 2016

Abstract

This study describes the effectiveness of the behavior resulting from strengthening infill walls in existing reinforced concrete frame systems with low resistance against earthquake effects using precast concrete panels. In this study, a strengthening method that can be applied without building occupants having to leave the building was investigated. For this purpose, six 1/2 scale, two-story and single span test specimens with brick infill walls and low earthquake resistance, which have common errors seen in existing reinforced concrete buildings, were generated. The first of test frames with equivalent properties was tested as the reference specimen under reversible repeatable lateral loads. Others were tested after high-strength concrete panels produced in different geometric shapes were strengthened by bonding them onto existing frame infill walls. Brick infill walls strengthened using concrete panels were modeled as shell elements by SAP2000 software package and the accuracy of experimental studies were compared with analytical results. Experimental and analytical studies demonstrated that the reinforcement method significantly improved properties, such as resistance to lateral loads, energy dissipation capacity, of brick infill reinforced concrete frames.

Keywords: *RC frame, seismic effect, infill wall, precast panel*

1. Introduction

Most reinforced concrete buildings in the territory of Turkey, almost all of which has significant seismic risk, have deficiencies in terms of strength, rigidity and ductility. The strength of these structures should be increased and their relative lateral displacement should be reduced. It is clear that this large-scale repair and strengthening work are required to be practical and economical.

Many methods have been developed for the strengthening of reinforced concrete structures from past to present (Kahn and Hanson, 1979; Kaldijan and Yüzügüllü, 1984; Frosh and *et al.*, 1996; Erdem and *et al.*, 2006; Binici and *et al.*, 2007; Akin and Sezer, 2012; Kaltakci and Yavuz, 2014). These usually include filling with complete or partial cast in-situ reinforced concrete shear walls of reinforced concrete frame spaces or rendering non-load bearing brick infill walls load-bearing as a result of strengthening them using a variety of methods (CFRP, braided steel reinforcement and shotcrete applications and precast panel). If the structure has rigidity problems and the number of elements to be strengthened is too high, applications carried out by adding cast in-situ reinforced concrete shear walls are the most preferred economical practices. However, these applications require evacuation of buildings because they are laborious and take a long time. The aim of this study was to correct such deficiency of reinforced concrete shear walls.

The said method can be applied to reinforced concrete framed structures with hollow brick walls, and does not require evacuation of buildings (Axley and Bertero, 1979). The said reinforcement method was discussed by (TEC-07, 2007), however, they failed to provide adequate information on its design and implementation. The first studies on this topic were conducted by (Frosch *et al.*, 1996). In (Frosh, 1996), non-ductile reinforced concrete frame systems have been strengthened using precast filler panels. As a result of that study, it was observed that the system with precast infill walls showed a good performance, that the frame system which is non-ductile against lateral loads was transformed into a system with ductile shear walls, and its strength and rigidity values significantly increased. In Turkey, the first experimental studies on this subject were conducted in early 2000's at Middle East Technical University, Faculty of Civil Engineering, Earthquake Laboratory (Baran, 2005; Süsoy, 2004; Duvarcı, 2003).

As distinct from previous studies, in this study, different panel shapes and anchoring details were applied to ½-scale reinforced concrete frames, and the effectiveness of the reinforcement method was investigated (Akin, 2011). The principle of the technique is based on bonding high strength precast concrete panels on hollow brick infill walls in the structure by employing simple methods (Baran *et al.*, 2010). It is not practical to transport and apply the panel in one piece so attention was paid

*Assistant Professor, Dept. of Civil Engineering, Selcuk University, Konya 42075, Turkey (E-mail: arifearslan@selcuk.edu.tr)
**Associate Professor, Dept. of Civil Engineering, Selcuk University, Konya 42075, Turkey (Corresponding Author, E-mail: rsezer@selcuk.edu.tr)

to ensuring that the panels designed in different geometric shapes remain within certain dimensions and weight limits so that two people can readily carry them.

In this study, in the case of test frames with the same properties, panel shapes were selected as a variable. The contribution of reinforcement carried out according to panels with 5 different geometric shapes on seismic behavior of reinforced concrete frames with hollow brick infill was investigated comparatively.

Table 1. Properties of Reinforcing Bars

Bar Diameter (mm)	f_{sy} (MPa)	f_{su} (MPa)	Type
ϕ8	413	522	S220
ϕ19	440	492	S220
ϕ12	394	518	S220
ϕ14	460	525	S220

2. Experimental Program

In this study, 6 test specimens were tested under the impact of reversed cyclic lateral loads. All test specimens had the same geometry and material properties. Specimens were two-story and single span. 6 reinforced concrete bare frames were produced in a horizontal position at the same time. Then, the specimens were brought to vertical position and their hollow brick infill walls were bonded and plastered. In order to produce frames with weak seismic behavior, deficiencies frequently encountered in existing structures were consciously reflected on test specimens. Vertical load applied to the frame system was $N \approx 0.1 \times A_c \times f_c$. Dimensions and reinforcement diagram of specimens are depicted in Fig. 1.

No bent bar is arranged in beams of frame specimens, thus span and support reinforcement ratios were kept fixed. In the beams, top and bottom reinforcements were extended to the outer face of the column, and from this point, they were bent upwards and downwards by 20ϕ (240 mm). Fig. 2 shows sections of beam, column and foundation members, and Table 1 lists the mechanical properties of the reinforcement used in test frames.

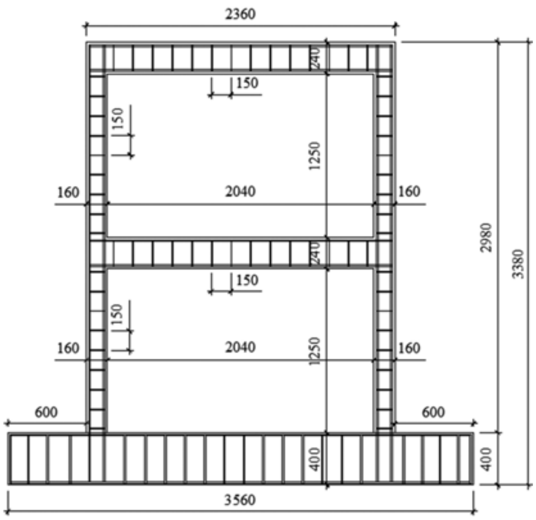


Fig. 1. The Dimension and Reinforcement Scheme of Test Frames (Dimensions are in mm)

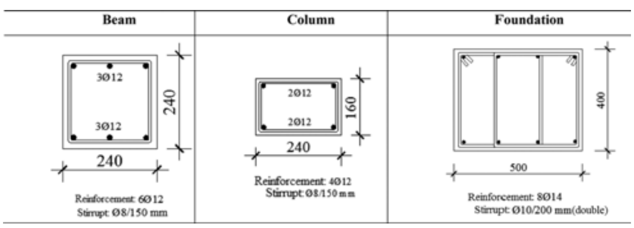


Fig. 2. Cross-section and Reinforcement Details of Test Frame Members

Before reinforcement elements were applied to test frames, 190 mm × 135 mm × 85 mm of commercially available bricks were laid, and their both sides were plastered with cement lime plaster up to a thickness of 8-10 mm.

Within the scope of this study, five different types of precast panels were produced. When the preparation of the molds for panels, A and B type panels were respectively produced as the rectangular panels close to square and the strip panels continuous along the story height in appropriate to TEC-07. C-TP was produced in the shape of a hexagonal honeycomb, D-TP and E-TP were produced as interlocking paving stones in order to transfer shear loads much effectively. The aim was to identify the effect of the panel shape on the strengthening process. Fig. 3 presents the dimensions of the panels.While selecting panel thickness and anchoring panels to frame elements in accordance with ½ scale test specimens, minimum requirements in (TEC-07, 2007) were taken into consideration (Akin, 2012). While making the panels, grout was used in order to obtain panels with high strength as well as a more homogeneous mixture compared to concrete and to prevent breaking up of panels while extruding them, due to their low thickness. To avoid shrinkage cracks and damages that may occur during the transportation and bonding

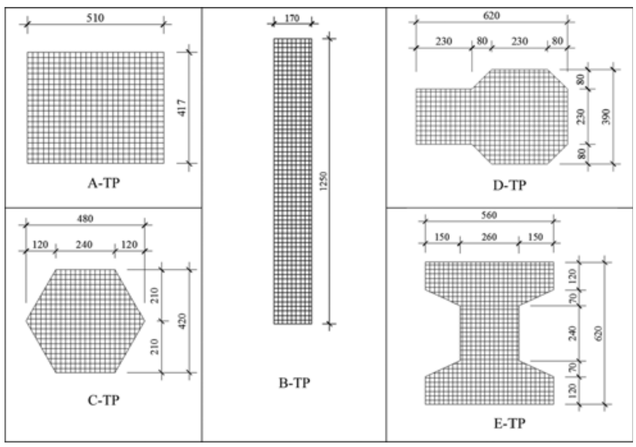
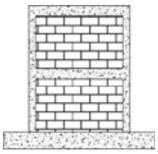
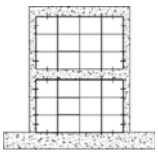
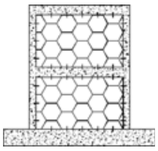
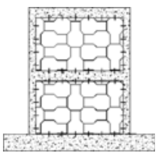
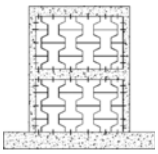


Fig. 3. Dimensions of the Panels in mm

Table 2. Properties of Test Specimens

Specimen no	Configuration	f_c (MPa)	
		Frame	Precast Panel
1 (RF)		13.24	-
2 (A-TPF)		14.73	55.53
3 (B-TPF)		13.48	60.44
4 (C-TPF)		13.67	58.44
5 (D-TPF)		14.88	58.25
6 (E-TPF)		14.76	58.29

processes of the panels, a welded wire mesh with 1.5 mm diameter and 20 mm spacing in both directions was placed inside the panels. High-strength epoxy adhesives were use to anchor the panels to the wall and the wall anchors to frame elements. Shapes of the specimens in the test program and concrete strength values are given in Table 2.

The schematic representation of test setup, loading system, and instrumentation is shown in Fig. 4 and the figure of frames before the test was shown in Fig. 5. The testing system consisted of a strong floor, reaction wall, loading equipment, instruments, and a data acquisition system. The foundations of the frames were fixed to the strong floor by using high-strength steel bolts.

Tests were conducted on the strong reinforced concrete wall and rigid testing platform consisting of strong concrete flooring in the laboratory. Foundation beam was designed rigid so that it can meet fixed support conditions for the test element as much as possible. Test elements were produced in such a way that they have the foundation system, and were secured through the holes in the existing laboratory flooring. First, load-controlled tests were conducted, followed by displacement-controlled tests, which were conducted after reaching nominal yield load value of the system. Horizontal load was applied to test frames such that 2 units is applied to the top floor and 1 unit is applied to the bottom floor, based on the assumption of triangular load which simulates seismic load, and equal amounts of vertical load is applied to both columns as an axial force of approximately N = 0.1~0.2.Ac.fc. (Fig. 6).

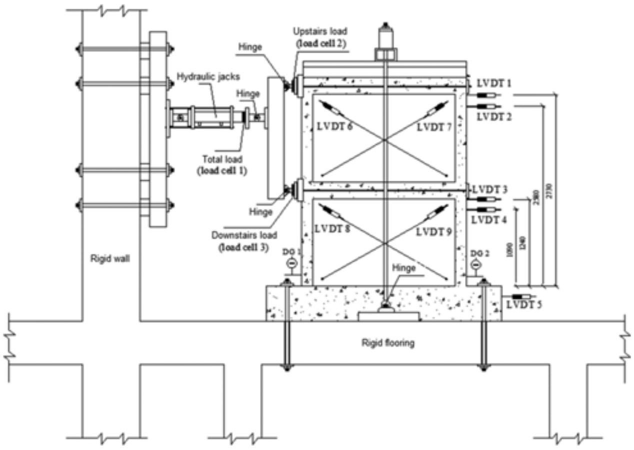


Fig. 4. Schematic Shapes Test Set-up and Instrumentation

Fig. 5. The Figure of Frame and Instrumentation before the Test

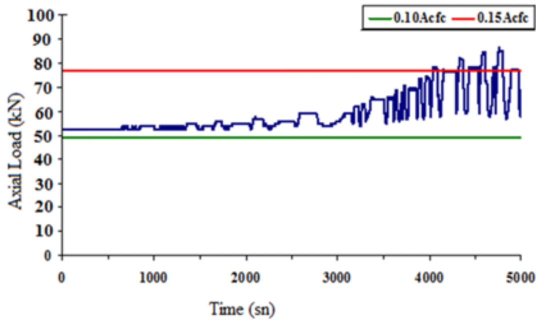
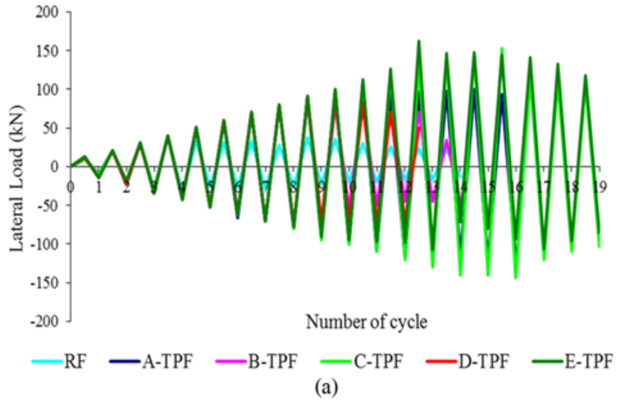


Fig. 6. The Variation of Axial Load During the Test

The tests began as a load control and continued as the



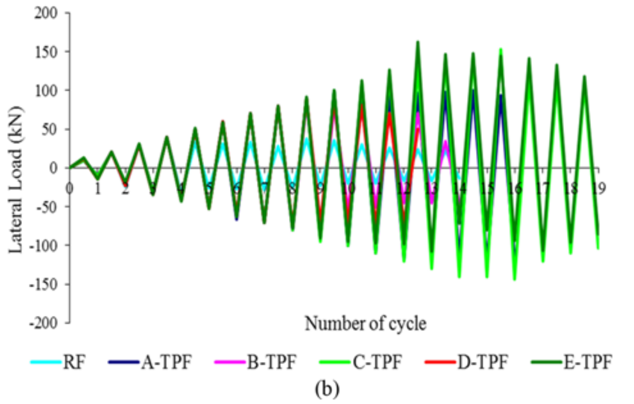


Fig. 7. Loading History of Test Specimens: (a) Loading History According to Lateral Load, (b) Loading History According to Lateral Displacement

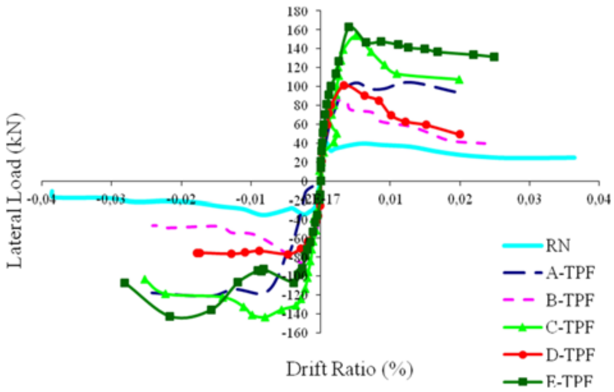


Fig. 8. Load-displacement Envelope Curves of Specimens

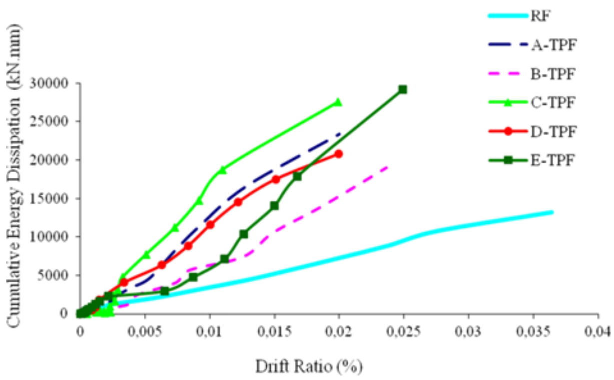


Fig. 9. Energy Dissipation Capacity Graphs of Specimens

displacement control after the nominal yield load value of the system (Fig. 7). The loading history was applied to:

a. The RF specimen as a 10 kN load controlled until yielding load (40 kN) and then, followed by 10 mm displacement controlled up to failure (100 mm).
b. The A-TPF specimen as a 10 kN load controlled until yielding load (110 kN) and then, followed by 10 mm displacement controlled up to failure (61.53 mm).
c. The B-TPF specimen as a 10 kN load controlled until yielding load (85 kN) and then, followed by 10 mm displacement controlled up to failure (60 mm).
d. The C-TPF specimen as a 10 kN load controlled until yielding load (140 kN) and then, followed by 10 mm displacement controlled up to failure (61.2 mm).
e. The D-TPF specimen as a 10 kN load controlled until yielding load (76 kN) and then, followed by 10 mm displacement controlled up to failure (50 mm).
f. The E-TPF specimen as a 10 kN load controlled until yielding load (98 kN) and then, followed by 10 mm displacement controlled up to failure (72.5 mm).

3. Discussion of Test Results

Figure 8 indicates the envelope curves of test specimens. In general, strengthened test specimens showed strength values varying by several ratios compared to reference specimen no.1. All strengthened specimens showed approximately the same behavior in terms of maximum displacement ratio they reached at the end of the test (2%). 1., while with a displacement ratio of 3.6%, test specimen no.1 made more displacement compared to strengthened specimens. This suggests that strengthening performed using high-strength precast concrete panels significantly increased lateral rigidity of reinforced concrete frames.

Total energy dissipation graphs of test specimens are shown in Fig. 9.

For numerical comparison of the test results, maximum horizontal loads carried by the specimens and corresponding displacement ratios are given in Table 3, their stiffness properties

Table 3. A Comparison on the Horizontal Load Bearing Capacity of Test Specimens

Specimen no	Ultimate load (kN)	Drift ratio at max. load (%) (δ/Σh)	*
1	**40**	**0.00256**	**1.000**
2	121	0.0065	3.025
3	87.48	0.0023	2.187
4	153.49	0.0051	3.837
5	101.38	0.0034	2.534
6	162.77	0.0041	4.069

*Ratio of ultimate lateral load of infilled frame to that of bare frame

Table 4. A Comparison on the Stiffness of Test Specimens

Specimen no	Stiffness values (kN/mm)			Drift Ratios (δ/Σh)		1. Cycle Stiffness ratio	Max. Load Stiffness ratio
	First Cycle	Max. Load	Last cycle	Max. Load	Last cycle		
1	**26.32**	**5.53**	**0.237**	**0.00256**	**0.036**	**1.000**	**1.000**
2	184.44	7.92	1.87	0.0065	0.024	7.00	1.43
3	524.2	13.90	0.617	0.0023	0.0236	19.9	2.51
4	197.65	11.112	1.98	0.0051	0.02	7.51	2.01
5	159.57	11.073	0.908	0.0034	0.02	6.06	2.00
6	382.45	14.63	1.933	0.0041	0.025	14.53	2.645

Table 5. A Comparison on the Energy Dissipation Capacity of Test Specimens

Specimen no	Energy dissipation values (kN.mm)		Energy dissipation ratios	
	At max. load	At the end of the test	At max. load	At the end of the test
1	**509.81**	**13220.58**	**1.000**	**1.000**
2	7961.47	23367.54	15.61	1.76
3	4029.037	18965.26	7.9	1.43
4	11176.24	27550.56	21.92	2.08
5	6331.019	20789.66	12.42	1.57
6	6250.336	29197.83	12.26	2.21

are listed in Table 4 and energy values dissipated by the specimens at maximum load and at the end of the test are tabulated in Table 5.

4. Analytical Studies

Displacement-controlled pushover analysis was applied using SAP2000 software package to perform analytical calculation of frame specimens (Akin, 2013). During modeling of test specimens, bearing system elements were modeled as bar elements, whereas during modeling of infill walls, infill walls of reference specimen were incorporated into the model as equivalent pressure bars. In the case of strengthened test specimens, the impact of brick infill was neglected and precast panel elements were modeled as shell elements. In Fig. 10, the results of analytical work carried out by SAP2000 package are given.

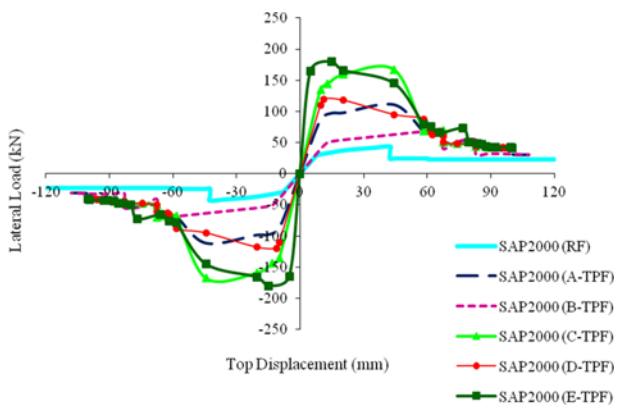


Fig. 10. The Strength Envelope Curves after Analytical Modelling of the Test Specimens

5. The Comparison of the Experimental and Analytical Results

Figure 11 presents total horizontal load-2nd story displacement envelope curve obtained from analytical modeling of test specimens and total horizontal load-2nd story displacement hysteretic curves obtained as a result of experimental work. As can be seen in these figures, the lateral drift was reduced, but strength and rigidity values of the frames were significantly increased by strengthening of infilled reinforced concrete frame using precast panels.

Figure 12 shows the actual damage distribution and Fig. 13 shows schematic representations of damage in test specimens at the end of the experiment. In the Fig. 13, the incline seen on the foundations of samples, in reality, did not exist in the test sample. In test specimen no. 1, damage occurred at low loads, while hinges in strengthening test specimens were concentrated in more advanced load levels.

6. Conclusions

In this study, the behavior of RC frames, hollow brick infill walls of which were strengthened using high-strength precast panels, under reversible repeatable horizontal loads was studied. The tests conducted brought a perspective on contribution, applicability to infilled RC frames under horizontal loads of the method of strengthening frame walls using precast panels.

During the tests, six 2-story, single span, 1/2-scale RC frames with hollow brick infill walls having designed and construction deficiencies, which is common in practice, were produced. One of these was tested as the reference specimen and the remaining 5 were tested after their walls were strengthened by bonding

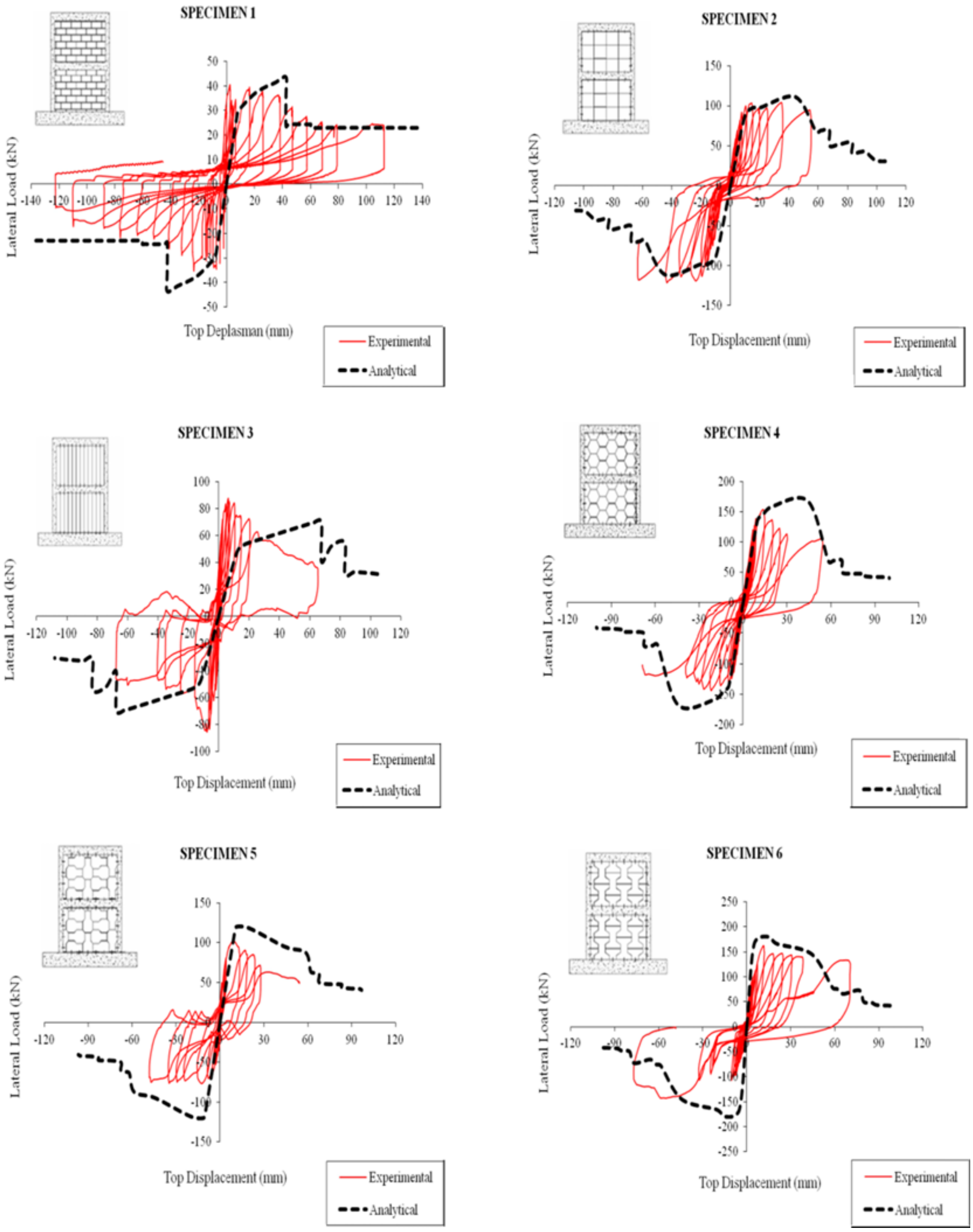


Fig. 11. Load-displacement Hysteresis Curve of Test Specimens

panels designed and produced in different geometric shapes onto them. As a result of the tests, the specimens were found to give better results in terms of maximum horizontal load-bearing capacity, initial rigidity and energy dissipation capacity. During the tests, damage occurred in brick infill walls of the reference specimen, whereas no major damage was observed on the walls of strengthened specimens. The damage was concentrated in the 1st story columns, connection points of columns and beams. This is thought to arise from inadequate anchorage length between the panels and frame elements and from notably high panel concrete strength compared to frame concrete strength. In fact, considerable rigidity of the walls is not desirable. However, it allowed the system to stand, although connection points between columns and beams crumbled toward the end of the test. E-TPF (specimen 6), one of strengthened test specimens, gave better results than other strengthened test specimens with respect to strength, rigidity and energy dissipation capacity. This demonstrated that whether panel geometry is smooth or recessed is effective in strengthening RC frames using precast concrete panels against lateral loads. In general, the findings of this study suggest that the

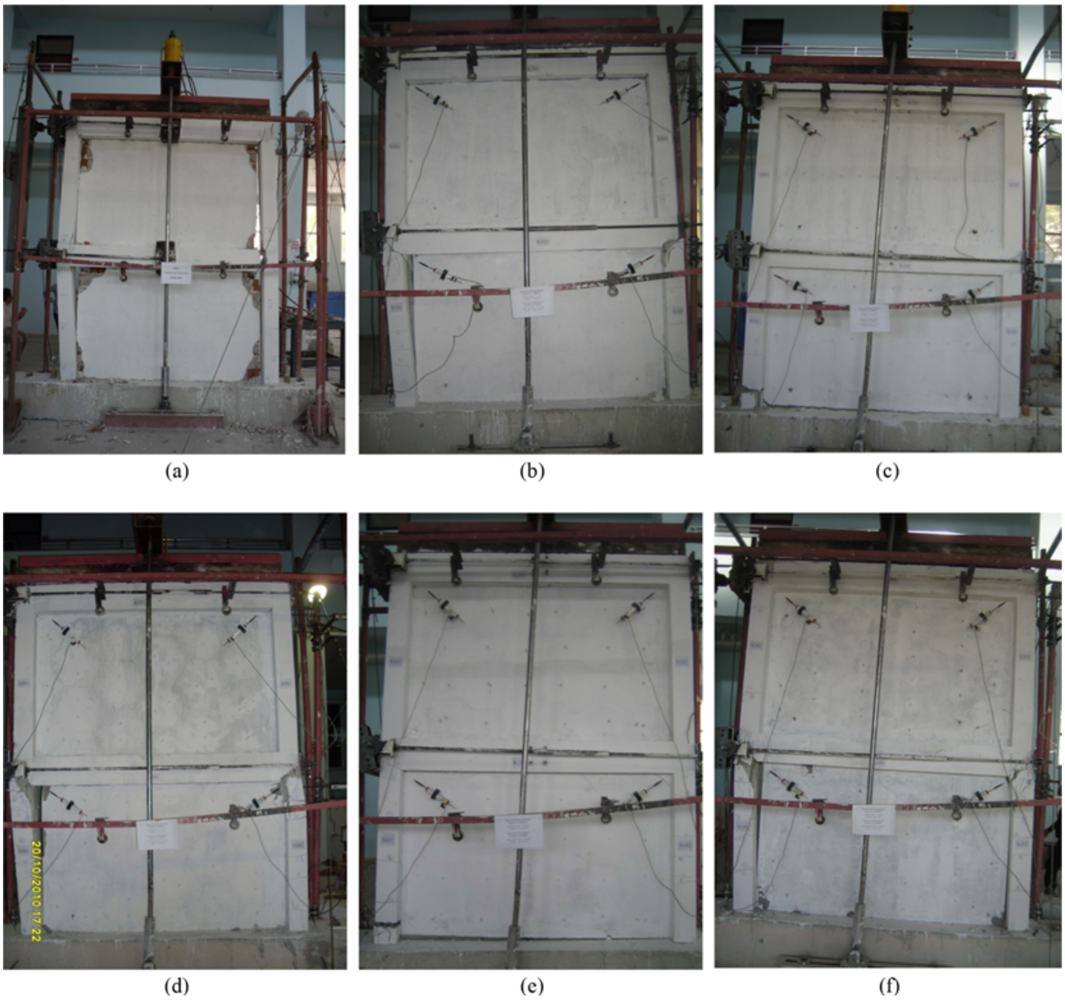


Fig. 12. Actual Damage Distribution of Frames after the Test: (a) RF, (b) A-TPF, (c) B-TPF, (d) C-TPF, (e) D-TPF, (f) E-TPF

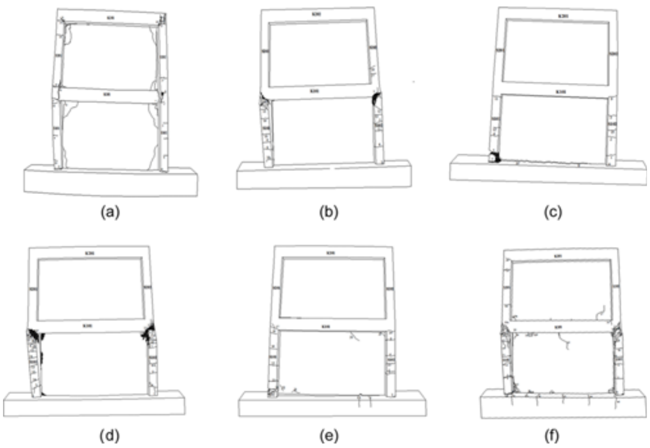


Fig. 13. Schematic Shapes of Test Frames after Failure: (a) Specimen 1: (b) Specimen 2, (c) Specimen 3, (d) Specimen 4, (e) Specimen 5, (f) Specimen 6

strengthening method utilizing precast high-strength panels are preferable compared to other strengthening methods in consideration of ease of application, the fact that it does not require evacuation of the building, the fact that it can be applied to adjacent structures and adequately increases the strength of the structure against horizontal loads.

Acknowledgements

This study was supported financially by S.U.-BAP (13701617). This study was prepared by using PhD thesis of Arife Akın. The author also thank Dr. Rıfat Sezer for his valuable help.

References

Akin, A. (2011). *Experimental and analytical study on the seismic behavior of the infill reinforced concrete frames with precast reinforced concrete panels*, PhD Thesis, Selcuk University, Konya, Turkey.

Akin, A. and Sezer, R. (2012). *Reinforced concrete panel design for the improvement of the seismic behavior of the frames with infill wall*, International Conference of Ecosystems (ICE), Tirana, Albania, June 1-6, pp. 740-745.

Akin, A., Sezer, R., and Akın, S. K. (2013). "Analytical modelling of RC frames with infill walls strengthened with precast panels."

International Journal on Advances in Mechanical Engineering and Civil Engineering, Vol. 3, No. 1, pp. 39-42.

Axley, J. W. and Bertero, V. (1979). *Infill panels: Their influence on seismic response of buildings*, EERC Report No. UCB/EERC-79/28, September.

Baran, M. (2005). *Precast concrete panel reinforced infill walls for seismic strengthening of reinforced frame structures*, PhD Thesis, Middle East Technical University (METU), Ankara.

Baran, M., Canbay, E., and Tankut, T. (2010). "The strengthening with concrete panels-Theoretical Approaches." *The Chamber of Civil Engineers Technical Journals*, 4959-4978, 324.

Binici, B., Özcebe, G., and Özçelik, R. (2007). "Analysis and design of FRP composites for seismic retrofit of infill walls in reinforced concrete frames." *Composites: Part B*, Vol. 38, Nos. 5-6, pp. 575-583, DOI: 10.1016/j.compositesb.2006.08.007.

Duvarci, M. (2003). *Seismic strengthening of reinforced concrete frames with precast concrete panels,* MSc Thesis, Middle East Technical University (METU), Ankara.

Erdem, I., Akyüz, U., Ersoy, U., and Ozcebe, G., (2006). "An experimental study on two different strengthening techniques for RC frames." *Engineering Structures Journal, Engineering Structures*, Vol. 28, No. 13, pp. 1843-1851, DOI: 10.1016/j.engstruct.2006.03.010.

Frosch, R. J. (1996). *Seismic rehabilitation using precast infill walls*, A Doctor of Philosophy Thesis in Civil Engineering, The University of Texas at Austin, Texas.

Frosch, R. J., Li, W., Jirsa, J. O., and Kreger, M. E. (1996). "Retrofit of non-ductile moment-resisting frames using precast infill wall panels." *Earthquake Spectra*, Vol. 12, No. 4, November, DOI: 10.1193/1.1585908.

Kahn, L. F. and Hanson, R. D. (1979). "Infilled walls for earthquake strengthening." *Journal of Structural Division*, ASCE, Vol. 105, No. ST2, pp. 283-296.

Kaldijan, M. J. and Yüzügüllü, O. (1984). *Efficiency of bolt connected reinforced concrete shear panels to repair and strengthen building structures*, Presented in Jordan.

Kaltakci, M. Y. and Yavuz, G. (2014). "The seismic improvement and control of weak concrete frames with partial concrete shear walls." *Journal of Vibration and Control*, Vol. 20, No. 8, pp. 1239-1256, DOI: 10.1177/1077546312467220.

Süsoy, M. (2004). *Seismic strengthening of masonary infilled reinforced concrete frames with precast concrete panels*, MSc Thesis, Middle East Technical University (METU), Ankara.

TEC-07 (2007). *Turkish earthquake code, regulations on structures constructed in disaster regions*, The Ministry of Public Works and Settlement. Ankara.