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Seismic Strengthening of Slightly Damaged RC Frames Using Axially Loaded Shotcreted Panels

Az Hasarlı Çerçevelerin Eksenel Yüklü Püskürtme Beton Paneller ile Güçlendirilmesi

Pınar Teymur*, Sumru Pala

Department of Civil Engineering, Structural and Earthquake Engineering Laboratory, Faculty of Engineering, Istanbul Technical University, Istanbul, Turkey

Abstract

The work presented in this study aimed to investigate the influence of axial loads applied on shotcrete panels. The experimental work is composed of strengthening of four bare reinforced concrete (RC) frames with shotcrete panels. In two of them, the panels are fully integrated to the frames and in the rest; the panels are connected only to the beams. At one of the specimens from each group, the beams are cambered before the construction of RC panels. After the cure of the concrete of the panel, the beams are released to create axial loads on the panels. The specimens are tested under lateral reversed cycling loads. From the results it has been observed that the axial load applied on the panel can cause increase on the lateral load carrying capacity and energy dissipation of the system at the fully integrated panel specimen. No significant effect of the axial load is observed at the partially integrated infilled frame.

Keywords: Axial load, Reinforced concrete frame, Strengthening, Thin panel,Wet-mixed shotcrete

Öz

Bu çalışmada sunulan araştırma, püskürtme beton panellerin üzerine etkiyen eksenel yüklerin etkisini incelemektir. Deneysel çalışmada, dört adet püskürtme beton panelli betonarme çerçevenin güçlendirilmesi yapılmıştır. İki adet çerçevede, paneller çerçeveler ile tam bağlı ve diğer ikisinde ise paneller sadece kirişe bağlanmıştır. Her iki grup numuneler içinden, birer tanesinde kirişlere betonarme panellerin imalatından önce ters sehim verilmiştir. Panel betonları priz aldıktan sonra, kirişler serbest bırakılarak paneller üzerine eksenel yüklerin etkimesi sağlanmıştır. Numuneler, çevrimsel yatay yükler altında denenmiştir. Sonuç olarak, panellere uygulanan eksenel yük, yanal yük taşıma kapasitesinde artış sağlamıştır ve tam bağlı panel numunede sistemin enerji dağılımı da artmıştır. Sadece kirişlere bağlı dolgu çerçevelerinde, eksenel yükün etkisi gözlemlenmemiştir.

Anahtar Kelimeler: Eksenel yük, Betonarme çerçeve, Güçlendirme, İnce panel, Islak karışımlı püskürtme beton

1. Introduction

As a retrofitting technique used for vulnerable RC frames, construction of shotcrete panel is quite beneficial against conventional shear wall, when formwork and workmanship is expensive and/or accessing to the work area is difficult. One layer of simply prepared formwork is adequate for the construction of shotcrete panel. The wet-mixed concrete is applied with a certain speed, and it will stick to the surface easily so that proper replacement of the wall is achieved.

*Corresponding Author: pteymur@gmail.com

Pınar Teymur orcid.org/0000-0002-5961-1020
Sumru Pala orcid.org/0000-0002-4255-6328

Strengthening a damaged RC frame with forming a thin concrete wall on the existing masonry walls (Zarnic and Tomazevic 1998, Yuksel et al. 1998a, 1998b) or using shotcrete on special wall-like structures in lieu of masonry walls (Mourtaja et al. 1998) showed that, these kinds of easily applicable retrofitting techniques increases lateral load carrying capacity and lateral rigidity of the structure.

Strengthening of infill walls using shotcrete is typically used in strengthening of damaged and/or undamaged masonry buildings in Turkey as stated in the studies of Wasti et al. (1997), Celep (1998), Aydoğan and Öztürk (2002).

Teymur (2009) in the PhD thesis used shotcrete panels to strengthen RC bare frames instead of traditional shear walls. The experimental work is composed of testing one bare frame for reference, six vulnerable RC frames by forming an infill wall using wet-mixed sprayed concrete and one conventional shear wall. In the study, fully and partially infilled frames were examined. The results were discussed in detail in Teymur et al. (2012, 2014).

The lateral load exerted on the wall depends on the conditions of the joints along the interface. In cases where the contact between the beam and the infill is not strong enough, the lateral force is mainly transferred by normal stresses developing in the contact zone between the columns and the panel. As a result; the stress state in the panel changes, in comparison to that of the integrated infilled frames especially in the loaded upper corner zone.

Wall tests that include axial load have been conducted and relatively few of them concluded with shear failures, so insufficient information exists to systematically assess the impact of axial load on shear strength. Orakcal et al. (2009) reported that wall shear strength is sensitive to axial load.

In this study, the beams of RC bare frames are cambered at a certain level before strengthened with wet-mixed shotcrete panels. When the beams are released, they form axial loads on the panels. The idea of imposing axial loads on panels is to enhance the contact interface between the beam and the infill wall causing the shotcrete panel and the surrounding frame to work together for a long time ensuring that the lateral loads continue to be transferred throughout the whole system and increase shear strength of panels.

Experimental research has been conducted to understand how the axial load on panels are effective on the lateral load carrying capacity, the lateral rigidity, the energy dissipation capacity and the damage mode of the system. To assess the effect of the behaviour of RC frames infilled with axial-loaded panels, the results of the experiments are compared with the ones that are strengthened with non-loaded panels presented in Teymur et al. (2012, 2014).

2. Material and Methods

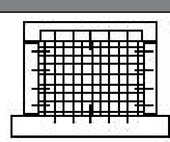
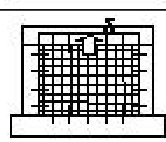
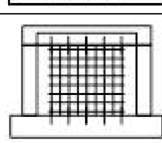
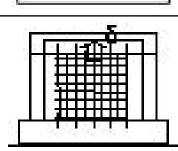
The experimental work is composed of strengthening of four bare vulnerable RC frames with thin shotcrete panels. The RC frames were chosen to represent the weak column/strong beam type structures that are very common in Turkey. Nearly ½ scale, one story, one bay specimens were tested under constant vertical loads acting on the columns and lateral reversed cycling loads acting at the centre of the loading beam. Two fully and two partially infilled frames were tested. One of the specimens from each group is retrofitted with axial-loaded panel.

2.1. Properties and Construction Details of the Test Specimens

Tested specimens are summarised in Table 1 and explained in detail below.

RC frames with a portion of slab on top and a foundation at the bottom has been constructed in the laboratory. The

Table 1. Test specimens.

Specimen	Type	Gap space between panel and columns	Pre-load on the panel	28-day concrete compressive strength (MPa)	
				Frame	Panel
Specimen 1		No	No	10	22
Specimen 2		No	Yes	12	25
Specimen 3		Yes	No	12	35
Specimen 4		Yes	Yes	12	25

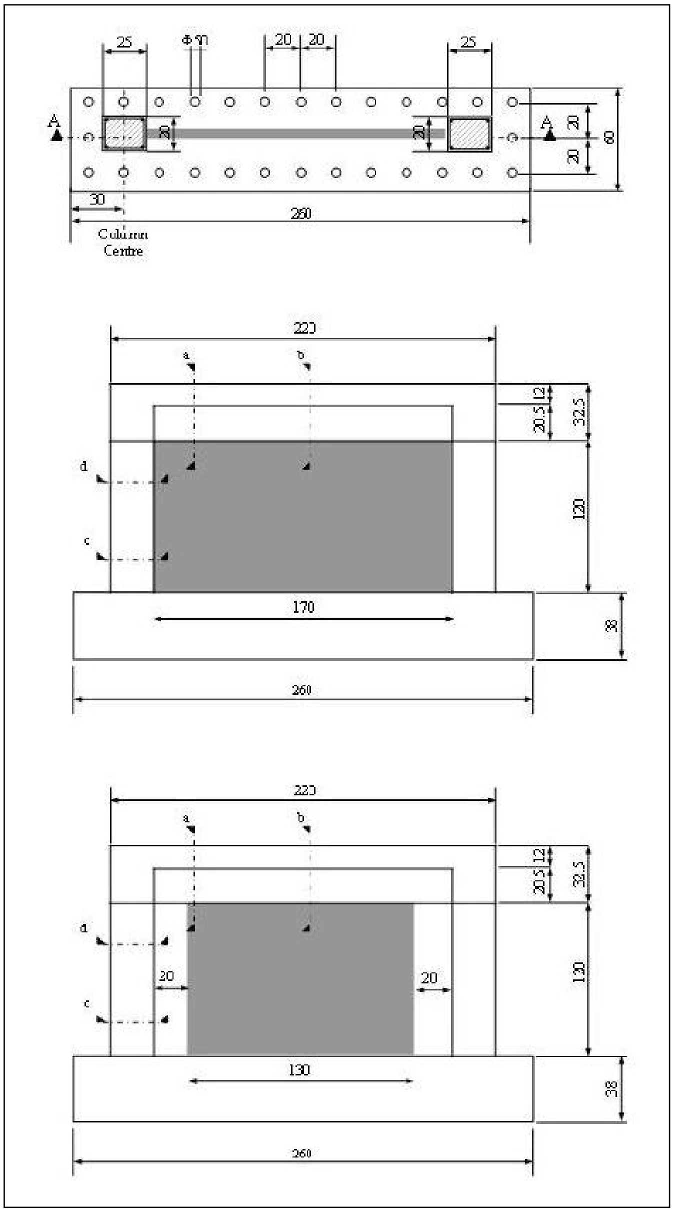


Figure 1. Geometry of the frames.

dimensional details of the frames can be seen in Figure 1. The widths of the shotcrete panels are 170 cm and 130 cm for fully and partially infilled frames, respectively as shown in Figs. 1a-1b. Longitudinal reinforcement of the frames consists of 16 mm steel bars which have average yield stress of 270 N/mm^2, and the wire mesh used in the panels has a diameter of 4.5 mm and has yield stress of 320 N/mm^2. The reinforcement ratio of the column and the panel are %1.6 and %0.2 respectively. The reinforcement detail of the frames can be found in Teymur et al 2012 and 2014.

A wire mesh was placed in the horizontal axis of symmetry of the frame. One layer of formwork was placed at a distance of 2.5 cm behind the wire mesh which can be seen in Figs. 2a-2b. For the fully infilled Specimens 1 and 2, the wire mesh is connected to the frame by lapping it to the anchorages that are placed in the beam, the foundation, and the columns. In the case of partially infilled Specimens 3 and 4, the wire mesh is connected to the anchorages placed only in the beam and the foundation and has a 20 cm distance to the columns. The anchorages used are 10 mm steel bars, and placed 30 cm and 20 cm apart from each other by using epoxy resin for the fully and partially infilled specimens, respectively which can be seen in Figure 3. Lengths of the anchorages are 35 cm; 20 cm of it is placed in the panel while 15 cm is left in the beam. By using wet-mixed shotcrete, a 5 cm-thick panel was formed.

Although the constructions of Specimens 2 and 4 are identical to Specimens 1 and 3 respectively, the beams of these specimens are cambered before the construction of the panels. The beams are cambered by means of special screws that are placed in the middle symmetrically and placed to the right and left side of the beam between the foundation and the slab as shown in Figs. 4a-4b when the concrete of shotcrete panels have cured, the screws are removed and

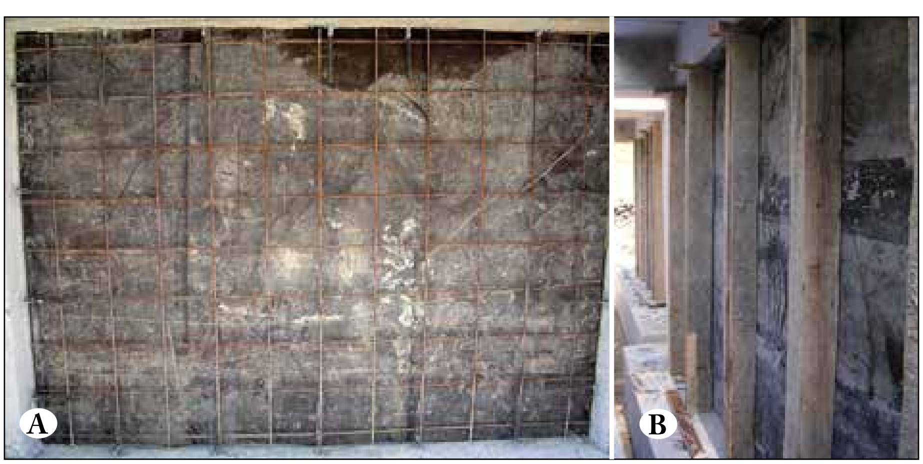


Figure 2. Construction of the shotcrete panels. **A)** Wire mesh and one layer of formwork.
B) Back veiw of formwork.

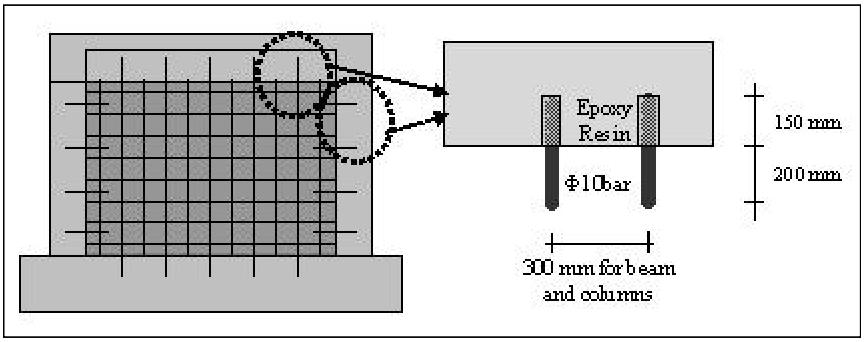


Figure 3. Details of shear keys used in the fully infilled specimens.

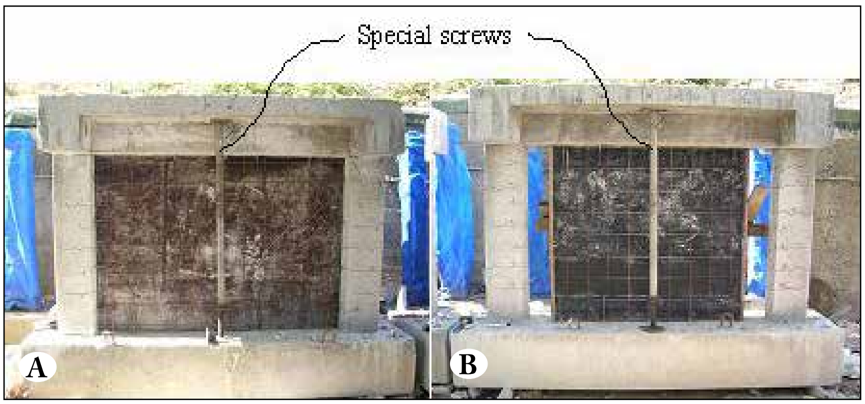


Figure 4. The construction of Specimens 2 and 4.

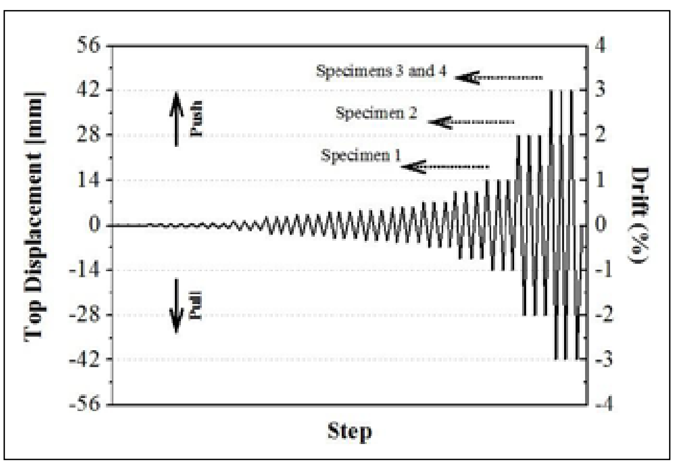


Figure 5. General load pattern.

the beams are released causing axial loads on the panels. The cambering deflection applied to each specimen with mechanical force which is produced by the screws is 7.4 mm.

The idea behind the intensity of the cambering deflection is that when the beams are cambered, the cracks that will occur in beams and columns are kept to be small in width and therefore no special repairing will be needed. Considering this fact, some calculations are done and the reasonable amount of cambering deflection is found to be 1/300-1/250 of the span.

During the process, deflection is continuously measured at the middle of the beam with a displacement transducer. The amount of deflection applied was 7.4 mm which is almost 1/260 of the span. From the calculations made it can be stated that the level of axial load applied is around 30 kN. As expected, shear cracks at columns and flexural cracks at the tension side of the beam occurred during the cambering process. The maximum crack widths occurred were 0.1 mm on the columns and 0.4 mm on the beam.

2.2. Test Setup, Instrumentation and Data Acquisition

Axial load which is kept constant throughout the test is applied on the columns by means of a hydraulic jack. The intensity of the axial load is 20% of the axial load carrying capacity of columns. Lateral cycling load imposed as displacement reversals is applied to the specimen with two MTS 250 kN-capacity hydraulic actuators that are placed at the beam centre line.

Since the loading is aimed to simulate the effect of seismic action, reversed cycling displacement reversals with increasing intensity was applied to the specimens. Up to 0.467 mm top displacement, while observing the elastic behaviour of the specimens, the target displacement values are applied once on the specimens. Beyond 0.467 mm, each displacement cycle is repeated thrice for both pushing and pulling cycles. The details of the load pattern are summarized in Figure 5.

Linear variable differential transformers (LVDTs) are used to measure the target displacement and several other displacements on the specimens as shown in Figure 6.

3. Results

Test results of Specimens 1 and 3 have already been discussed in detail in Teymur et al. (2012) and Teymur et al. (2014), respectively. So in this section of the paper only test results of Specimens 2 and 4 are going to be presented.

3.1. Test Results of Specimen 2

Specimen 2 was the frame, retrofitted with fully integrated axial-loaded shotcrete panel. The largest displacement applied to this specimen was 28 mm.

Base shear versus top displacement diagram is given in Figure 7. Maximum load occurred in pushing cycles was obtained at +28 mm displacement cycles and was 374 kN. In pulling cycles, maximum load was 359 kN obtained at 10.5 mm displacement cycles. The ultimate lateral load carrying capacities of the frame are 156 kN and 110 kN in pushing and pulling of the third displacement cycles, respectively.

The first separation between the panel and the frame members and the first shear crack at lower end of the right column (the column where the actuator was connected) occurred during the +0.467 mm displacement cycles. The load was reported as 71.4 kN. The first diagonal crack was observed on the panel during the –0.467 mm displacement cycles. The load was reported as 70.5 kN.

Crack patterns occurred at the end of the test in the pulling and pushing cycles are shown in Figure 8. Table 2 summarizes the width of cracks at 1% drift ratio. No severe shear cracks were observed on the columns ends. Pieces of the shotcrete panel felt at some regions of the wall.

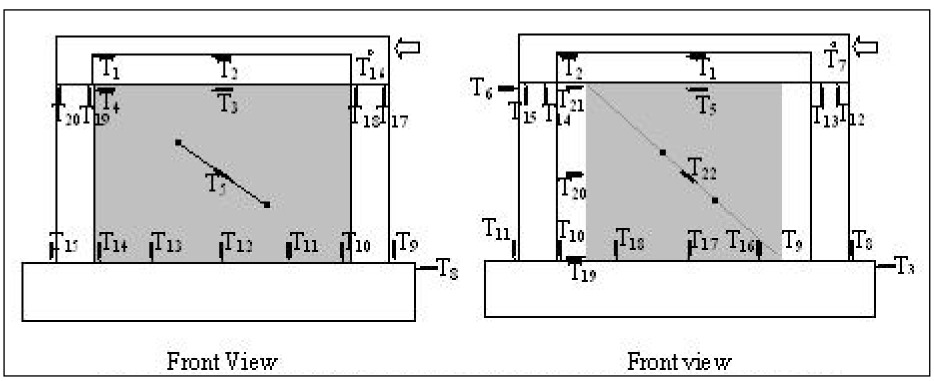


Figure 6. Locations of LVDTs on fully and partially infilled frames.

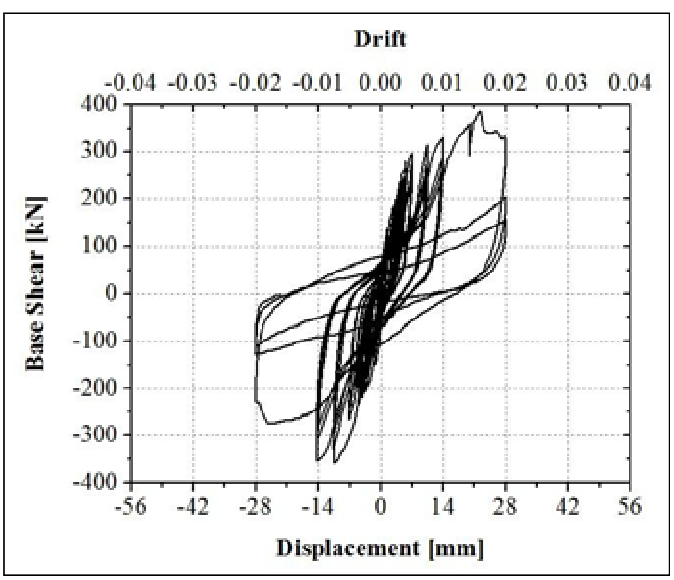


Figure 7. Base shear-top displacement curve of Specimen 2.

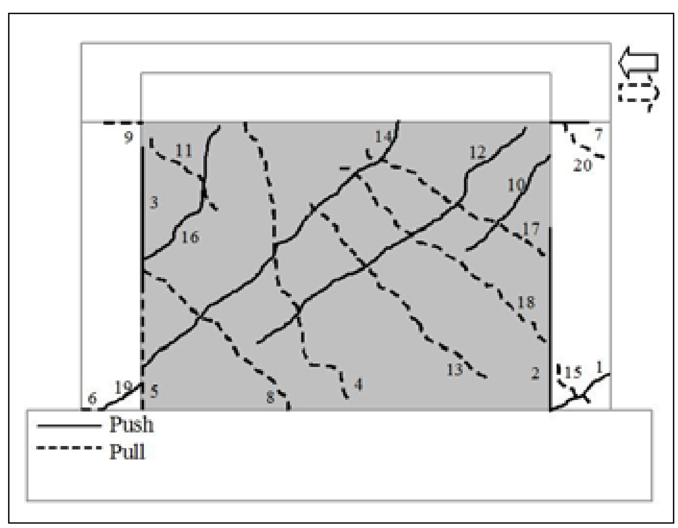


Figure 8. Crack pattern of Specimen 2 at the end of the test.

3.2. Test Results of Specimen 4

Specimen 4 was the frame retrofitted with partially infilled axial-loaded shotcrete panel. The largest displacement applied to this specimen was 42 mm.

Base shear versus top displacement diagram is given in Figure 9. The maximum load occurred at the end of the positive displacement cycles was 213 kN obtained at 14 mm displacement cycles which correspond to 1% story drift and in negative displacement cycles was 211 kN obtained at 10.5 mm displacement cycles. The maximum story drift reached is 3%. The ultimate lateral load carrying capacities of the frame are 51 kN and 54 kN in pushing and pulling of the third displacement cycles, respectively.

Table 2. The maximum crack widths of Specimen 2 at 1% story drift.

Crack #	Drift = 1%	Crack #	Drift = 1%
1	1.60	11	0.40
2	1.60	12	1.20
3		13	1.20
4	1.20	14	0.80
5	2.50	15	0.30
6	1.20	16	1.00
7	2.50	17	0.70
8	0.70	18	0.30
9	3.00	19	NA
10	0.30	20	NA

The separation at the end of the left column firstly occurred during the -0.7 mm displacement cycles. In that cycle, the load was 54 kN. The shear crack at the upper end of the right column occurred during the +4.2 mm displacement cycles. In that cycle, the load was 131 kN. The first diagonal crack observed on the panel occurred during the +2.8 mm displacement cycles. In that cycle, the load was 106 kN.

Crack patterns occurred at the end of the test are shown in Figure 10. Table 3 summarizes the width of cracks at specific drift ratios. The failure observed at the specimen was shear failures occurred at bottom ends of the both columns.

4. Discussion

The evaluation of the results obtained from the four test specimens are explained briefly below. Failure modes, load carrying capacities, initial stiffnesses, energy dissipation capacities and lateral stiffnesses of the specimens are discussed.

Table 3. The maximum crack widths of Specimen 4 at 1% story drift.

Crack #	1	2	3	4	5	6	7	8	9	10
Maximum crack width (mm)	1.80	2.00	1.40	2.50	3.50	3.00	0.70	2.50	0.70	0.30

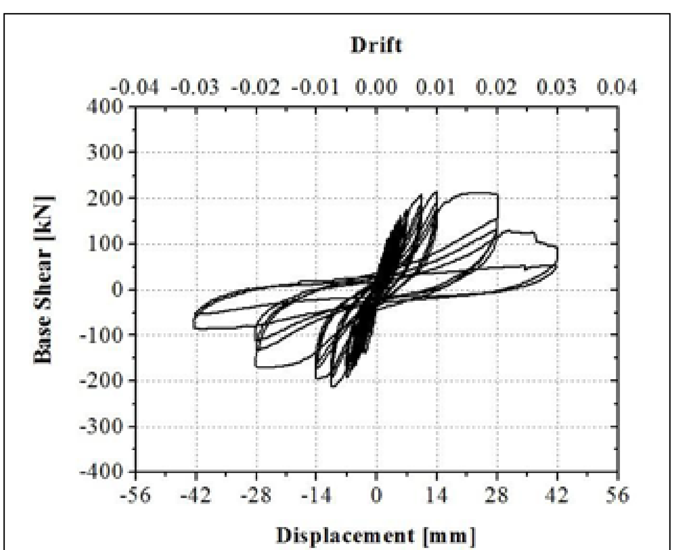


Figure 9. Base shear-top displacement curve Specimen 4.

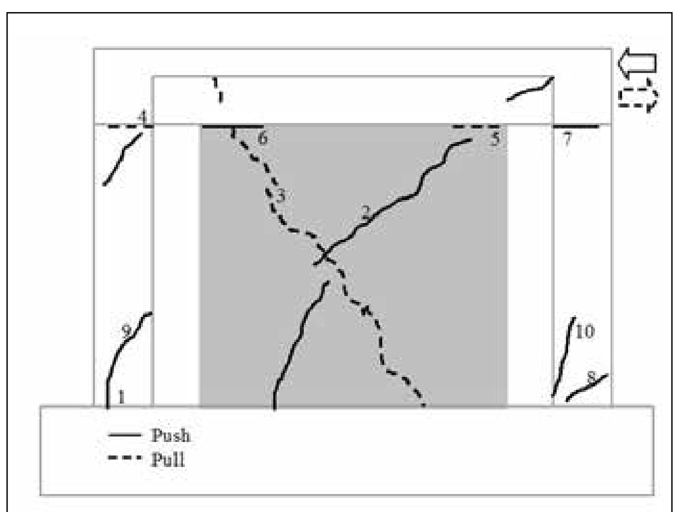
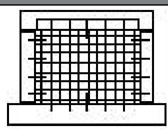
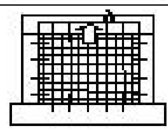
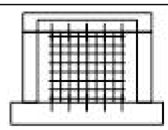
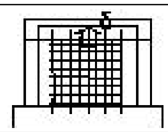


Figure 10. Crack pattern of Specimen 4 at the end of the test.

Table 4. Effect of retrofitting on general quantities.

Specimen	Type	Failure mode	$+P_{max}$ (kN)	$+\delta_{max}$ (mm)	Story Drift %	$-P_{max}$ (kN)	$-\delta_{max}$ (mm)	Story Drift %	$+P_{ult}$ (kN)	$-P_{ult}$ (kN)	δ_{ult} (mm)	Story Drift %
1		Shear failure at column ends	279.0	10.5	0.75	-279.0	-10.5	0.75	165.0	-146.0	14.0	1.00
2		Shear failure at column ends	331.0	28.0	2.00	-359.0	-10.5	0.75	156.0	-110.0	28.0	2.00
3		Shear failure at column ends	217.0	28.0	2.00	-223.0	-14.0	1.00	84.0	-74.0	42.0	3.00
4		Shear failure at column ends	213.0	14.0	1.00	-211.0	-10.5	0.75	51.0	-54.0	42.0	3.00

+ : Push, - : Pull, P_{max} *= The greatest load carried out through the experiment,* δ_{max} *= The displacement corresponds to* P_{max}*,* P_{ult} *= The smallest load that corresponds to the ultimate displacement,* δ_{ult} *= The ultimate displacement carried out.*

Table 5. Maximum base shears observed during the tests.

Specimen	Maximum load [kN]		Ratio	
	Push	Pull	Push	Pull
1	279	-279	1.00	1.00
2	331	-359	1.19	1.29
3	217	-223	1.00	1.00
4	213	-211	0.98	0.95

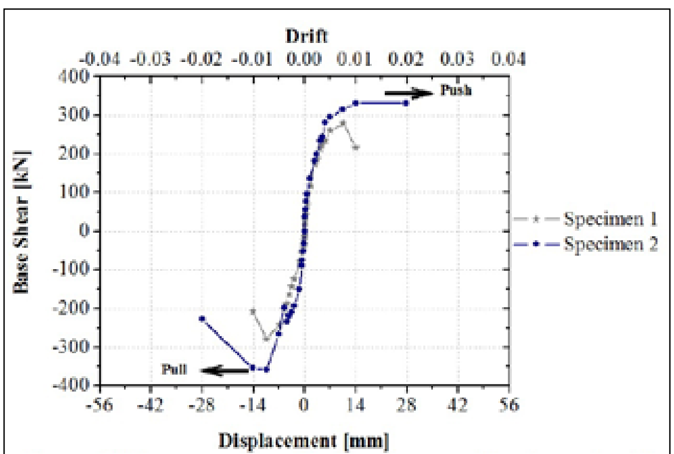


Figure 11. The comparison of backbone curves of Specimens 1 and 2.

4.1. Lateral Load Carrying Capacity

Table 4 summarizes the maximum loads (P_{max}) and the ultimate loads (P_{ult}) that each frame has carried in pulling and pushing cycles and the displacement levels (d_{max}, d_{ult}) corresponding to these loads. Table 5 summarizes the lateral load carrying capacity increments of the specimens with axial-loaded panels as a ratio of one's without the axial loads in pushing and pulling cycles.

The comparison of the backbone curves of the hysteretic responses of the fully infilled specimens are given in Figure 11. The data of backbone curves are taken as the maximum values of lateral loads at the first cycles of each target displacement levels. Axial load on the panel seems to make a 30% increase in the lateral load carrying capacity of the specimen compared to non-loaded panel specimen. In Specimen 1, the lateral load carrying capacity of the frame increases gradually till 10.5 mm target displacement which corresponds to 0.75% story drift. Maximum load is observed during these cycles. After this point, the load begins to decrease and the test ended at 1% story drift. There is a drop of lateral strength at around 0.75% drift due to the widening of shear cracks at top ends of the columns followed by detachment of the shotcrete panels from the columns.

On the other, in Specimen 2 the load kept increases till 2% story drift and maximum load is observed during these cycles. This shows that axial load exerted by the beams enhance the contact interface between the beam and the infill wall causing the shotcrete panel and the surrounding frame to work together for a long time ensuring that the lateral loads continue to be transferred throughout the whole system.

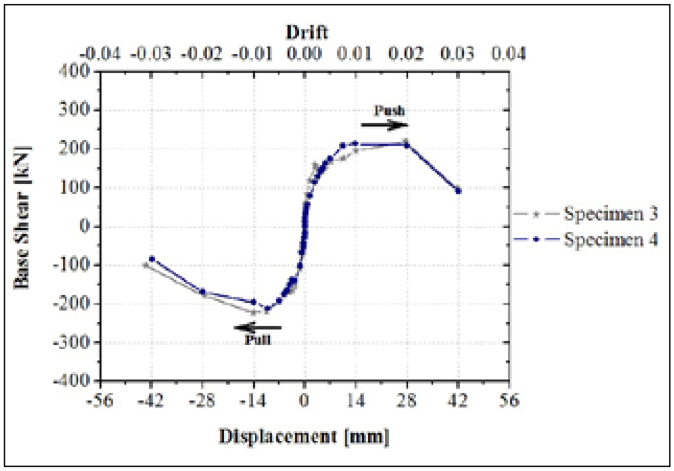


Figure 12. The comparison of backbone curves of Specimens 3 and 4.

Backbone curves of partially infilled specimens are presented in Figure 12. Axial load on the panel seems to have no significant effect on the lateral load carrying capacity of partially infilled specimens. In Specimen 3, the lateral load carrying capacity of the frame increases gradually till 28 mm target displacement which corresponds to 2% story drift. After this point, the load begins to decrease till 3% story drift. On the other, in Specimen 4 maximum load is reached at 0.75% story drift. It is kept constant till 2% story drift. After this point, the load begins to decrease till 3% story drift.

4.2. Failure Modes

The failure modes which were observed are summarised in Table 4. As can be seen in the table; shear failure at column ends were observed in the frames. Axial load on the panel does not affect the failure mode of the surrounding frame. The reason is that the frames have low shear strength properties. No matter how strong wet-mixed sprayed concrete panels were, the ultimate failure modes of the systems were controlled by the existing shear capacity of the outer frames. The final failure mode of the specimens at the end of test is shown in Figure 13.

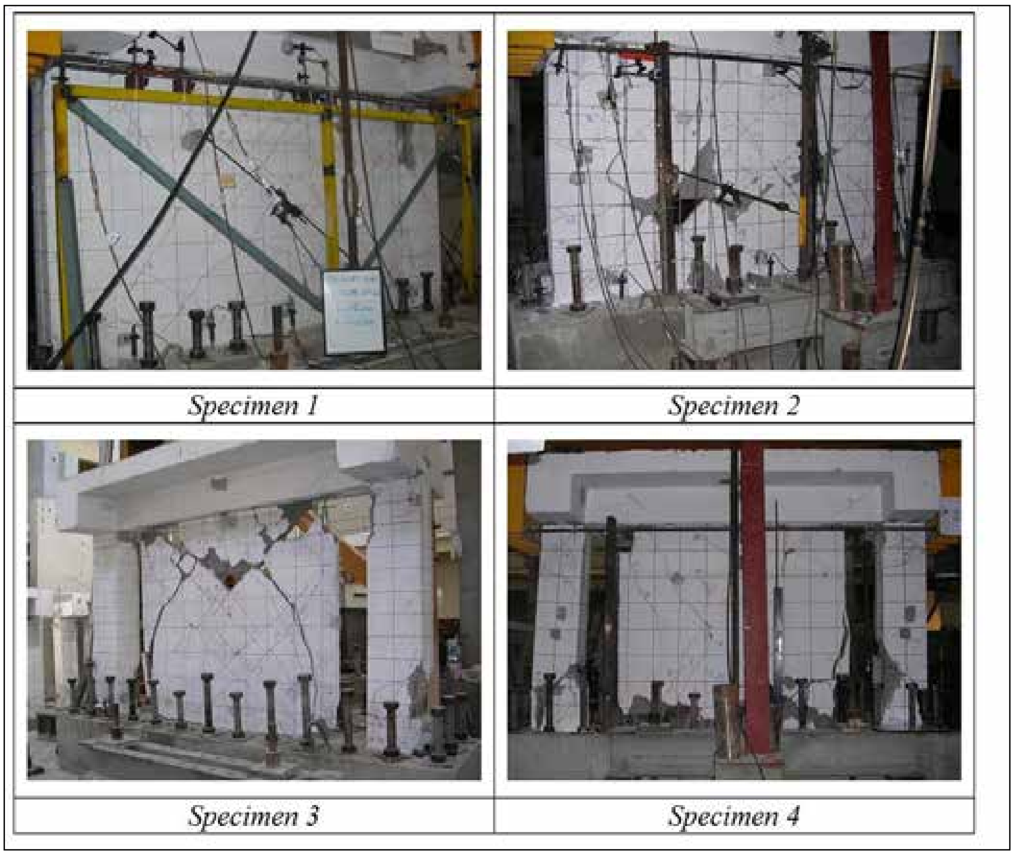


Figure 13. The ultimate state of the specimens.

In case of fully infilled specimens unlike Specimen 1, no severe shear cracks were observed on the columns ends at the end of the test of Specimen 2. The differences in resistance mechanisms developed in the system due to vertical load can be explained considering the force distribution in the infill and RC columns. On the other hand axial load on the panels seem to cause more damage on the shotcrete panel in case of fully infilled specimen. Pieces from some regions of the shotcrete panel have fallen.

In case of partially infilled specimens, in Specimen 3 tensile failure and toe crushing at four corners of the panel is observed. Panel acts similar to failure behaviour of a masonry wall. On the other hand in Specimen 4, damage is more concentrated at the lower regions of the specimen. Severe shear cracks observed at the bottom end regions of the columns. Pieces from some lower regions of the shotcrete panel have fallen. Panel acts similar to diagonal compression failure behaviour of a shear wall.

4.3. Initial Stiffness

Table 6 compares the initial stiffnesses of the four specimens. In the table, the increments are also given as a ratio of initial stiffnesses observed in the specimens with axial-loaded panels to the initial stiffnesses observed in the ones with non-loaded panels. The initial stiffness values are calculated as the slope of the line joining the points of the maximum loads in pushing and pulling cycles that has occurred during the initial steps of the test.

The axial load on the panel seems to make a 36% increase in the lateral stiffness of the fully infilled specimen but has no significant effect on the partially infilled specimen.

4.4. Cumulative Energy Dissipation

The comparison of the cumulative energy dissipation capacities of the fully and partially infilled specimens are given in Figs. 14-15, respectively.

The axial load on the fully integrated panel seems to cause a 36% increase in the cumulative energy dissipation capacity, but no significant effect on the partially infilled specimen.

Table 6. Initial stiffness of the specimens.

Specimen	Initial stiffness [kN/mm]	Ratio
1	183.9	1.00
2	249.9	1.36
3	188.5	1.00
4	179.3	0.95

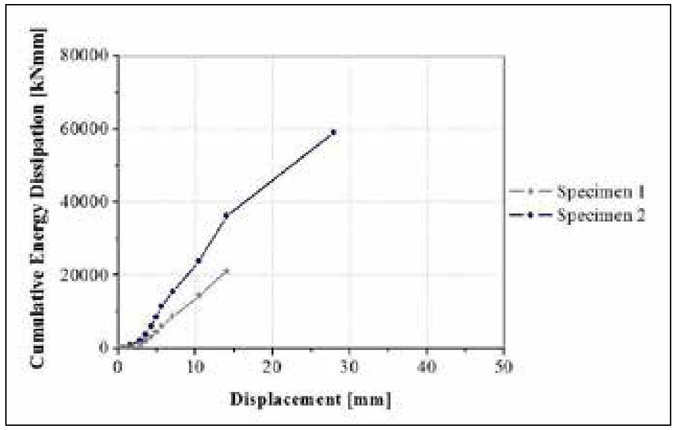


Figure 14. Cumulative energy dissipation capacities of Specimens 1 and 2.

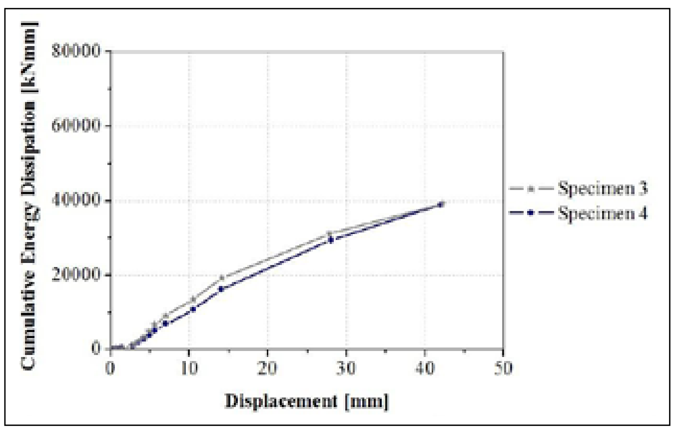


Figure 15. Cumulative energy dissipation capacities of Specimens 3 and 4.

5. Conclusion

In this study, before the construction of a thin RC panel, beam of a RC frame is cambered. The beam is released causing axial load on the infill panel to improve contact interface between the beam and the panel for raising the frame's seismic performance. The results of the frames formed by using this method compared with the one with a panel which no axial load imposed on it and following conclusions are drawn.

The axial load exerted by the beam does not affect the failure mode of the surrounding frame. Hence the existing shear capacities of the frames control the ultimate failure modes of the systems. The entire strengthened frame experiments were terminated as a result of severe shear cracks that have occurred at the end of the columns. Therefore improvement of the shear capacities of the columns and beam-column joints is suggested before the construction of the panels.

Even though the frames are damaged heavily, the panels continue to carry lateral loads. As a result of this, the specimens present more ductile behaviour when they are exposed to axial load.

6. Acknowledgement

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