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SEISMIC STRENGTHENING OF MASONRY INFILLED REINFORCED CONCRETE FRAMES WITH STEEL FIBER REINFORCEMENT

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ABSTRACT

Seismic resistance of several buildings in Turkey is deficient. Strengthening of these buildings with commonly used reinforced concrete (RC) infills requires excessive construction work. The main objective of this study is to develop a feasible, effective, and yet economical strengthening technique that does not disturb the inhabitants. The proposed method is based on application of steel fiber reinforced higher strength mortar on the plaster of masonry walls. An optimum steel fiber reinforced mortar (SFRM) was obtained in preliminary material tests. RC frames strengthened by applying the mortar onto brick masonry plastered infill walls were tested under reversed cyclic lateral loads simulating earthquake. The frames were 1/3 scale, 1 bay, and 2 story. Totally 10 frame tests were performed. Tests included 4 different reference tests, and 6 strengthened frame tests having various mortar thicknesses and steel fiber volumetric percentages. Frame having 2 percent SFRM anchored to the frame with 20 mm thickness carried approximately 2 times the lateral load of the plastered brick masonry reference frame.

Introduction

Turkey is a country of high earthquake risk, such that 91% of land is located in seismically active zones. During the last 10 years, 7 major earthquakes occurred in different regions of Turkey. Majority of buildings in Turkey do not have enough seismic resistance (inadequate strength and/or ductility and/or stiffness). Strengthening of existing reinforced concrete (RC) framed buildings to improve the seismic resistance is an important problem. Different intervention techniques being used range from conventional techniques, which use braces, jacketing, or RC infills, to more recent practices such as base isolation, supplemental damping devices or advanced materials.

Strengthening of RC framed structures by using cast-in-place RC infills leads to a huge construction work and is also time consuming. Studies on more feasible, rapid and easy techniques that do not require evacuating the structure, have been successfully implemented in Structural Mechanics Laboratory of Middle East Technical University (METU). Studies on strengthening of masonry infilled walls with carbon fiber reinforced polymer (CFRP) or prefabricated panel infills

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may be cited in the context of these studies. Those studies have been almost completed and offer practical alternatives for seismic strengthening. Still, it has to be mentioned that CFRP is an export material and this leads strengthening costs to take a significant portion among the overall costs. Attaching the prefabricated panels onto the masonry walls by means of epoxy based adhesives also increases the overall strengthening budget.

The object of this research was to develop a method that gives importance to the use of domestic materials while utilizing the knowledge acquired from the strengthening methods being developed. When the number of buildings that have to be strengthened is concerned, this approach becomes significantly important in terms of country's economy. Steel fibers are being widely used in the construction sector. In this study, possibilities of using steel fibers also in strengthening of structures were investigated. The proposed method is based on the application of high strength mortar, containing steel fibers on masonry wall. The aim of this study was to produce masonry infill wall that behaves similar to a shear wall by applying steel fiber reinforced mortar (SFRM) on the masonry wall.

Concrete is a brittle material. If steel fibers are added into the concrete matrix (fiber reinforced concrete, FRC), they randomly bridge the cracks and cause more ductile failure. Polypropylene (PP) fibers are used in concrete applications mostly due to their effectiveness in controlling plastic shrinkage cracking, and also due to their relatively low cost, alkali resistance, and high elongation. A combination of two or more types or sizes of fibers (hybrid fiber reinforced concrete, HFRC) can improve the composite performance by taking advantage of benefits of each fiber.

Masonry infill is frequently found as interior and exterior partitions in RC structures. Since they are generally considered as nonstructural components, they are ignored in structural analysis. However, they interact with the surrounding frame when the structure is subjected to earthquake loads. Masonry can carry great in-plane compression if properly confined. The masonry infill provides significant lateral stiffness, thus reducing lateral drift, while the frame provides confinement and ductility to the frame-infill system. This considerably changes the dynamic response of the structure from that of the bare frame structure without the infill. Therefore, it is important that the interaction of the masonry infills with the bounding frames be taken into account while analyzing or designing buildings.

Past Studies

Studies, conducted in the Structural Mechanics Laboratory of the METU, on infill walls will be summarized in this part.

The first published experimental research in the RC infilled frame is the one reported by Ersoy and Uzsoy in 1971. The researchers tested nine 1/2-scale, one-story, one-bay frames with RC infills under monotonic loading. It was concluded that the presence of the infill increased the lateral load capacity of the frame and reduced the lateral displacement at failure significantly.

Altın, Ersoy, and Tankut (1992) investigated the behavior of infilled frames under seismic loads. For that purpose, fourteen two-story, one-bay infilled frames were tested under reversed cyclic loading simulating seismic action. The main variables investigated were, the effect of the type of infill reinforcement and the connection between the frame and the infill. The effect of column axial loads and flexural capacity of columns on strength and behavior were the other two variables studied. It was concluded that the use of RC infills seemed to be very feasible. The infills increased both strength and stiffness significantly under lateral loads, provided that infills were properly connected to the frame.

Sonuvar (2001) constructed five two-story, one-bay, 1/3 scale RC frames having the deficiencies observed in common practice in Turkey. The frames were tested under the reversed cyclic loading until considerable damage was observed, and then they were rehabilitated by means of cast-in-place RC infill walls and local strengthening techniques. Later, the rehabilitated frames were tested under reversed cyclic loading in order to observe the performance of the repaired specimens. It was concluded that performance of the RC infills, especially of the dowels, largely depended on workmanship. It was also concluded that local strengthening techniques (e.g. strengthening of insufficient lap splices by means of fiber reinforced polymer (FRP) wrapping) in addition to infills were quite effective. Energy dissipation capacity of the frames was considerably increased.

Duvarcı (2003) aimed to strengthen buildings by using precast concrete panels. In the study, two preliminary test were conducted to verify the proper functioning of the newly developed test setup and then three hollow clay tile infilled, one-third scale, one-bay, two-story RC frames which reflect the common deficiencies of the buildings in Turkey were constructed as test specimens. The tests indicated that precast concrete panels improved the system behavior considerably. The shear keys and the epoxy mortar functioned successfully. When the economy is concerned, it could be said that precast concrete panel strengthening technique was less expensive than monolithic shear wall.

Süsoy (2004) aimed to observe the seismic behavior of RC frames strengthened by precast concrete panel infills. He tested different types of panel and connection designs in eight single-story, single-bay RC frame specimens. It was concluded from the study that strengthening with precast concrete panels was a very effective and convenient method for strengthening seismically vulnerable RC structures. Strengthened infill failed by excessive diagonal cracking on the panels, and the frame failed by crushing or failure at the column bases or at the beam-column joints. The method proved to be effective also for specimens with lap-spliced reinforcement, although bar slip problems were observed.

Baran (2005) proposed a strengthening technique in his thesis on the basis of the principle of strengthening the existing hollow brick infill walls by using high strength precast concrete panels. For that purpose, a total of fourteen one-bay, two-story RC frames with hollow brick infill wall were tested under reversed cyclic lateral loading simulating earthquake loading. The specimens were strengthened by using six different types of precast concrete panels. Test results indicated that the proposed seismic strengthening technique could be very effective in improving the seismic performance of the RC framed building structures commonly used in Turkey. In the analytical part of the study, hollow brick infill walls strengthened by using high strength precast concrete panels were modeled once by means of equivalent diagonal struts and once as monolithic walls having an equivalent thickness. On the basis of the analytical work, practical recommendations were made for the design of such strengthening intervention to be executed in actual practice.

Experimental Program

Test Specimens

The frame specimens had a clear span of 1300 mm, and a net story height of 750 mm. The columns were 100 × 150 mm and the beams were 150 × 150 mm. The rigid foundation beam was 400 × 450 × 1900 mm. Details of the test specimens were selected to present the lack of satisfactory qualifications seen in most of the structures in Turkey. For beams, 6ϕ8 plain bars were used as longitudinal reinforcement. For columns, 4ϕ8 plain bars were used as longitudinal reinforcements. For both the columns and beams, ϕ4 plain bars were used as stirrups at 100 mm intervals. Ends of the stirrups were bent only 90º. The details and reinforcement patterns of the test specimens are illustrated in Fig. 1. Reinforcement details of the columns and beams are given in Fig. 2. Rigid foundation beams were prepared and cast with each frame. Foundations had dimensions of 1900 mm length, 450 mm width, and 400 mm height.

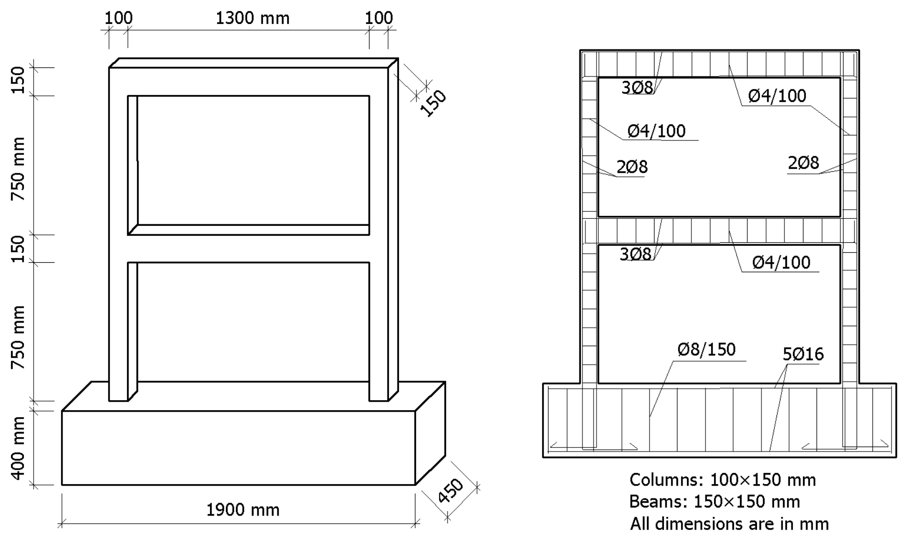

Figure 1. Dimensions and reinforcement patterns of the test specimens

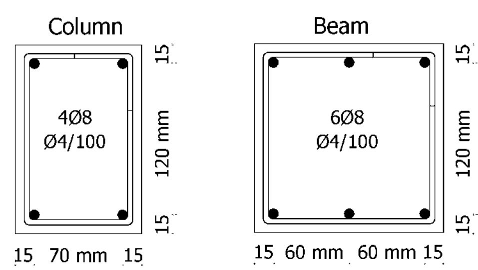

Figure 2. Column and beam reinforcement

Concrete of the frames was produced in the Structural Mechanics Laboratory of the METU. Concrete of one frame specimen was cast in 3 batches. Totally 10 test cylinders were taken from each specimens. Test cylinders were 150 mm in diameter and 300 mm in height. Cylinders were kept under same conditions as the test specimens. Curing was done by covering the specimens with wet burlap.

After minimum 7 days of curing, forms were removed and specimens were put in up-right position. Afterwards, bricks were laid in the frame and 6 mm thick plaster was applied on the brick wall. At last, mortar with 2% volumetric ratio of steel fibers was applied on the plaster. For comparison purposes, one specimen was strengthened with 2% PP, another specimen with 2% hybrid fiber (1% steel fiber, 1% PP), and one specimen with mortar lacking of any fiber.

To ensure force transfer between frame and strengthened masonry infill wall, anchorage bars were fixed to the surrounding frame. As anchorage, deformed bars having 180 mm length and 8 mm diameter were used. Bars were placed at 200 mm intervals with 60 mm embedded in to the frame and 120 mm remained in the mortar. Totally 80 anchorage bars were used for one frame. Properties of the specimens are summarized in Table 1.

Table 1. Properties of the test specimens

Specimen	Brick	Plaster (mm)	Anchorage	Steel fiber ratio	Polypropylene fiber ratio	Thickness of fiber reinforced mortar (mm)
REFBA	-	-	-	-	-	-
REFB	+	-	-	-	-	-
REFBM	+	6	-	-	-	-
REF2ABM	+	6	+	-	-	20
SF1NABM	+	6	-	2%	-	10
SF2NABM	+	6	-	2%	-	20
SF1ABM	+	6	+	2%	-	10
SF2ABM	+	6	+	2%	-	20
PPF2ABM	+	6	+	-	2%	20
HF2ABM	+	6	+	1%	1%	20

Materials

Concrete mix design of frames is given in Table 2. Target compressive strength of the frame concrete was 10 MPa. Concrete strengths of the frames are shown in Table 3. As can be seen in Table 3, concrete strength of frames varied considerably. This variation can be attributed to curing condition, curing time, temperature difference, and water content difference in sand.

In columns 4ϕ8 and in beams 6ϕ8 plain bars were used as longitudinal reinforcement. In columns and beams, ϕ4 plain bars, which had 90º hooks at the ends, were used as stirrups. In foundation beams, ϕ16 deformed bars were used as longitudinal reinforcement and ϕ8 deformed bars were used as stirrups. For each steel 3 test coupons were taken randomly from the batch. Coupons were tested in tension. Typical properties of steel bars are provided in Table 4.

Table 2. Concrete mix proportion of the frames

	Weight (kN)	Ratio by weight (%)
Cement	1.54	12
0-3 mm aggregate	2.43	19
3-7 mm aggregate	4.86	38
7-15 mm aggregate	2.56	20
Water	1.40	11
Total	12.79	100

Table 3. Strengths of mortars and concrete of the specimens

	Compressive strength at test day (MPa)						
	Frame Concrete	Brick laying mortar	Plastering mortar	Strength mortar with 2% SF	Strength mortar with 2% PP fiber	Strength mortar without fiber	Strength mortar hybrid
REFBA	12.7	-	-	-	-	-	-
REFB	13.3	3.4	-	-	-	-	-
REFBM	12.7	8.4	8.2	-	-	-	-
REF2ABM	8.6	8.7	6.0	-	-	40.8	-
SF1NABM	9.9	7.5	6.4	17.0	-	-	-
SF2NABM	14.8	7.4	7.2	20.8	-	-	-
SF1ABM	17.0	6.0	7.2	22.0	-	-	-
SF2ABM	13.6	12.9	7.6	20.9	-	-	-
PPF2ABM	10.0	10.8	6.6	-	29.3	-	-
HF2ABM	11.6	9.9	6.2	-	-	-	24.8

Table 4. Properties of reinforcing bars

Bar diameter	Type	Yield stress, f_{sy} (MPa)	Ultimate stress, f_{su} (MPa)
ϕ4	Plain	271	398
ϕ8	Plain	365	511
ϕ8	Deformed	557	782
ϕ16	Deformed	453	682

In all of the specimens, hollow brick was used as infill material. Brick was specially produced by scaling down with 1/3 scale factor. The results of the compressive tests parallel to holes indicated that gross and net compressive strengths are 13.1 MPa and 27.3 MPa.

Mix proportions of the mortars are presented in Table 5. Compressive strength of the mortars was determined by testing 3 cylinders having 75 mm diameter and 150 mm height. Test results of mortars are also given in Table 3.

Test Set-up and Loading System

The test set-up and loading system used for the tests consisted of strong floor, reaction wall, loading equipment, instrumentation, and data acquisition system. The loading system consisted of a hydraulic jack, a load cell, adaptors, and hinges at both ends. In order to prevent out-of-plane deformations of the frames, an external steel guide frame was constructed around the test specimen. During the tests, axial load was kept constant at 53.38 kN. This axial load corresponds between 9.2% and 14.6% of axial load capacity depending on frame concrete strength. General view of the test set-up is illustrated in Fig. 3.

Table 5. Mix proportions of the mortars

	Weight (kg)					
	Brick laying mortar	Plastering mortar	Strength mortar with 2% SF	Strength mortar with 2% PP fiber	Strength mortar without fiber	Strength mortar hybrid
Cement (CEM I 32.5 R)	13.8	11.9	22	23.3	23.4	22.6
0-3 mm aggregate	66.0	67.9	60	63.4	63.8	61.6
Lime	6.4	5.5	-	-	-	-
Water	13.8	14.7	12	12.7	12.8	12.3
Plasticizer	-	-	0.04	0.042	0.043	0.041
Steel fiber	-	-	6	-	-	3.1
PP fiber	-	-	-	0.63	-	0.41
Total	100	100	100	100	100	100

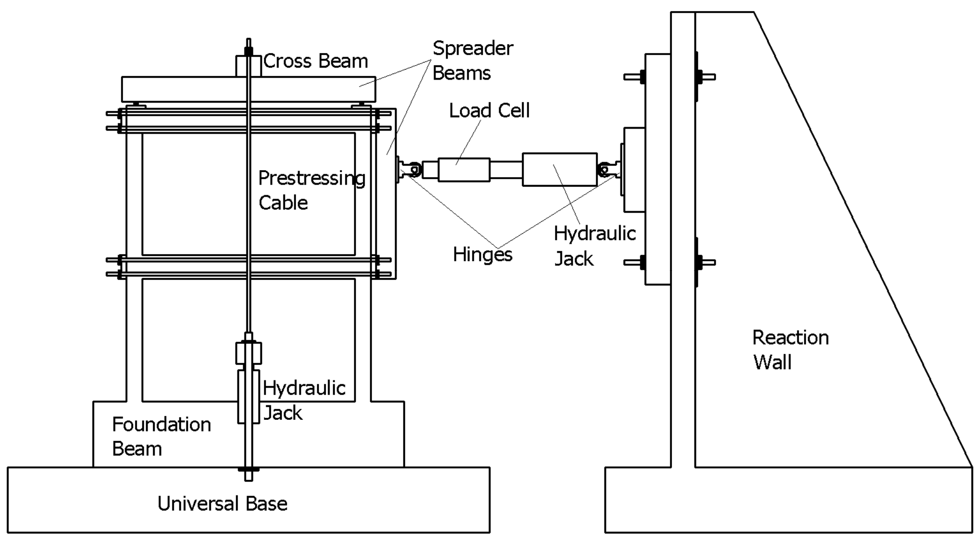

Figure 3. Test set-up

Behavior of Test Specimens

Table 6 summarizes the test results. In this table, axial load ratio of the columns, maximum applied lateral load, first and second story drifts levels both at the forward and backward cycles, initial stiffness, and cumulative dissipated energy values are given. Fig. 4 shows the first story lateral load-first story inter-story displacement/drift graphs drawn to a common scale.

In order to make comparison between the behaviors of the frames, first story envelope graphs of the specimens are prepared and shown in Fig. 5. General views of specimens after the tests are illustrated in Fig. 6.

Table 6. Summary of the test results

Specimen	Axial load level N/N_0	Forward loading			Backward loading			Initial slope (kN/mm)	Cumulat. energy dissipat. (kNm)
		Max. load (kN)	1st story drift ratio* Δ_1/h_1	2nd story drift ratio* $(\Delta_2-\Delta_1)/h_2$	Max. load (kN)	1st story drift ratio** Δ_1/h_1	2nd story drift ratio** $(\Delta_2-\Delta_1)/h_2$		
REFBA	0.11	14.53	0.0160	0.0076	12.03	0.0151	0.0090	1.74	2.06
REFB	0.11	50.23	0.0113	0.0062	50.29	0.0103	0.0065	24.44	5.88
REFBM	0.11	66.59	0.0043	0.0032	66.59	0.0032	0.0042	21.39	4.49
REF2ABM	0.15	104.52	0.0124	0.0055	101.52	0.0047	0.0124	61.08	10.78
SF1NABM	0.13	80.56	0.0043	0.0018	80.69	0.0023	0.0025	101.31	8.40
SF2NABM	0.10	96.58	0.0033	0.0027	90.51	0.0020	0.0023	34.25	15.56
SF1ABM	0.09	125.66	0.0084	0.0017	116.84	0.0025	0.0058	53.91	9.52
SF2ABM	0.11	140.42	0.0056	0.0024	134.17	0.0021	0.0080	67.12	9.43
PPF2ABM	0.13	123.85	0.0174	0.0	113.34	0.0024	0.0090	93.82	15.74
HF2ABM	0.12	122.04	0.0078	0.0040	119.03	0.0033	0.0054	93.70	12.27

* values at the maximum forward load

** values at the maximum backward load

There is excessive difference in the lateral load carrying capacity of the bare frame (REFBA) and brick masonry infilled frame (REFB). Therefore, considering the non-structural walls in the analysis can considerably change the results. Even application of regular plaster on the brick wall increased the capacity approximately 30% (REFBM vs. REFB).

If the SFRM is applied on the plastered wall without any anchorage to the surrounding frame (SF1NABM and SF2NABM), the capacity increase is less as compared to the anchoraged cases, Fig. 5. Specimen strengthened without steel fiber showed approximately 55% increase in lateral load carrying capacity as compared to the plastered brick reference specimen REFBM. It should be noted that, the compressive strength of strengthening mortar of this specimen was much higher as compared to other specimens.

In steel fiber (SF1ABM and SF2ABM), PP fiber (PPF2ABM), and hybrid (HF2ABM) cases lateral load carrying capacities were close to each other. The best result, however, was attained by SF2ABM in which 140 kN maximum lateral load was measured.

Conclusions

The main objective of this study was to develop a feasible, effective, and yet economical strengthening technique that does not disturb the inhabitants. In this scope steel fiber reinforced higher strength mortar was applied on the plaster of masonry walls. Specimens were tested under reversed cyclic lateral loads simulating earthquake. The frames were 1/3 scale, 1 bay, and 2 story. Totally 10 frame tests were performed. The conclusions drawn here should be used carefully with the limitations of the tests performed and not be generalized.

- Using steel fiber inside higher strength plastering mortar offers an economical strengthening technique.
- The lateral load capacity of the frames can be increased by applying higher strength mortar containing steel fibers on regular brick masonry walls.
- Application of strengthening mortar on brick masonry wall retards the early out of plane failure and converts the existing non-structural wall into load carrying wall.
- To get safe results and ensure load transfer between frame and strengthened wall, anchorage should be utilized along the surrounding frame of the wall.
- The best result was achieved by anchored, 20 mm thick and 2% SFRM application.

Acknowledgments

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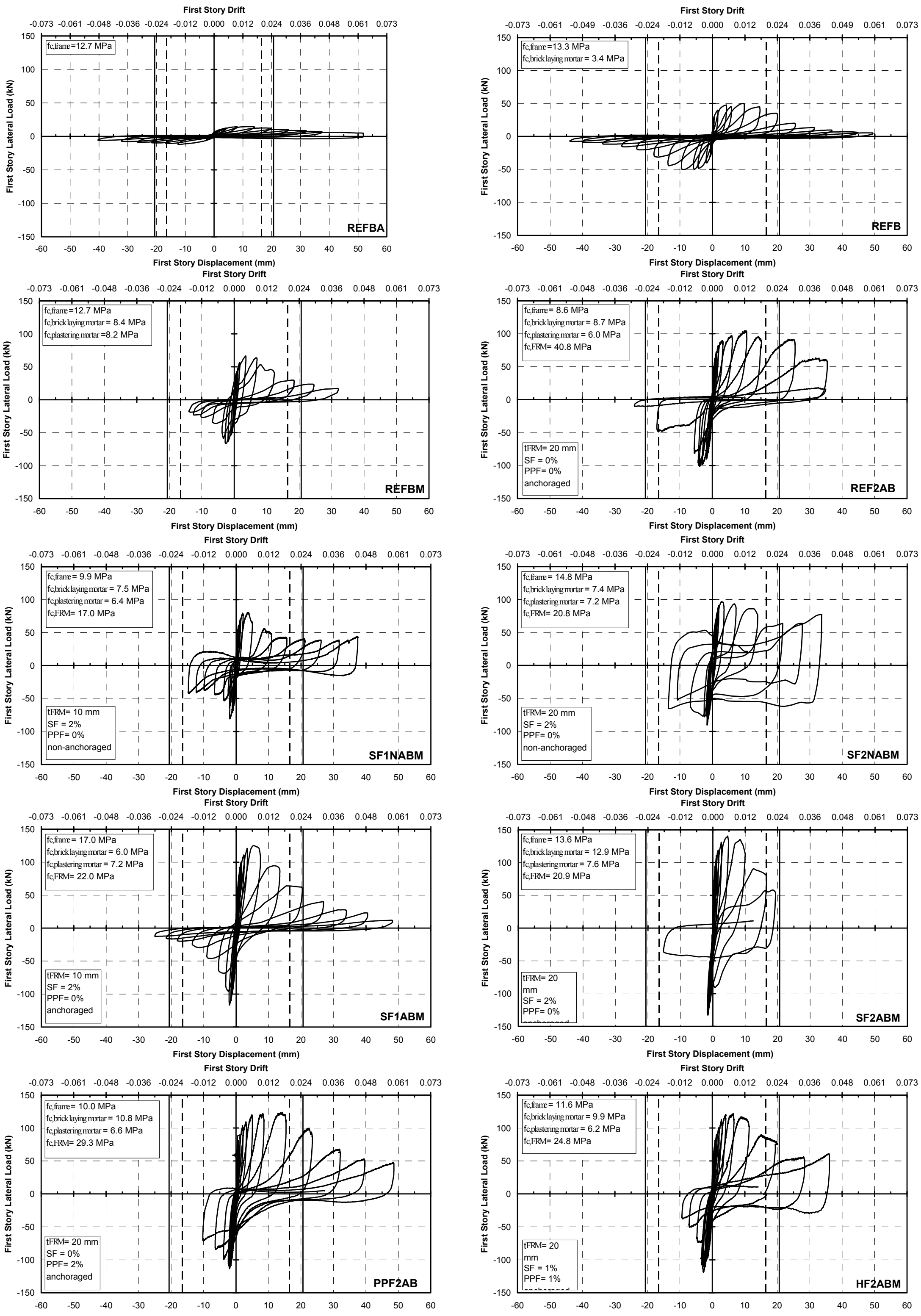

Figure 4. First story lateral load-first story inter-story displacement/drift graphs of the specimens

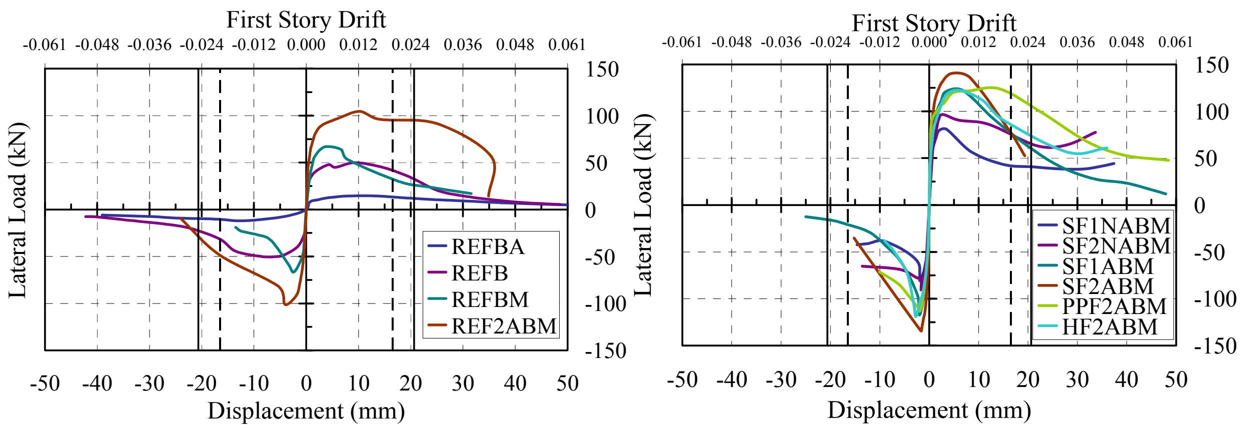

Figure 5. First story envelope graph of specimens

Figure 6. General view of the specimens after the tests