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RCC frames with ferrocement and fiber reinforced concrete infill panels under reverse cyclic loading

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Abstract. An experimental investigation was carried out to study the strength and behavior of reinforced cement concrete (RCC) frames with ferrocement and fiber reinforced concrete infill panel. Seven numbers of $1/4^{th}$ scaled down model of one bay-three storey frames were tested under reverse cyclic loading. Ferrocement infilled frames and fiber reinforced concrete infilled frames with varying volume fraction of reinforcement in infill panels viz; 0.20%, 0.30%, and 0.40% were tested and compared with the bare frame. The experimental results indicate that the strength, stiffness and energy dissipation capacity of infilled frames were considerably improved when compared with the bare frame. In the case of infilled frames with equal volume fraction of reinforcement in infill panels, the strength and stiffness of frames with fiber reinforced concrete infill panels were slightly higher than those with ferrocement infill panels. Increase in volume fraction of reinforcement in the infill panels exhibited only marginal improvement in the strength and behavior of the infilled frames.

Keywords: ferrocement; fiber reinforced concrete; infill panel; reinforced concrete frame; cyclic loading

1. Introduction

Reinforced cement concrete (RCC) framed structures are usually infilled with masonry, which serve as either interior or exterior partitions. However, due to the complex behavior of the frame-infill interaction, masonry infills are commonly considered as non-structural elements. Ignoring the effect of infills may lead to inaccurate prediction in the strength and stiffness of the structure. On the other hand, if the infills are properly connected to the frame, the resulting system becomes stiffer and attracts higher lateral loads. These high loads will be rapidly transferred to the frame after the infill is partially or fully damaged. Hence, considering the lateral stability of the frame, an accurate assessment of the contribution of infills to the strength and stiffness of the frame system is essential for a safe design.

The behavior of masonry infilled RC frames were studied by a large number of researchers (Kahn and Hanson 1979, Mehrabi *et al.* 1996, Colangelo 2005, Misir *et al.* 2012, Zovkic 2013). The test results indicated that the presence of infills significantly enhanced the strength and

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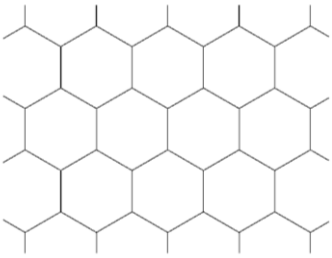


Fig. 1 Hexagonal wire mesh

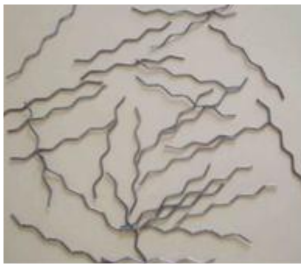


Fig. 2 Crimped steel fibers

stiffness of RC frames and resulted in a better energy dissipation capacity of the structure. However, after reaching the peak load, damage in the masonry increased and the frame-infill interface gets deteriorated. As a result, strength and stiffness degraded significantly, and only low to medium displacement ductilities were achieved. In addition, the past earthquake effects showed that masonry infills in RC buildings resulted in several undesired effects, such as soft-storey effect, short column effect, torsion and out-of-plane collapse (Sezen *et al.* 2003, Li *et al.* 2008).

To protect human life and property, efforts were made by researchers to develop different strengthening techniques for the frames so that the lateral strength and behavior of frames could be improved. These techniques included the introduction of RC infills, precast panels and steel bracing. Among the techniques, the incorporation of RC infills was found to be the most suitable strengthening technique for medium rise RC buildings (Hayashi *et al.* 1980, Altin *et al.* 1992, Canbay *et al.* 2003, Sonuvar *et al.* 2004, Turk *et al.* 2006, Anil and Altin 2007). The proper application of RC infills considerably increased the lateral strength and stiffness, and reduced the lateral drift at ultimate load. However, this technique was found to be time consuming and provides additional mass to the structure, leading to higher lateral load.

In this context, precast concrete panels finds its application as a strengthening technique because it is easy to apply, cheap to produce, provides good quality control and structurally effective in use. Numerous tests were conducted in the past to study the behavior of frames infilled with precast concrete panels (Frosch *et al.* 1996, Duvarci 2003, Susoy 2004, Kesner and Billington 2005, Baran and Tankut 2011).

In the present study, an attempt is made to compare the strength and behavior of frames infilled with different types of precast infills such as ferrocement and fiber reinforced concrete panels.

2. Experimental program

The experimental investigation consisted of casting and testing of ferrocement and fiber reinforced concrete infilled frames with varying volume fraction of reinforcement in infill panels.

2.1 Material properties

Portland Pozzolana Cement conforming to IS 1489 (Part 1): 1991, crushed stone fine aggregate passing through 4.75 mm IS sieve conforming to grading zone II of IS: 383-1970 (reaffirmed 2002) with fineness modulus 2.66 and specific gravity 2.54, and coarse aggregate having a maximum size of 12 mm with specific gravity 2.74 were used for this study. Hexagonal mesh of 24 gauge wire used in the ferrocement infill panel and crimped steel fibers used in the fiber

Table 1 Properties of hexagonal mesh

Property/Description	Hexagonal mesh
Raw material	Steel
Width (m)	0.90
Mesh opening size (mm)	20 × 15
Diameter of wire (mm)	0.59
Unit weight (kg/m^2)	0.390
Density (kg/m^3)	7850
Yield strength (MPa)	280
Modulus of elasticity (MPa)	2×10^5

Table 2 Properties of steel fiber

Type	Crimped steel fiber
Length (mm)	30
Diameter (mm)	0.45
Aspect ratio	66
Ultimate tensile strength (MPa)	800

Table 3 Properties of reinforcing bars

Bar diameter (mm)	Yield strength (MPa)	Ultimate strength (MPa)	Modulus of elasticity (MPa)
6	515	655	2.14×10^5
8	425	610	2.21×10^5
10	426	570	2.32×10^5

reinforced concrete infill panel is shown in Fig. 1 and Fig. 2, and their properties are given in Table 1 and Table 2 respectively. The compressive strength of concrete used in the test frames, which represents the concrete commonly used in existing building structures, was found to be approximately 27 MPa. The compressive strength of precast ferrocement infill panels and fiber reinforced concrete infill panels was determined to be 33 MPa and 28 MPa respectively. The properties of reinforcing bars used are given in Table 3.

2.2 Description of test specimens

Tests were done on 1/4th scaled down model of one bay-three storey RC frames subjected to reverse cyclic lateral loading. Details of specimens with varying volume fraction of reinforcement in ferrocement and fiber reinforced concrete infill panels is shown in Table 4. The geometric dimensions and reinforcement patterns of the RC frame were identical for all specimens. The cross section of the columns and the beams was rectangular having 100 mm×150 mm size. The longitudinal reinforcement in beams and columns of RC frames consisted of HYSD bars of diameter 8 mm and 10 mm respectively. The stirrups provided in the beams and ties in the columns were of 6 mm diameter bars. Dimensions and reinforcement details of the frames are shown in Fig. 3.

Table 4 Details of specimens

Sl. No.	Type of frame	Specimen designation	Effective volume fraction in ferrocement infill panel (%)	Effective volume fraction in fiber reinforced concrete infill panel (%)
1	Bare frame	BF	---	---
2	Ferrocement infill frame with 0.20% volume fraction of hexagonal mesh reinforcement	FC0.2	0.2	---
3	Ferrocement infill frame with 0.30% volume fraction of hexagonal mesh reinforcement	FC0.3	0.3	---
4	Ferrocement infill frame with 0.40% volume fraction of hexagonal mesh reinforcement	FC0.4	0.4	---
5	Fiber reinforced concrete infill frame with 0.40% volume fraction of steel fibers	FRC0.4	---	0.2
6	Fiber reinforced concrete infill frame with 0.60% volume fraction of steel fibers	FRC0.6	---	0.3
7	Fiber reinforced concrete infill frame with 0.80% volume fraction of steel fibers	FRC0.8	---	0.4

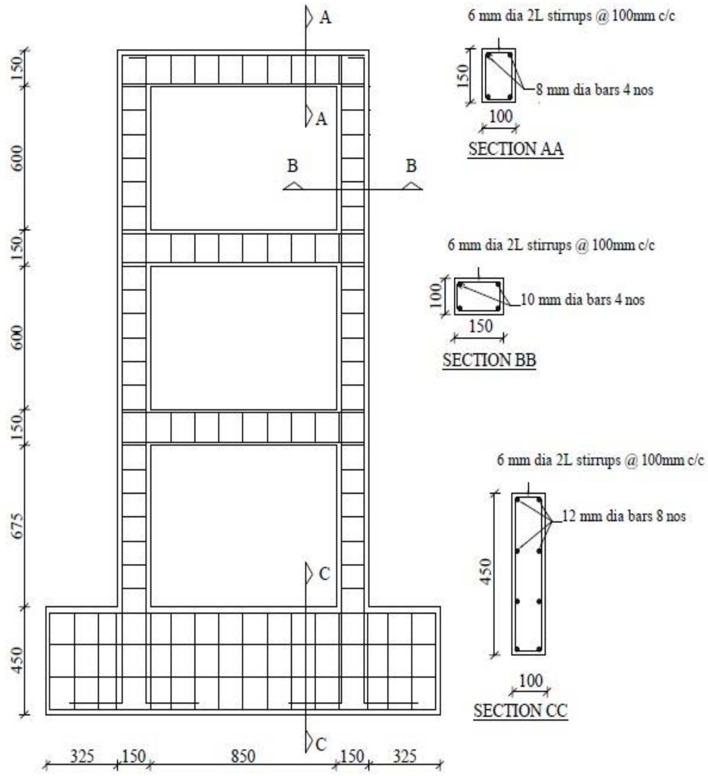
2.3 Casting of frames

Mix proportions for cement, fine aggregate and coarse aggregate for RC frames were computed for M20 grade concrete as per IS 10262:2009. The proportions of cement, fine aggregate and coarse aggregate was obtained as 1:1.55:2.78 by weight. The water-cement ratio for the mix was taken as 0.50 by weight. After casting, the specimens were cured using wet gunny bags for a period of 28 days.

2.4 Casting of infill panels

Ferrocement infill panel: The wire mesh reinforcement considered for ferrocement was hexagonal wire mesh since it is cost effective when compared with other type of wire meshes. The volume fraction of meshes were varied as 0.20%, 0.30% and 0.40%. Skeletal reinforcement bars of 6 mm diameter were provided in the infill panel to provide shape and support for layers of mesh attached to it on either side. The ratio of cement-sand mortar used for making the panels was 1:2 by weight and water-cement ratio was taken as 0.5 by weight. To start with, 1 layer of cement-sand mortar was applied to an oiled surface. Subsequently the reinforcement was placed on the mortar and the specimen was finished by applying additional mortar onto the reinforcement. The thickness of the infill panel was kept as 50 mm. The specimens were cured for 28 days and then placed centrally in the hollow portion of the frame to serve as infill.

Steel fiber reinforced concrete infill panel: Fiber reinforced concrete infill panel consisted of randomly oriented, short, crimped steel fibers. The steel fibers used in the infill panel had a length of 30 mm which was less than the thickness of the infill panel (50 mm). As a result, the fibers would be oriented at random in three dimensional array. Hence all the fibers would not be effective in resisting the load. For a random three dimensional array, only 50% of the fibers prove to be effective in resisting the load (Swamy 1984). On the other hand, in ferrocement infill panels, as the



All dimensions are in mm

Fig. 3 Dimensions and details of reinforcement of frame

wires are aligned in the direction of force, all the wires would be effective in resisting the load. In the present study, the volume fraction of mesh considered in the ferrocement infill panel was 0.20%, 0.30% and 0.40%. For comparing the volume fraction of reinforcement in both the infill panels, the volume fraction of fibers in fiber reinforced concrete infill panel was taken as twice that of volume fraction of meshes in ferrocement infill panel. Therefore the volume fraction of fibers used in fiber reinforced concrete infill panels were varied as 0.40%, 0.60% and 0.80%. The effective volume fraction in ferrocement infill panel and fiber reinforced concrete infill panel is summarized in Table 4. The grade of concrete used for the fiber reinforced concrete infill panel was M20. Required quantity of steel fibers were added to the cement and aggregates in the mixer, and thoroughly mixed with water to obtain fiber reinforced concrete mix. Dowel bars were also provided in the infill panel, in order to anchor the same with the frame. The specimens were cured for 28 days using wet gunny bags. After curing, the specimens were cleaned and then placed centrally in the hollow portion of the frame to serve as infill.

2.5 Assemblage of infill panel with frame

In order to keep the infill panel in the frame, the following procedure was adopted. Initially holes of 8 mm diameter were drilled in the inner faces of the frame members for a depth of 60 mm. Dowel bars of 6 mm diameter and 90 mm long were inserted into the holes and fixed by epoxy

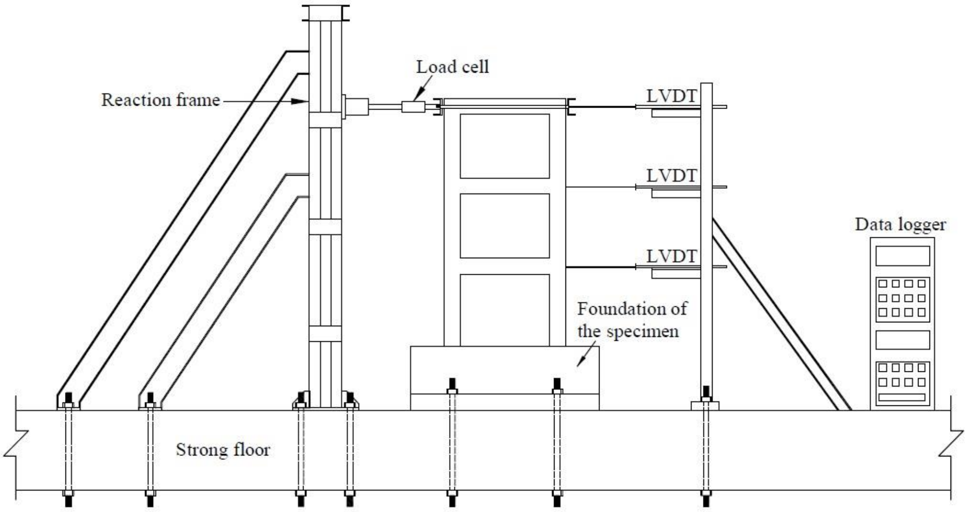


Fig. 4 Test set up

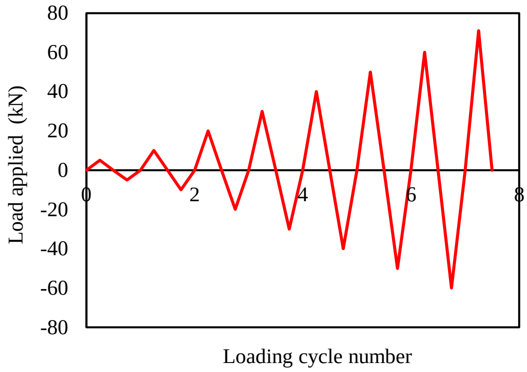


Fig. 5 Typical load history diagram for an infilled specimen

grout so that a projection of 30 mm length was available for the dowel bars. The precast infill panels were then placed in the frames and the dowel bars from the frame were lap welded with the projecting portion of bars from the infill panel. The gap between the frame and infill panel was then filled by the same material as that of the infill panel material.

2.6 Test setup and instrumentation

The schematic representation of test setup, including the loading system and instrumentation is shown in Fig. 4. The foundation of the test specimen was inserted into the foundation block available in the laboratory and anchored by means of high strength steel bolts. The frames were tested under reverse cyclic lateral loading applied at the top storey of the frame using a hydraulic jack with a load cell of 250 kN capacity. One cycle of loading comprised of both forward and reverse cycles and the amplitude of loading was increased after each cycle. This process was continued till the lateral failure occurred. A typical load history diagram for the infilled frame is shown in Fig. 5. Linear variable differential transducers (LVDTs) were attached to the frame to

(a) Bare frame (b) Infilled frame

Fig. 6 Testing of specimens

measure storey displacements. After each cycle, the crack propagations were marked on the frames until the failure occurred. Fig. 6 shows bare frame and infilled frame under testing.

3. Experimental results

3.1 Behavior of test specimens

Lateral load versus displacement hysteresis curves for the test specimens are shown in Fig. 7. From the figures it can be seen that, the addition of infill panels significantly increased the lateral load carrying capacity and reduced the displacement. The first crack load, ultimate load, stiffness and energy dissipation capacity of the test specimens were calculated from the experimental data.

The photographs of the frames after failure are shown in Fig. 8. Initial cracks in the bare frame formed at the portions near the beam-column joints in the 2nd storey. Further cracks were formed at the base of 1st storey column and end portions of beam in the 1st, 2nd and 3rd storey. In the subsequent cycles of loading, the cracks in the beam-column joints of 1st and 2nd storey started widening. Finally, the failure occurred at the base of columns in the 1st storey. Severe distress was observed in the beam-column joints also.

In all the infilled specimens, initial flexural cracks were observed at the bottom part of 1st storey columns. In the subsequent cycles of loading, more flexural cracks were formed in the 1st and 2nd storey columns. As the loading was increased, the cracks started to widen in the 1st and 2nd storey columns and the failure occurred at the base of 1st storey column. Unlike the bare frame, no major distress was observed in the beam-column joints. However, even after the failure, the infill panel was free from cracks and was found to be intact with the frame.

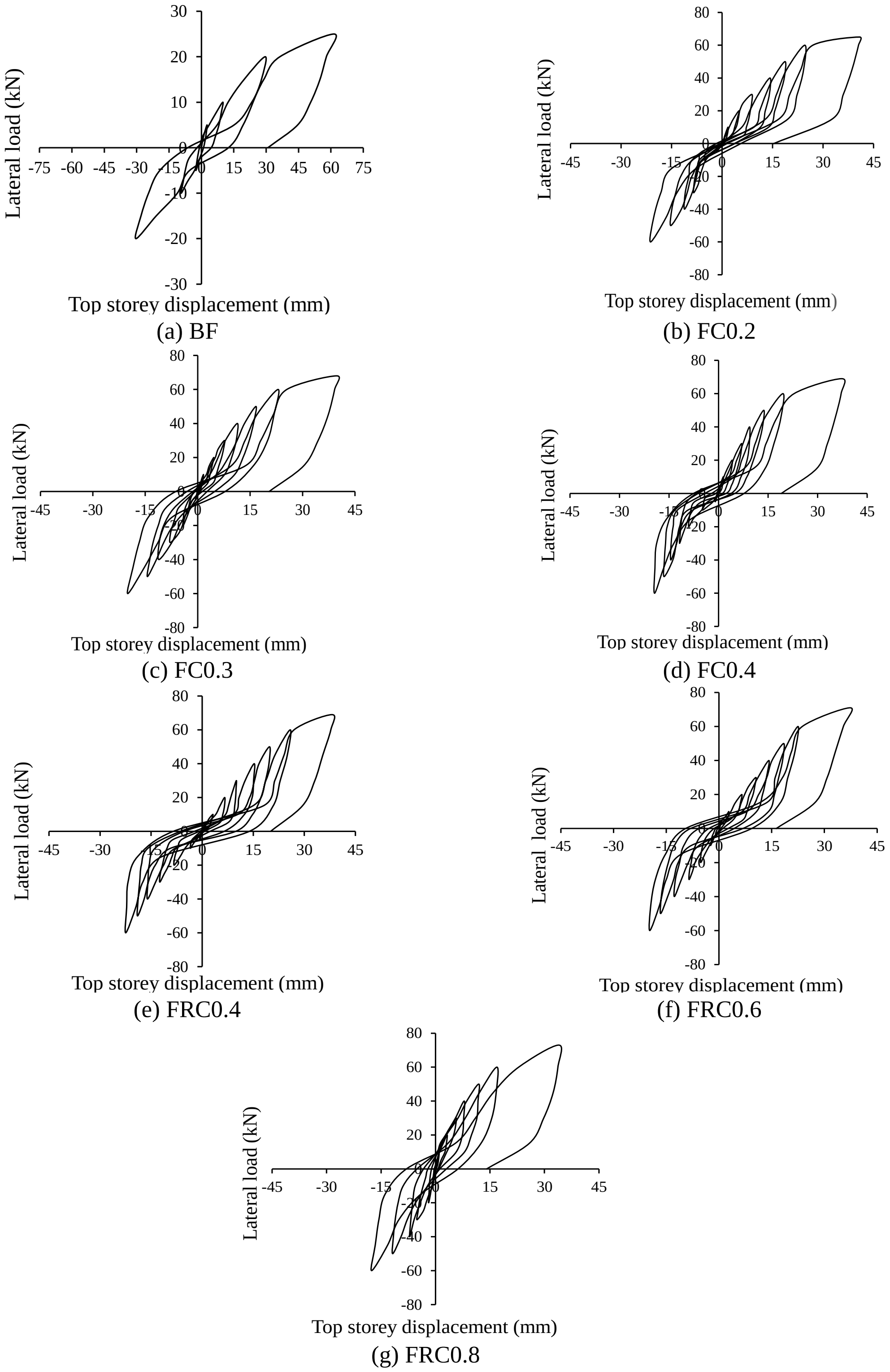
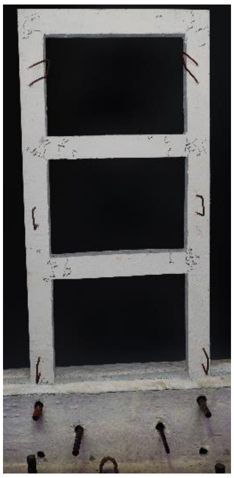


Fig. 7 Load-displacement hysteresis curve for frames


(a) BF


(b) FC0.2


(c) FC0.3


(d) FC0.4


(e) FRC0.4


(f) FRC0.6


(g) FRC0.8

Fig. 8 Frames after failure

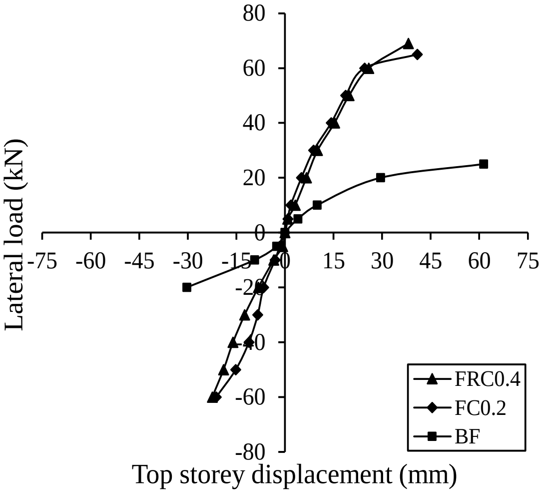


Fig. 9 Comparison of envelopes of hysteretic response of bare and infilled frames having effective volume fraction of 0.20%

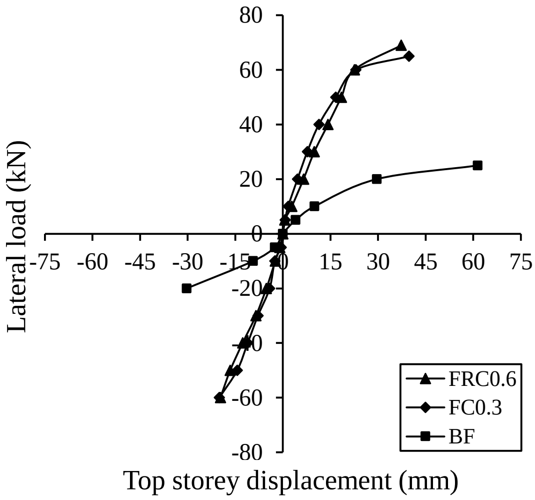


Fig. 10 Comparison of envelopes of hysteretic response of bare and infilled frames having effective volume fraction of 0.30%

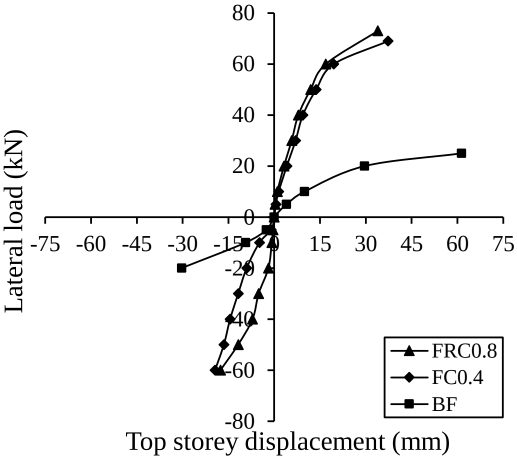


Fig. 11 Comparison of envelopes of hysteretic response of bare and infilled frames having effective volume fraction of 0.40%

4. Analysis of test results

4.1 Strength

Response envelopes for infilled frames with equal volume fraction shown in Figs. 9-11 were plotted by connecting the peak points of hysteresis curves. Response envelope curves were used to evaluate the strength and stiffness characteristics of the specimens. From these figures it can be seen that, the strength and stiffness of the infilled frames were considerably greater than the bare frame. Table 5 shows the details of test results. As can be seen from the table, there is a substantial increase in the first crack load and ultimate load in the infilled frames when compared with the bare frame. The values of lateral load carrying capacity of frames with fiber reinforced concrete

Table 5 Details of test results

Specimen designation	First crack		Ultimate	
	Load (kN)	Relative values with respect to BF	Load (kN)	Relative values with respect to BF
BF	10	1	25	1
FC0.2	30	3	65	2.6
FRC0.4	33	3.3	69	2.76
FC0.3	32	3.2	68	2.72
FRC0.6	35	3.5	71	2.84
FC0.4	38	3.8	69	2.76
FRC0.8	40	4	73	2.92

Table 6 Stiffness of test frames

Specimen designation	Initial		At ultimate load	
	Stiffness (kN/mm)	Relative values with respect to BF	Stiffness (kN/mm)	Relative values with respect to BF
BF	1.92	1	0.41	1
FC0.2	5.75	3.00	1.59	3.88
FRC0.4	6.02	3.14	1.81	4.41
FC0.3	7.04	3.66	1.71	4.17
FRC0.6	8.33	4.34	1.90	4.63
FC0.4	9.43	4.91	1.85	4.51
FRC0.8	16.67	8.68	2.15	5.24

infill panels were slightly higher than that of ferrocement infill panels with equal volume fraction of reinforcement.

4.2 Stiffness

The initial stiffness and stiffness at ultimate load of the frames are listed in Table 6. Initial stiffness was evaluated as the slope of the linear part of load-displacement curve in the first forward half cycle. The stiffness at ultimate load was evaluated as the average of the slopes of linear lines connecting the positive and negative ultimate loads with the origin of load-displacement curves. The table shows that as the volume fraction in infill panels increased, the stiffness also increased. It may be also noted that the stiffness of fiber reinforced concrete infilled frames were slightly higher than the corresponding ferrocement infilled frames with equal volume fraction of reinforcement.

4.3 Energy dissipation capacity

The energy dissipation was measured by calculating the areas inside the hysteresis loops for each cycle. The cumulative energy dissipated was calculated as the sum of the area enclosed by each hysteresis loop. The comparison of cumulative energy dissipation of bare and infilled frames

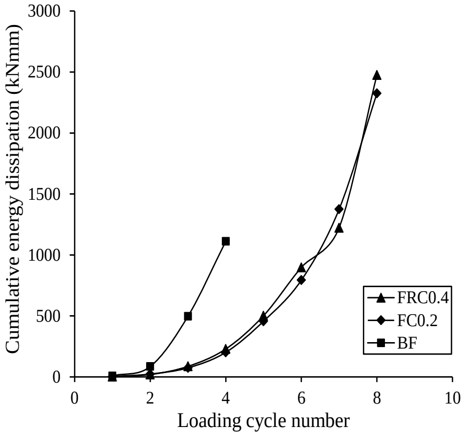


Fig. 12 Comparison of cumulative energy dissipation of bare and infilled frames having effective volume fraction of 0.20%

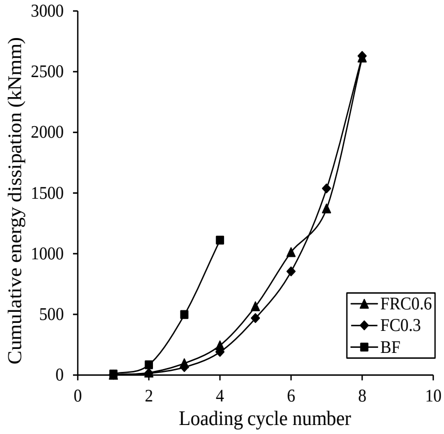


Fig. 13 Comparison of cumulative energy dissipation of bare and infilled frames having effective volume fraction of 0.30%

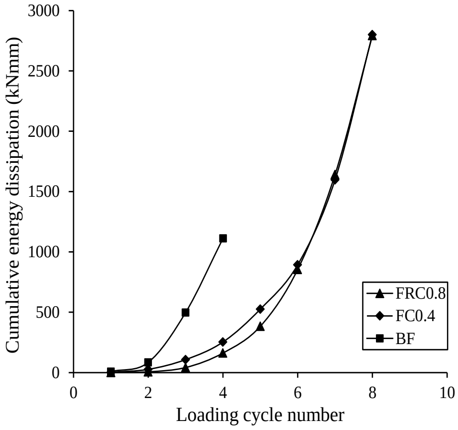


Fig. 14 Comparison of cumulative energy dissipation of bare and infilled frames having effective volume fraction of 0.40%

Table 7 Cumulative energy dissipation of test frames

Specimen designation	Cumulative energy dissipation (kN mm)	Relative values with respect to BF
BF	1111.6	1
FC0.2	2324.7	2.09
FRC0.4	2476.2	2.23
FC0.3	2628.3	2.36
FRC0.6	2616	2.35
FC0.4	2800.2	2.52
FRC0.8	2793.5	2.51

is shown in Figs. 12-14. The cumulative energy dissipation of each frame is given in Table 7. The results indicated that the frames with infill panels dissipated almost 2 to 2.5 times more energy than the frame without infill panel. However, it can be seen that the variation in values were marginal for the infilled frames with equal volume fraction of reinforcement.

5. Conclusions

In this study, the strength and behavior of infilled RC frames with different volume fraction of reinforcement in infill panels under reverse cyclic loading was investigated. Based on the test results, the following conclusions were drawn.

• The infill panel was found to be intact with the frame and no cracks were observed in the infill panel, and in fact, the failure occurred in the frame.

• The first crack load and ultimate load of fiber reinforced concrete infilled frames were slightly higher than the ferrocement infilled frames with equal volume fraction of reinforcement.

• The stiffness of fiber reinforced concrete infilled frames were slightly higher than the ferrocement infilled frames with equal volume fraction.

• The energy dissipation capacity of fiber reinforced concrete infilled frames and ferrocement infilled frames with equal volume fractions were almost the same.

• Only marginal enhancement was observed in the lateral strength, stiffness and energy dissipation capacity of frames with the increase in the volume fraction of reinforcement in both the infill panels.

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