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Behaviour of Reinforced Concrete Squat Shear Walls with Utility Openings

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Key words: Shear wall, Wall openings, Shear strength, Fiber Reinforced Concrete (FRC).

Abstract: Reinforced concrete (RC) squat walls are often encountered for various inevitable purposes in many civil engineering structures, which play role on failure due to lateral forces produced by seismic, wind and explosive loads. This paper discusses on some investigations on RC squat walls with openings in comparison with controlled walls without openings. Experimental studies have been carried out on RC shear walls with and without openings. The walls under gravity loads were tested under lateral loads due to the effect of earthquake motions on buildings. The lateral strength and load transfer mechanism have been significantly altered with the provision of utility openings in RC walls. The shear strength and load transfer paths have been evaluated through nonlinear finite element analysis of RC walls with and without openings for validating the experimental results. Plain concrete is modelled as multi linear isotropic material using SOLID65 element, which captures plastic deformation, cracking in three orthogonal directions, and crushing. The reinforcement bars are modelled as discrete bilinear elements using LINK8 element. In order to control the cracking of concrete in corner regions of openings, fibre reinforced concrete (FRC) was adopted, in which the steel fibres were smeared. The addition of steel fibres improves the shear strength by 60%. The confinement and cracking resistance of concrete have been significantly improved by FRC, exhibiting that is an efficient solution for mitigating the stress concentration induced cracking in RC walls with openings.

1 INTRODUCTION

Reinforced concrete shear walls are effective in resisting, and transferring lateral loads from earthquake and wind loads on structural system. They efficiently control the construction cost and damage due to earthquakes in structural system. During the past few decades, a considerable improvement has been noticed in the design and construction of RC walls. Behaviour of such shear walls primarily depends up on the ratio of applied moment-to-applied shear force. This ratio linearly corresponds to the aspect ratio (A/R) of the shear wall; which is the ratio of height-to-length of wall.

Shear walls can exhibit cantilever action as in slender or high rise walls (with A/R > 2) and by truss action in squat/short or low rise walls (with A/R<2). Slender walls predominantly fail in flexure, while squat walls fail in shear. Local buckling of web can be minimized by boundary elements at the wall ends with minimum web thickness. It has been observed that boundary elements, aspect ratio, wall thickness, reinforcement ratio, yield strength of steel, compressive strength of concrete, and applied axial stress showed significant influence on the shear strength of shear walls and seismic performance in terms of stiffness degradation, energy dissipation, crack patterns and modes of failure. Practically, openings in shear walls are inevitable in the form of doors, windows or some other functional requirements, whose influence is tremendous under seismic loading. These shear walls with openings are recommended as per the codes with additional corner reinforcement around the openings, whose area is equal to the area of interrupted bars. Some codes do not have such recommendations.

2 RESEARCH SIGNIFICANCE

The information on behaviour of RC squat shear walls with openings is very limited. The seismic response is significantly affected by the size of openings and their location in the wall. Hence, the research on behaviour and strengthening of walls with openings is an important issue. Also, investigation for various measures of strengthening of shear walls with openings using FRC or other materials is gaining importance. Hence, such research efforts are needed at this juncture. This study presents the numerical analysis of shear walls with openings using FRC to be used as strengthening agent around the opening.

3 NUMERICAL STUDY

In the present study the finite element package ANSYS 15.0 is used for modelling. The package delivers greater accuracy, fidelity, higher productivity and more computational power. The region around the opening is vulnerable due to stress concentration and severe cracking. Instead of providing FRC throughout, it is recommended only to certain vertical distance around the opening. The spread of FRC from opening edge is vertically varied as 0.0 mm, 50 mm, 100 mm, 150 mm, 200 mm and 300 mm. Figure 1 shows the addition of FRC around opening up to a depth of 150 mm from opening edge in the present study. This study is carried out in ANSYS15.0.

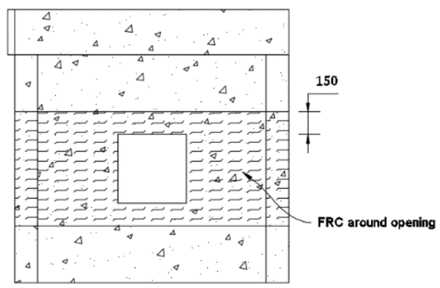

Figure 1: Fibre Reinforced Concrete (FRC) around opening

It has been recognised that effect of FRC around opening exhibited only up to a certain vertical distance from the edge of opening. Table 1 shows the shear strength of shear wall with FRC around the opening with varying vertical distance from edge of opening.

The geometry of the wall is shown in Figure 2.

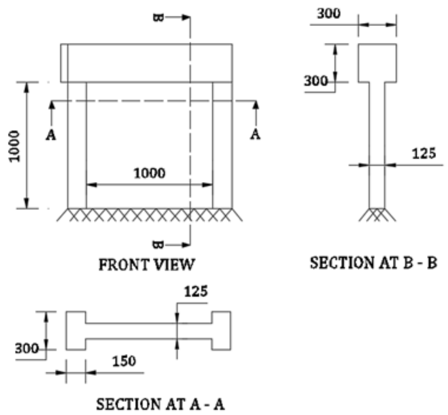

Figure 2a: Geometry of the Wall

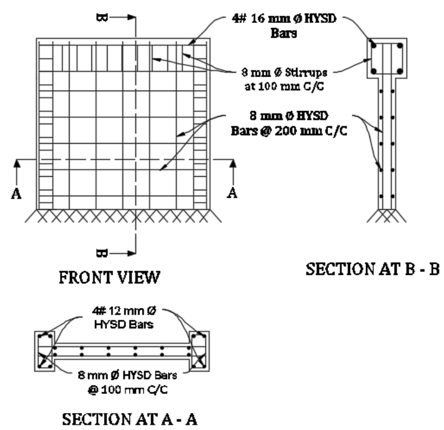

Figure 2b: Reinforcement Details of the Wall

Three types of elements were adopted for modelling the shear walls. Eight noded SOLID65 (Concret65) elements for modelling concrete, two noded LINK 8 elements for modelling reinforcement and eight noded solid 185 elements for modelling loading steel plate. FRC was modelled as concrete with smeared fibre property with different orientation angle. The reinforcement and steel plate used in the study are assumed to exhibit elasto-plastic response with identical properties in tension and compression. Modelling of concrete behaviour is a difficult task due to its quasi-brittle material response and exhibiting different behaviour in compression and tension. SOLID65 element was developed exclusively for concrete. The portions of FRC in the wall are modelled by smeared concrete model. The mesh convergence study performed to find the appropriate mesh size was found to be 25 mm.

A nonlinear structural analysis was performed to study the nonlinear material behaviour of RC wall. ANSYS15.0 employs "Newton-Raphson" method to solve nonlinear problems. The load was sub-divided into series of load increments as load steps. A nonlinear structural analysis was performed to study the nonlinear material behaviour of the wall. ANSYS15.0 employs "Newton-Raphson" method to solve nonlinear problems. The load was sub-divided into series of load increments as load steps. The large displacement static condition considered for analysis and the tolerance limits are kept in the order of 10-2. Failure of the model identified where the solution fails to converge even with very low load increment.

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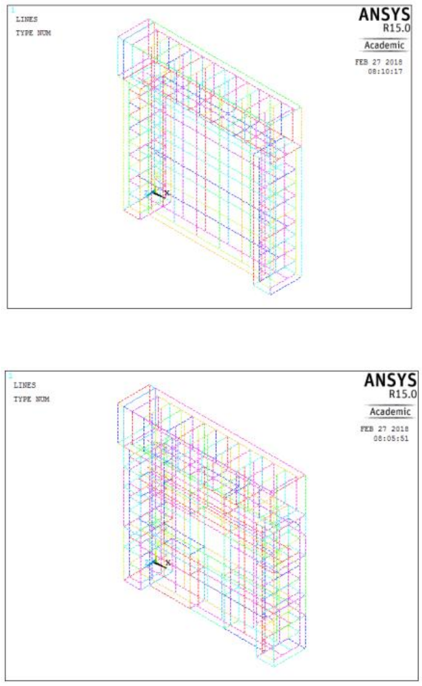


Figure 3: Rebar Model in ANSYS in RC walls.

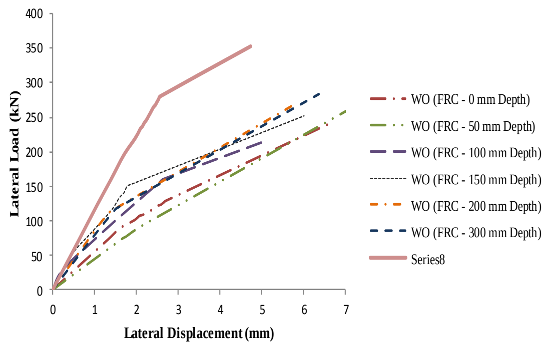


Figure 4: Load - Deflection response in RC wall with varying depth of FRC

Table 1: Strength of wall with varying depth of FRC

	No Opening	Depth of FRC from Opening (mm)					
		0	50	100	150	200	300
Shear Strength (kN)	353	162	180	216	252	270	283.5
Percentage of strength compared with wall without opening	1	32	36	43	50	54	56

The load-deflection response of the wall with varying vertical distance of FRC is reported in Figure 4. It has been observed that the addition of FRC around the opening improves not only the strength but also the lateral stiffness of the wall up to certain extent. It was also be noticed that the addition of FRC beyond 150 mm distance away from the edge of opening does not show much variation in strength and lateral stiffness of the wall.

In RC walls without opening, first crack was observed at the top left corner and slowly developed as diagonal crack. Simultaneously, the crack was observed at the bottom of the wall as well. In the wall with window opening, the first crack was observed at the top left corner of the opening and progressed gradually towards the corner of the wall. Meanwhile, another crack started at the bottom right corner of the opening and developed towards the bottom right corner of the wall.

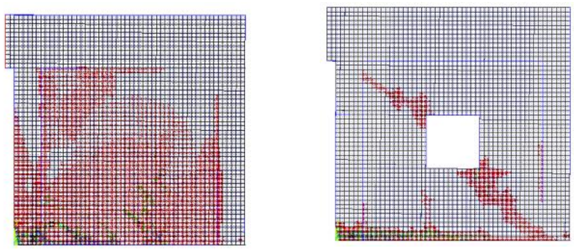


Figure 5: Crack Pattern of shear wall without opening (Left) and with opening (Right)

4 EXPERIMENTAL STUDY

4.1 Geometry of specimen

The test series includes three one-third scaled reinforced concrete squat shear wall with and without opening. It is presumed that the tested cantilever wall subjected to constant vertical load and static cyclic lateral load exhibits similar behaviour of shear wall under earthquake loading. The shear wall consists of three components. The first component is the top beam through which the vertical and lateral loads are transferred to the wall. The second component is the wall web. The third component is the bottom beam which anchors to the strong floor for fixity. The three shear walls designed for the experimental study includes: shear wall without opening (SW-1.0), shear wall with concentric window opening (SW-1.0-CW) and shear wall with concentric window opening with FRC (SW-1.0-CW-FRC).

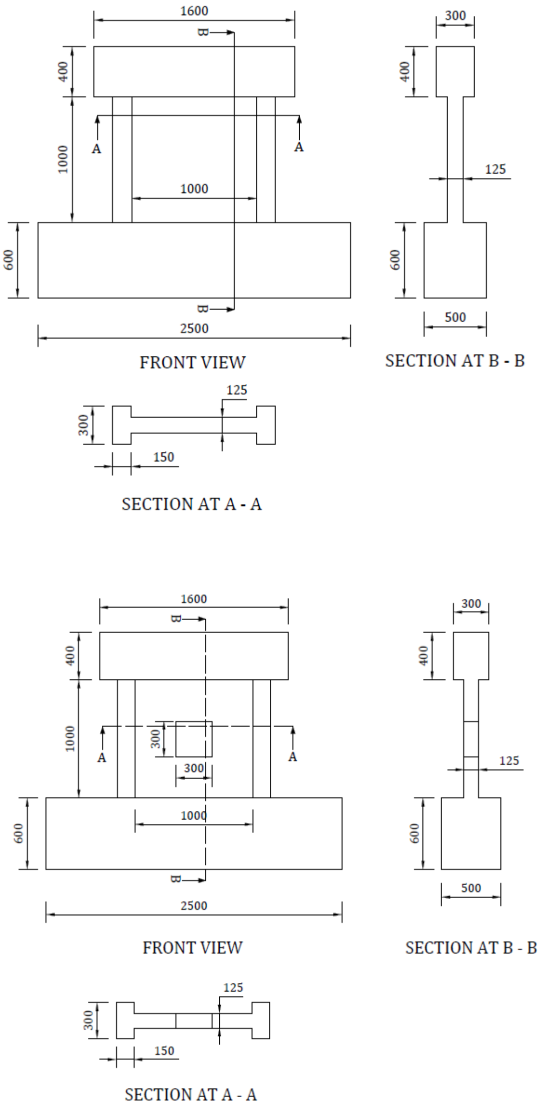


Figure 6: Geometric details of the specimen

Table 2 Geometrical details of RC Shear wall for Experimental Programme

S. No	Specimen ID	L mm	H mm	T mm	Boundary Elements		Opening		ρ_l %	ρ_h %	ρ_{BE} %	f_y MPa	f_{ck} MPa	N kN
					l mm	h mm	a mm	b mm						
1	SW–1.0	1000	1000	125	300	150	-	-	0.4	0.4	1	500	24	200
2	SW-1.0–CW – IS	1000	1000	125	300	150	300	300	0.4	0.4	1	500	26	200
3	SW–1.0–CW- FRC	1000	1000	125	300	150	300	300	0.4	0.4	1	500	24	200

All shear walls have same geometric dimension. The Top beam has a length of 1600 mm and cross section of 300 mm x 400 mm. The wall portion has length of 1000 mm, height of 1000 mm and thickness of 125 mm. The length and breadth of boundary elements are 300 mm and 150 mm respectively. The bottom beam has a length of 2500 mm and cross section of 500 mm x 600 mm. The bottom beam and top beam are designed to possess sufficient stiffness to bear and transfer forces with negligible deformation. The reinforcement details which are listed in Table 2 are provided as per the requirements IS13920:2014. The details of the shear walls are also illustrated in Figure 7.

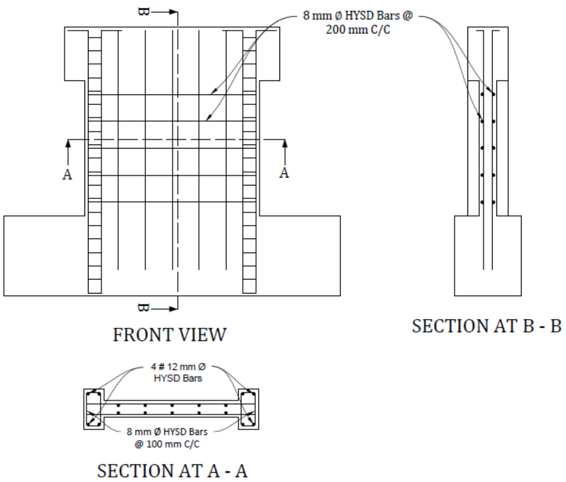


Figure 7a: Reinforcement detail of shear walls without opening

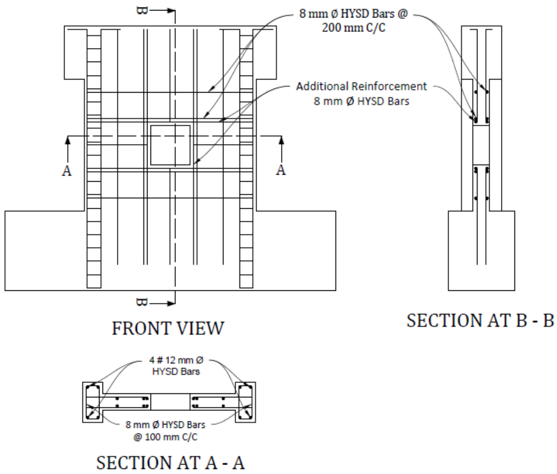


Figure 7b: Reinforcement detail of shear wall with opening

4.2 Construction

The shear walls were constructed in different stages. The walls were concreted in fully upright position. The bottom beam, wall and top beam were concreted in three stages in three consecutive days. After concreting, the walls were cured for 28 days.

4.3 Test set-up

The walls were tested as per the set-up illustrated in Figure 8. The bottom beam was anchored to the strong floor rigidly to prevent the rocking of the wall. The bottom beam was also restrained horizontally to prevent sliding of the wall. A hydraulic actuator with 1000 kN capacity was fixed to the reconfigurable reaction wall in the lateral direction. The vertical load was applied vertically using loading frame through two hydraulic jacks each with 300 kN capacity. The hydraulic jacks were connected to a stiff beam for transferring the load from two jacks and the stiff beam was placed over two hinges. In addition to that, a spreader beam was placed on the top of the wall to make sure that vertical load was applied uniformly to the wall.

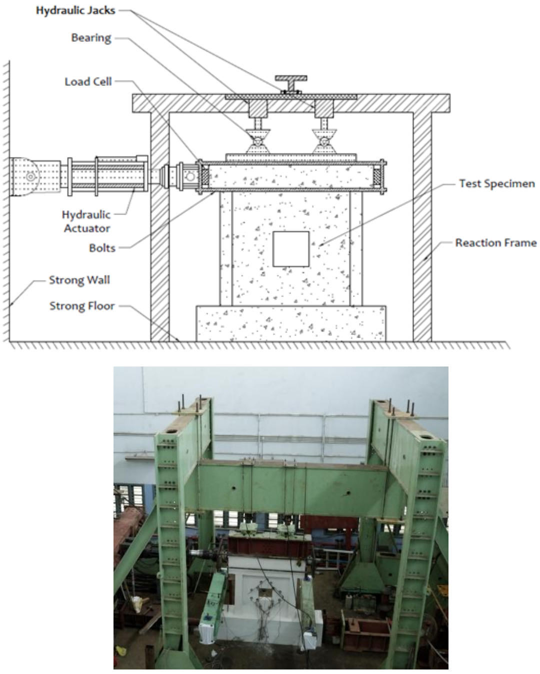


Figure 8: Test Setup

4.4 Loading procedure

The vertical load was kept constant throughout the testing maintaining the axial load ratio (ALR) as 10%. Cyclic lateral loading was accompanied by a displacement control system as per ASTM E2126-11. As per ASTM E2126-11, first displacement pattern comprises of five single cycles at displacements of 1.25, 2.5, 5, 7.5 and 10%, and second displacement pattern comprises of three fully reversed cycle starting from 20, 40, 60, 80 ,100, 120% and so on as illustrated in Figure 9, until failure or up to 10% lateral drift (i.e. 10 mm).

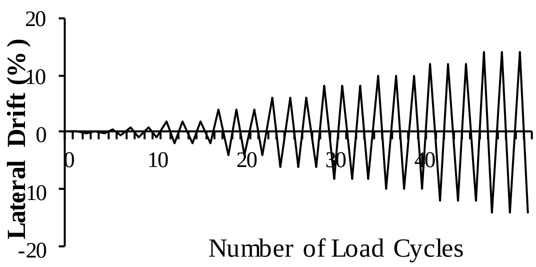
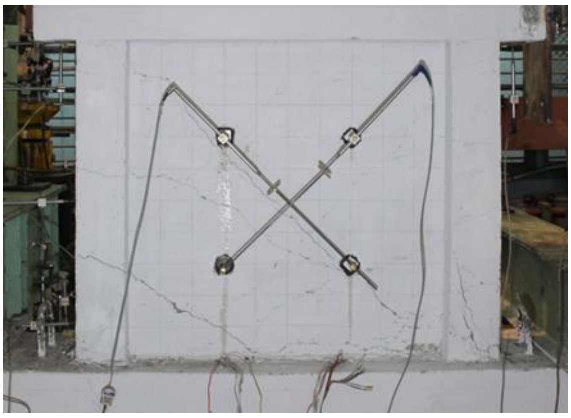


Figure 9: Loading Protocol

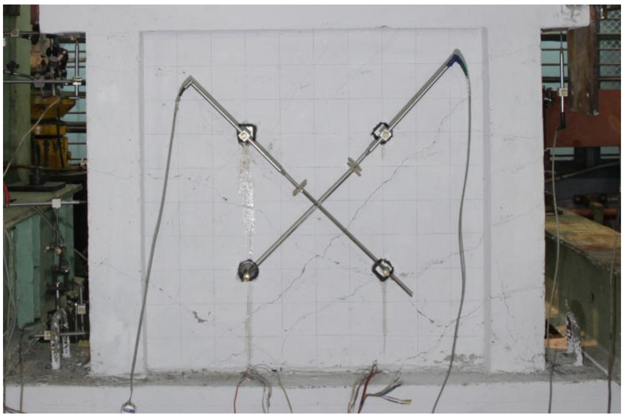
5 EXPERIMENTAL RESULTS

5.1 Wall without opening (SW–1.0)

The first horizontal cracking was noticed in the upper half of boundary element during 0.4% drift. In the following loading stages, the horizontal crack formed at boundary element inclines towards opposite toe of the web of the wall. Many short inclined cracks developed in the web portion of the wall. The crack pattern in the wall at the peak and failure load is shown in Figure 10. At the failure load, the crushing of concrete in both left and right toes of boundary elements was observed under both positive and negative cycles. Peak loads of +541.06 kN and -455.853 kN were observed with corresponding drift values of +2.34% and -1.82% respectively.



a. Positive Cycle



b. Negative Cycle

Figure 10: Crack pattern at Peak Load for SW-1.0

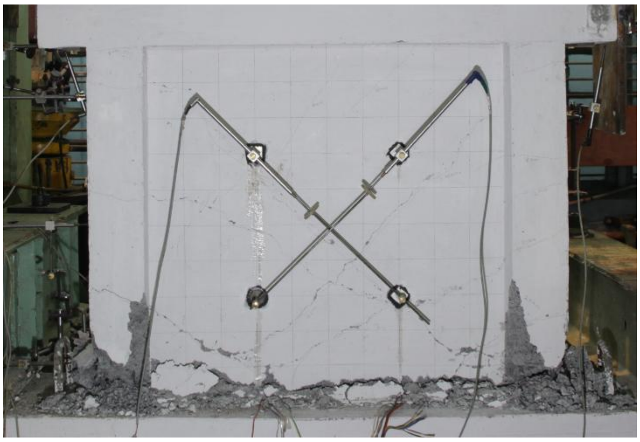


Figure 11: Crack pattern at Failure Load in SW-1.0

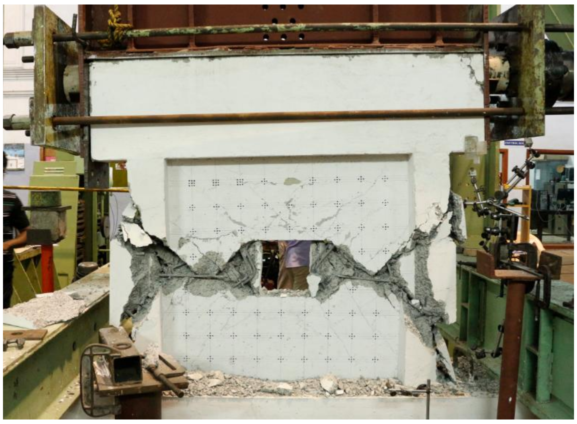


Figure 13: Crack pattern at Failure Load in SW-1.0-CW-IS

5.2 Wall with window opening (SW-1.0-CW-IS)

The first crack was observed at top corner of the opening and develops diagonally towards the top corner of the wall during 0.2% drift cycle. On further loading, cracks from all the four corners of the opening were formed and developed towards the nearest corners of the wall. The crack pattern of the wall at the peak and failure load is shown in Figure 12 and Figure 13. At the failure load, the weak plane near opening was sheared off horizontally. Peak loads of +292.65 kN and -289.38 kN were observed at drift values of +2.00% and -2.05% respectively.

Figure 12: Crack pattern at Peak Load in SW-1.0-CW-IS

5.3 Wall with window opening with FRC (SW-1.0–CW–FRC)

This wall was designed with FRC around the opening, where the wall is highly prone to stress concentration. The first cracking was observed at top corner of opening and developed diagonally towards the top corner of the wall at 0.2% drift. Almost same crack pattern was observed similar to the wall with window opening without FRC at initial stages. On loading, the cracks from all the four corners of the opening were formed and developed towards the nearest corners of the wall. The crack pattern of the wall at the peak and failure load is shown in Figure 14. At the failure load, the crushing of concrete in both left and right toes of boundary elements was observed in both positive and negative cycles as observed in wall without opening. Peak loads of +519.75 kN and -428.77 kN were observed with corresponding drift values of +2.26% and -2.27% respectively.

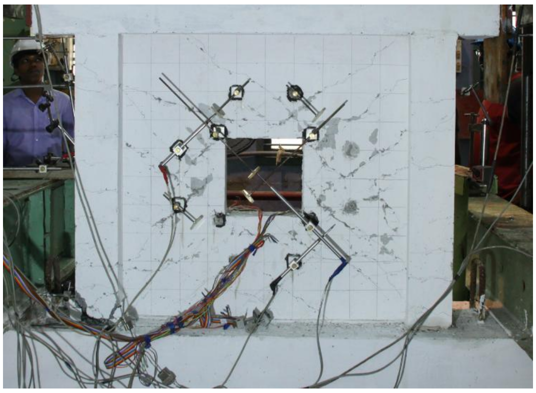


Figure 14: Crack pattern at Peak Load in SW-1.0-CW-FRC

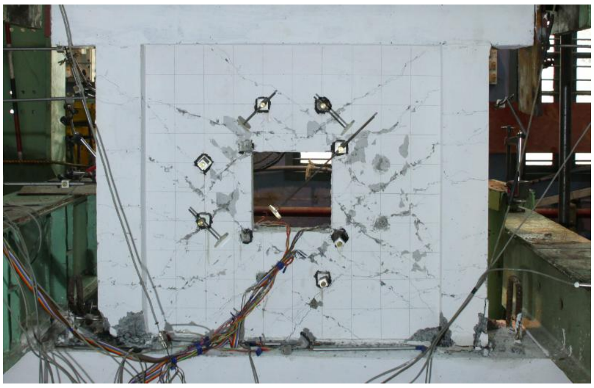
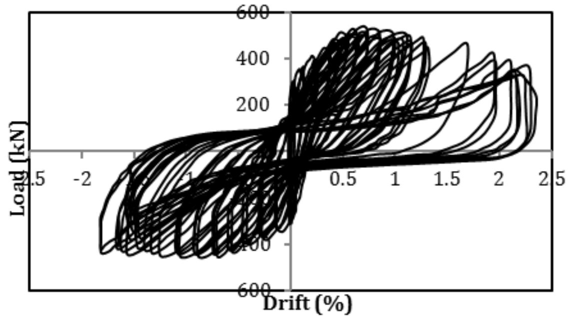


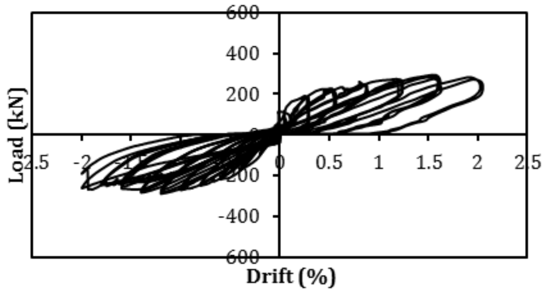
Figure 15: Crack pattern at Failure Load for Wall 3

5.4 Discussion of test results

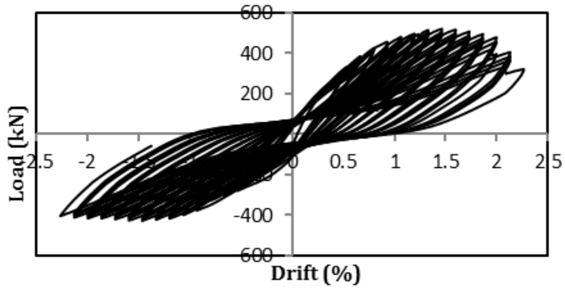
The Load vs. Drift response in all three walls are shown in Figures 16. The strength, displacement and ductility of the specimen were listed in Table 3. The drift capacity of the wall with opening was lesser than the wall without opening. However, it was improved by the adding FRC around the opening. It is to note that the shear capacity of the shear wall has been drastically affected by the presence of opening. The shear capacity of the wall without opening has been observed to be 498 kN. The shear capacity of the wall with opening has been observed to be 291 kN where 42% of reduction in the strength is noted. The shear capacity of wall with window opening with FRC has been observed to be 474 kN. Addition of FRC around the opening improves the strength by 61%. Moreover, the failure pattern of the wall changed completely with the presence of FRC.



Wall SW-1.0



Wall SW-1.0-CW-IS



Wall SW-1.0-CW-FRC

Figure 16: Load vs. Drift response in shear walls under static cyclic tests

Table 3 Test Results

Specimen	V_{peak}^{+} (kN)	V_{peak}^{-} (kN)	V_{Peak} (kN)	τ_{max} (MPa)	Δ_{peak}/H (mm)	Δ_u/H (mm)	μ
SW-1.0	541	-456	498	2.32	0.7	2.34	3.34
SW-1.0-CW-IS	293	-289	291	1.35	1.58	2.00	1.27
SW-1.0-CW-FRC	520	-429	474	2.21	1.46	2.26	1.55

6. CONCLUSION

The following conclusions have been drawn from this study,

1. The shear strength and ductility of shear wall have been reduced drastically due to presence of opening in the wall.

2. The addition of FRC around the opening improves the shear strength by 61% and ductility by 18%.
3. For the wall with opening, the failure mode has been due to shearing off the weaker plane of the wall (i.e) across the opening. For the wall without opening and with opening with the addition of FRC, the failure mode occurred due to crushing of concrete at both left and right toes of boundary elements. Interestingly, the addition of FRC around the opening alters the cracking pattern of the wall.
4. The extent of FRC from the edge of opening along height of wall to half width of opening seems to exhibit improved response.
5. Use of FRC is an alternate solution for strengthening of shear wall with opening.

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