CHAPTER 5

Flexural Response of Masonry Walls

5.1 Introduction

This chapter deals with the characterization of flexural behavior of strengthened masonry walls with and without opening. Masonry walls of size 762 × 480 × 230 mm (height × width × thickness) were cast using locally available burnt clay bricks and cement mortar. The opening was provided at the center of masonry walls of size 252 × 160 × 230 mm (height × width × thickness) with the opening ratio of 11.02%. These masonry walls were externally strengthened with different layers of NSM FRP strips and ECC sheets. These masonry walls were subjected to flexural static loading and loaded monotonically up to failure. Flexural performance of tested unstrengthened/control masonry walls and strengthened masonry walls in terms of modes of failure and the load-deflection response is presented and discussed. The experimental results show that the flexural strengthened masonry walls demonstrate a drastic improvement in their load carrying capacity and deformation capacity. The present study results reveal that the application of precast ECC increases the strength and deformability of masonry walls and hence demonstrate its effectiveness as strengthening element for masonry structures.

5.2 Flexural Response of Masonry Walls Strengthened with FRP and ECC

This section deals with experimental descriptions and methodology of the strengthened and unstrengthened masonry walls with FRP and ECC sheets. This section includes the specimen preparation, instrumentation and testing, and result & discussions of the tested masonry walls. The flexural response of masonry walls along with the various failure patterns developed during the experimental test is discussed in this section.

5.2.1 Specimen preparation

A total of twelve burnt-clay brick masonry walls (Fig. 5.1) of dimensions 762 × 480 × 230 mm (height × width × thickness) were constructed by an experienced mason. Out of twelve, four masonry walls were constructed with the opening at the center of size 252 × 160 × 230 mm (height × width × thickness) with the opening ratio of 11.02% (opening area/total surface area of wall).

Burnt clay bricks of C3 type were immersed in water for 24 hours before manufacturing of the walls, to avoid the absorption of water from the fresh mortars. The mortar mix ratio of 1:3 (cement: sand) (M1 type) was used to construct the masonry walls. The thickness of mortar was maintained from 10 to 12 mm. Masonry walls were cured by wet jute bag for 28 days before strengthening and testing. In order to undertake the investigations, the walls were divided into six series each made of two specimens.

Fig. 5.1 Masonry walls

Series #1

Unstrengthened/ control masonry walls without opening act as bench mark (control specimens) and referred to as Series #1 (Fig. 5.2).

Series # 2

This series consists of two specimens i.e., unstrengthened/ control masonry walls with opening at the center. The schematic diagram of control masonry wall with opening is shown in Fig. 5.3.

Series #3

This series comprises of two specimens flexurally strengthened with pultruded CFRP bars. NSM CFRP bars were installed into the masonry horizontal joints. Grooves are cut along the entire width of the wall; epoxy is filled half way in the joint followed by placing the NSM bars in the joints and pressing them to allow the epoxy to flow around the bars. Afterwards, grooves are filled completely with epoxy and left for the epoxy to harden. The walls were strengthened with 8 mm

diameter pultruded CFRP bars along wall width. The size of the grooves was 12 mm with a spacing of 85 mm center to center. The schematic diagram of Series #3 specimen is shown in Fig. 5.4.

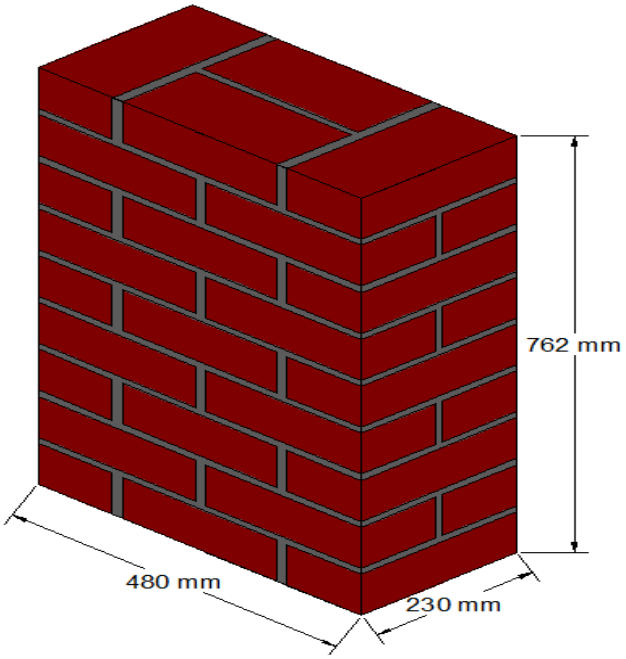

Fig. 5.2 Schematic diagram of control masonry wall without opening (Series #1)

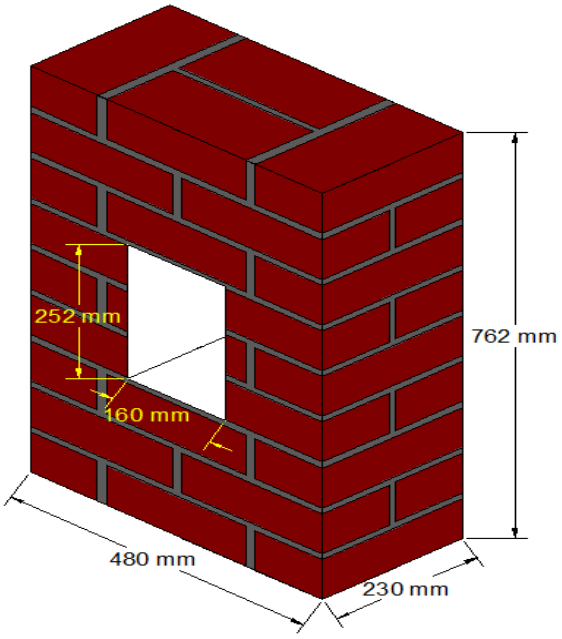

Fig. 5.3 Schematic diagram of control masonry wall with opening (Series #2)

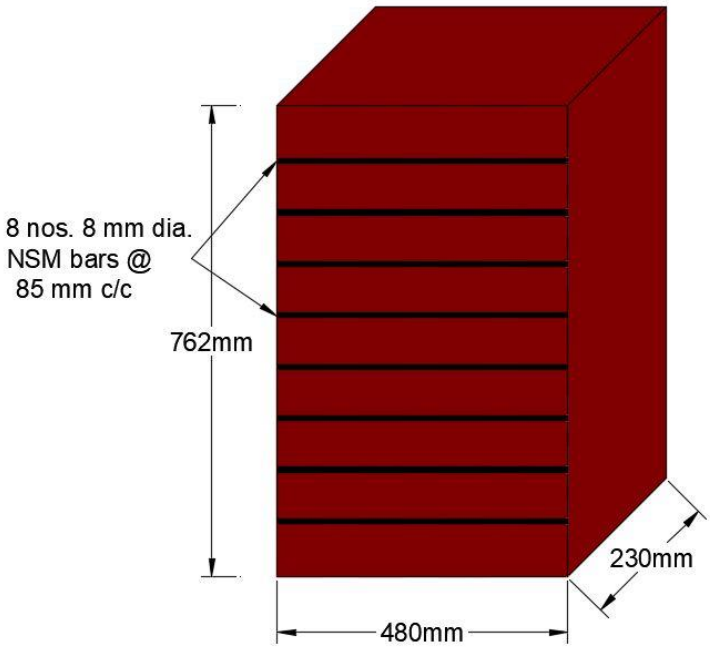

Fig. 5.4 Strengthening details of Series #3 specimen

Series #4

This series specimens were first strengthened in flexure like in the case of Series #3, then strengthened with CFRP strips. Epoxy was applied to the wall at the positions of the strips and spread evenly. First strip was placed on the epoxy, pressed gently and uniformly over the wall to prevent any air gaps, and then epoxy was applied and spread evenly on the first strip. This follows placing the second strip over the first one and similarly the third strip forming a three-layered thick unidirectional CFRP strips as shown in Fig. 5.5. The wall is covered and uniform pressure is applied to allow the strips to fix to the wall without formation of any air gaps. The CFRP strips strengthened walls were left for air curing for fourteen days. The walls were strengthened with 8 mm diameter CFRP bars along wall width and 2 mm thick longitudinal CFRP strips along the height of wall. The schematic diagrams of Series #4 walls are shown in Figs. 5.6-5.7.

Fig. 5.5 Masonry wall with NSM CFRP bars along with CFRP strips (Series #4)

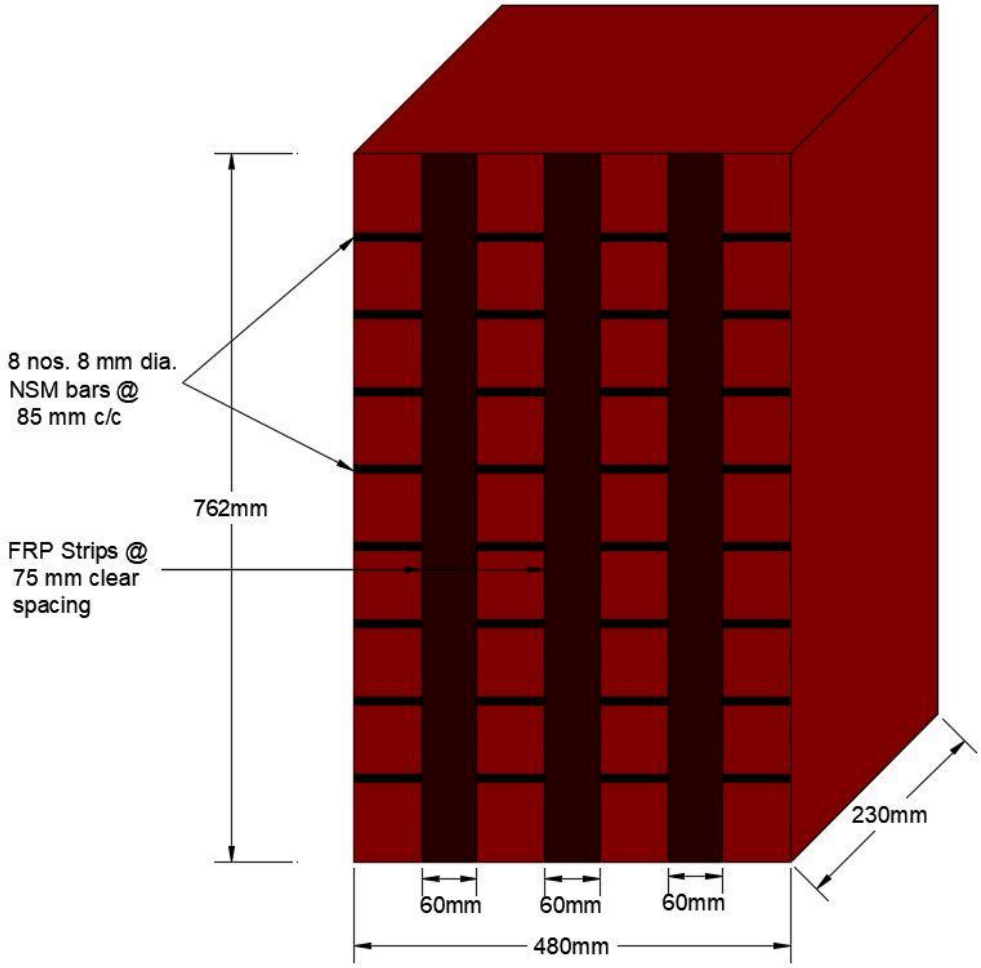

Fig. 5.6 Strengthening details of Series #4 specimen

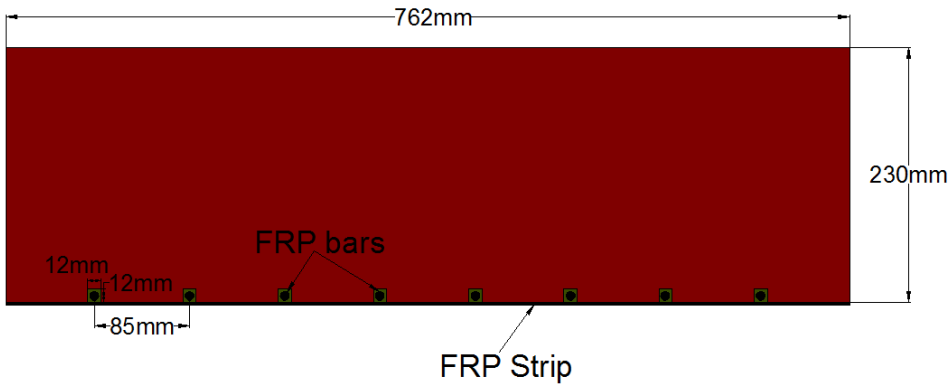

Fig. 5.7 Side elevation of Series #4 specimen

Series #5

This series consists of two flexurally strengthened masonry walls with ECC sheet of thickness 25 mm (Fig. 5.8). Installation of ECC sheet on the face of masonry walls was executed using epoxy adhesive (Sikadur 330). The surface of walls was clean and leveled of all extraneous material to improve resin-masonry adhesion. First, epoxy was applied on the walls at the position of the sheet and spread evenly. Then, ECC sheet was pasted on the surface of masonry walls. The thickness of epoxy was maintained approximately 1 mm. The walls were covered and the uniform pressure was applied to allow the sheet to fix to the wall without formation of any air gaps. The ECC strengthened walls were left for air curing for fifteen days before testing.

Series #6: This series comprises of two ECC strengthened masonry wall with opening at the center (Fig. 5.9). The ECC sheet of 25 mm thickness having same opening dimensions to that of masonry wall was used. The ECC sheet was bonded to the masonry surface using epoxy as adhesive. The strengthened masonry walls were left for air curing for fifteen days before testing.

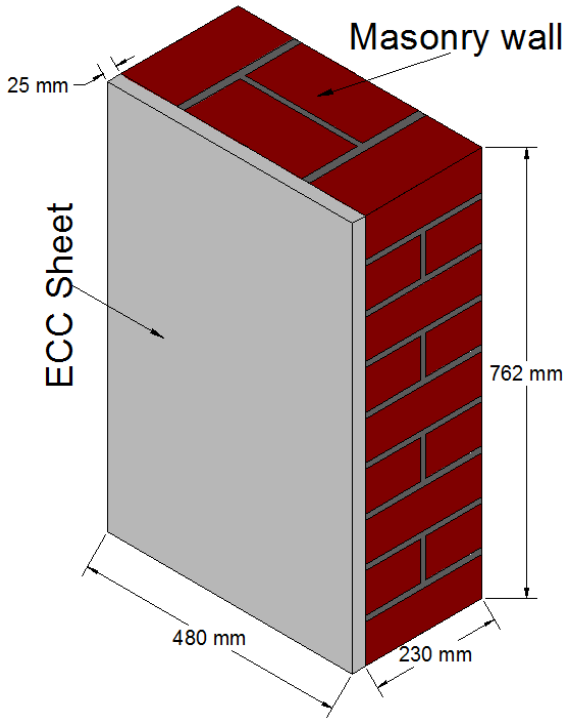

Fig. 5.8 Schematic diagram of ECC strengthened wall without opening

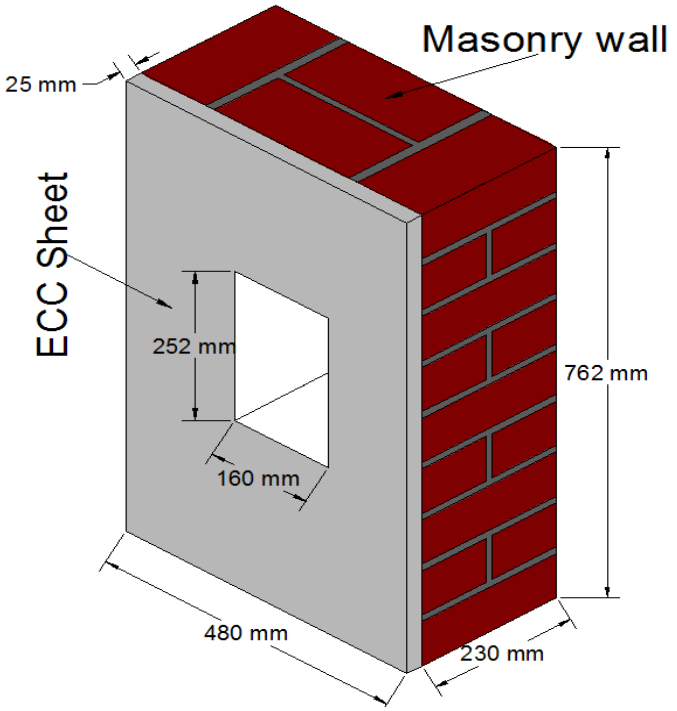

Fig. 5.9 Schematic diagram of ECC strengthened wall with opening

5.2.2 Instrumentation and testing

A servo-hydraulic actuator of capacity 200 kN was used to apply the four-point loading on the masonry wall as shown in Fig. 5.10. Load and deflection of the walls were measured through the control system. The walls were subjected to a ramp loading at a displacement control rate of 0.05 mm per sec till failure.

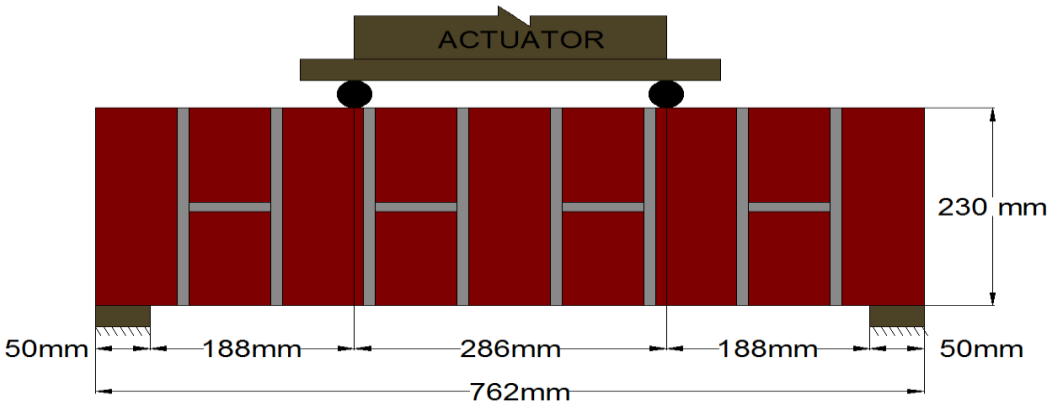

Fig. 5.10 Four-point bending test-setup of masonry wall for flexure failure

5.2.3 Result and discussion

The experimental test results of the control and strengthened masonry walls along with specimen ID details are presented in Table 5.1. Responses and failure patterns of the masonry walls are described in the following sections.

Series #1

In the unstrengthened/control masonry walls (Series #1), the flexural cracks started at the tension face and propagated towards the compression face leading to sudden failure. A joint bond failure took place near the center of the wall as shown in Fig. 5.11. The unstrengthened/ control masonry walls (MW) failed at ultimate average load of 15.48 kN and corresponding mid-span deflection of approximately 1.02 mm was observed. The load-deflection response of the control specimens is linear up to the peak load then sudden collapse occurred as shown in Fig. 5.12.

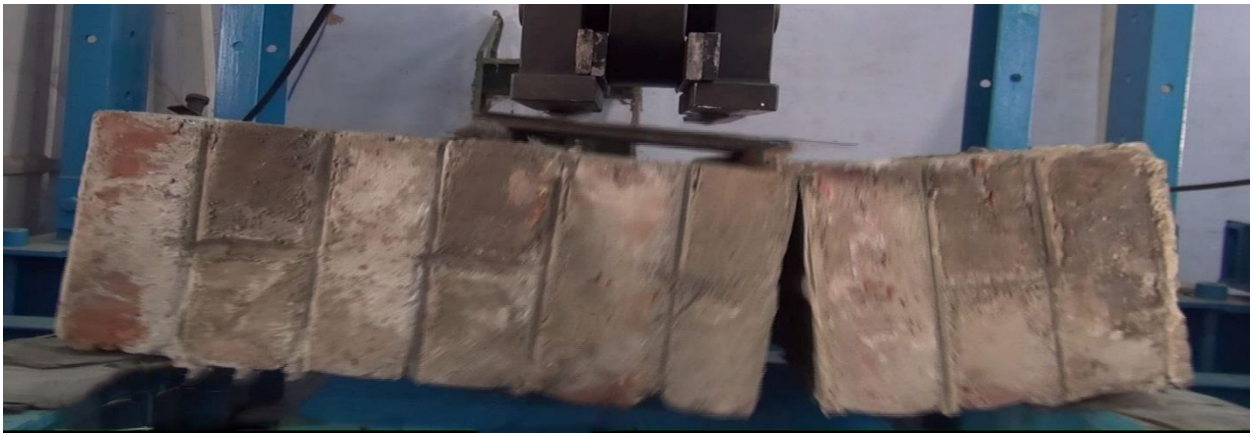

Fig. 5.11 Failure pattern of control masonry wall without opening (Series #1)

Table 5.1 Experimental results of all the specimens

Series No	Specimen ID	Specimen details	Avg. failure load (kN)	Avg. center displacement (mm)	P_{us}/P_{uc}^{*}	δ_s/δ_u^{**}	Mode of failure
Series #1	MW	Control/unstrengthened masonry wall without opening	15.48	1.02	-	-	Flexural
Series #2	MWO	Control/unstrengthened masonry wall with opening	10.62	0.85	-	-	Flexural
Series #3	FMWB	Flexural strengthened masonry wall with CFRP bars	27.06	3.73	1.74	3.67	Flexural
Series #4	FMWBS	Flexural strengthened masonry wall with CFRP bars along with CFRP strips	76.65	9.05	4.95	8.91	Shear
Series #5	FW	ECC strengthened masonry wall without opening	83.80	9.45	5.41	9.26	Flexural

Series #6	FWO	ECC strengthened masonry wall with opening	63.85	7.41	6.01	8.71	Flexural

* P_{us} = Load carrying capacity of strengthened wall
* P_{uc} = Load carrying capacity of unstrengthened/control wall
**δ_s = Mid-span displacement of strengthened wall
**δ_u = Mid-span displacement of unstrengthened/control wall

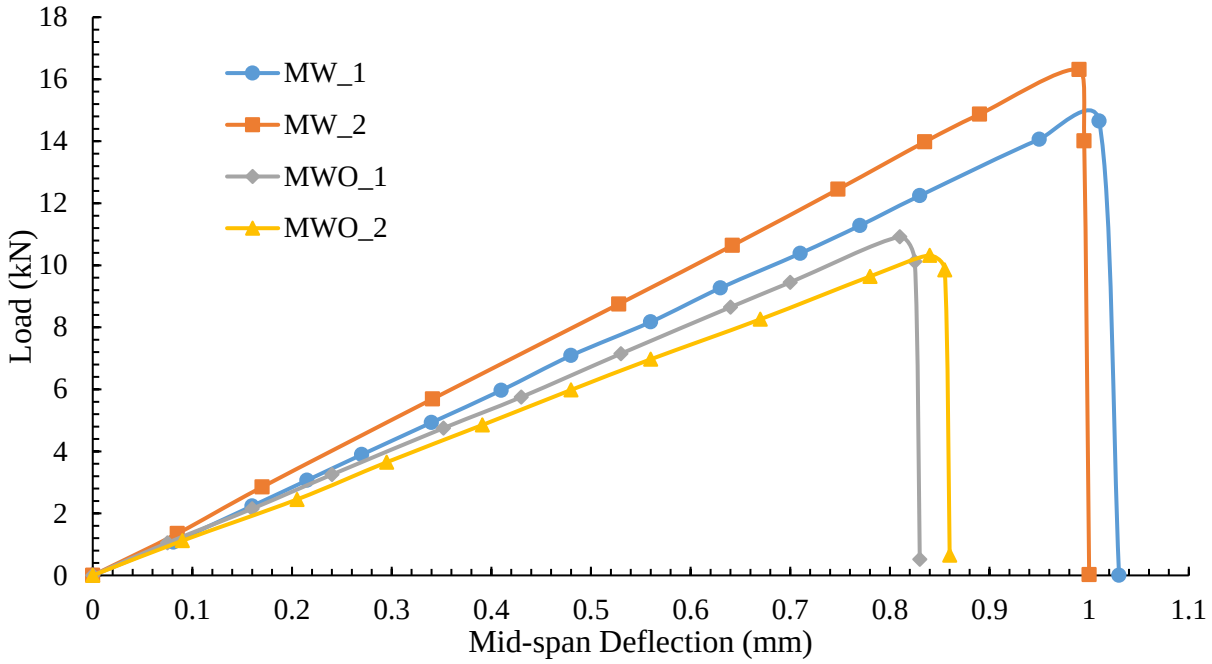

Fig. 5.12 Load-deflection response of unstrengthened/ control specimens (Series #1-2)

Series #2

In the unstrengthened/control masonry walls with opening (Series #2), initially vertical flexural cracks started close to the left side of the loading point and propagated towards the compression face leading to sudden failure as shown in Fig. 5.13. The control masonry walls with opening (MWO) failed at ultimate average load of 10.65 kN and corresponding mid-span deflection of approximately 0.85 mm was observed. The pattern of load-deflection response of the masonry wall with opening is similar to Series #1 specimens as shown in Fig. 5.12.

Fig. 5.13 Failure pattern of control masonry wall with opening (Series #2 specimen)

Series #3

In the flexural strengthened masonry walls with CFRP bars along the width (Series #3), vertical flexural crack appeared close to the right side of loading point, as shown in Fig. 5.14. The normal flexural failure was observed in the Series #3 specimens. The failure pattern of the strengthened masonry walls (FMWB) is shown in Fig. 5.14. The load-deflection response of the Series #3 specimens is shown in Fig. 5.15. The response of the Series #3 specimens (FMWB) is linear up to peak load then sudden drop in load occurred. The brick-mortar bond failure was observed in the Series #3 specimens. It is observed that the NSM CFRP bars which are inserted along the width have not played considerable role for flexural strengthening. However, unexpectedly there is slight improvement in the flexural strength even with horizontal bars placed along width.

Fig. 5.14 Failure pattern of Series #3 specimen subjected to four-point loading

Series #4

In Series #4 specimens (FMWBS), the shear crack developed at the mid-span of the loading which propagated towards the support. As the load increased, crack widened and failed in shear near the supports as shown in Fig. 5.16. The load-displacement response of Series #4 specimens is shown in Fig. 5.15. The response of the specimens (FMWBS) is linear up to peak load where a sudden drop in load occurred. Then, the specimen featured a gradual increase in load and deflection, possibly because of the progressive failure of CFRP strips, followed by another load decay. Finally, the rapid drop in the load response was observed. The average failure load of Series #4 specimens is observed to be 76.65 kN with corresponding average mid-span deflection of 9.04 mm. Series #4 specimens have shown better response in comparison to Series #1-3 in terms of load carrying capacity and deformation capacity.

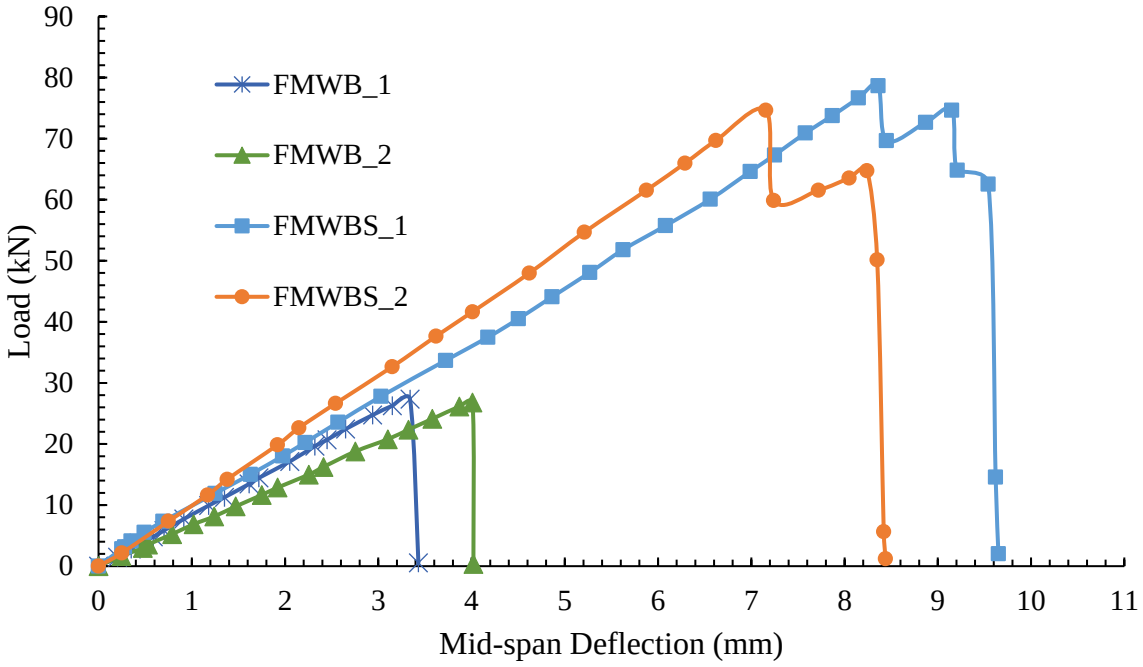

Fig. 5.15 Load-deflection response of FRP strengthened masonry walls (Series #3-4)

Fig. 5.16 Failure pattern of Series #4 specimen

Series #5

In Series #5 specimens (FW), the vertical crack developed near to the left side of loading point due to stress concentration which leading to the flexural failure of the wall as shown in Fig. 5.17. The load-displacement response of Series #5 specimens is shown in Fig. 5.19. The response of Series #5 specimens is initially linear followed by a softening trend due to ductile behavior of ECC. Finally, the rapid drop in the load response was observed. The tension strengthened masonry walls with ECC sheet (FW) failed at unltimate average load of 83.80 kN which is almost 5 times of that of control masonry wall (MW).

Fig. 5.17 Failure pattern of ECC strengthened masonry wall (Series #5 specimen)

Series #6

In Series #6 specimens (FWO), first crack appeared in the vertical direction close to the left side of loading point as shown in Fig. 5.18. As the load is increased, the cracks widened in the tension zone and propagated towards the compression face. The normal flexural failure was observed in the specimens. ECC strengthened masonry walls with opening failed at an ultimate load of 63.85

kN with corresponding average mid-span deflection of 7.41 mm. The load-deflection response of Series #6 specimens is shown in Fig. 5.19. The flexural response of Series #6 specimens is similar to Series #5 specimens with less flexural capacity due to opening at the center.

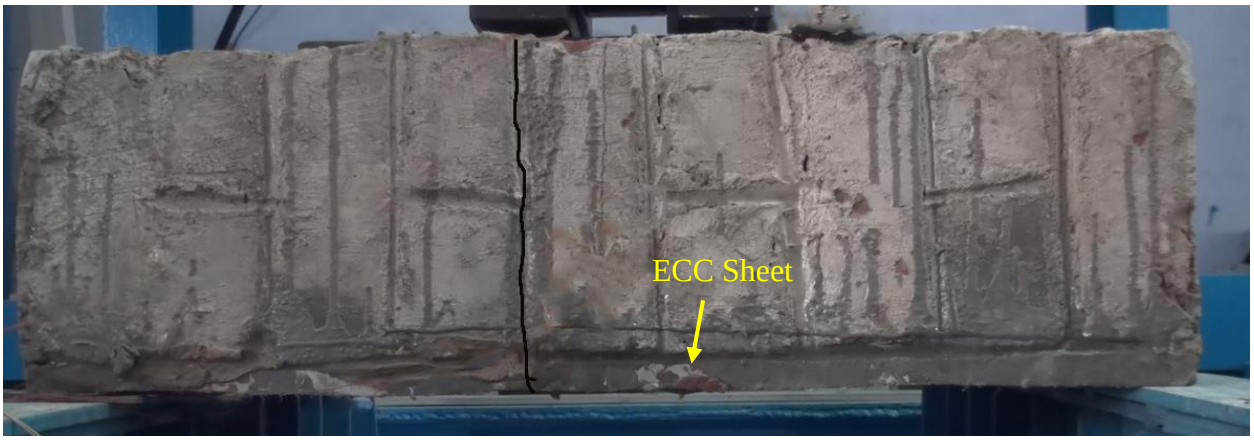

Fig. 5.18 Failure pattern of ECC strengthened masonry wall with opening (Series #6 specimen)

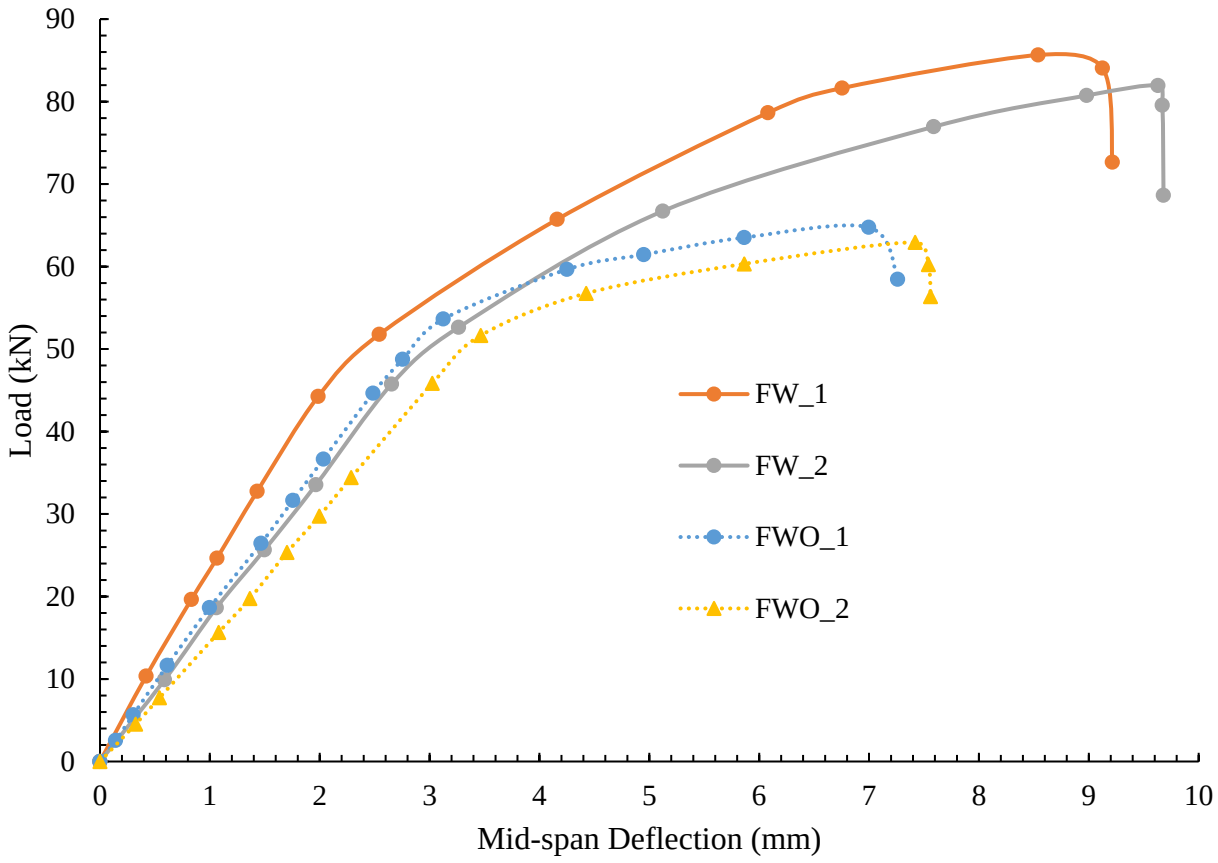

Fig. 5.18 Load-deflection response of ECC strengthened masonry walls (Series #5-6)

5.3 Concluding Remarks

The experimental study was conducted on unstrengthened and FRP & ECC strengthened masonry walls with and without opening subjected to flexural loading. The following concluding remarks are made based on results of this Chapter.

- Load carrying capacity of flexural strengthened masonry walls with CFRP bars (Series #3) has increased by 1.9 times of that of unstrengthened/ control masonry walls.
- Flexural strengthened masonry walls with CFRP bars along with CFRP strips (Series #4) has demonstrated a drastic improvement in their load carrying capacity as well as deformation capacity.
- Load carrying capacity of flexural strengthened masonry walls with CFRP bars and strips (Series #4) has increased 5 times of that of the unstrengthened/ control masonry walls.
- Due to high flexural strength of flexurally strengthened masonry walls with NSM CFRP bars and strips (Series #4) failed in shear which could be avoided by adequate shear strengthening.
- Load carrying capacity of flexural strengthened masonry walls with precast ECC sheet (Series #5) is found to be about 5.4 times of that of control/unstrengthened masonry walls.
- Load carrying capacity of ECC strengthened masonry walls with opening (Series #6) is found to be about 6 times of that of control/unstrengthened masonry walls.