CHAPTER 4

Flexural Response of Masonry Beams

4.1 Introduction

In this chapter, results have been primarily presented in two sections. The first section deals with the experimental investigations carried out for the flexural response of masonry beams. Masonry beams were made in different ways with cement mortar and ECC as a bed joint. Masonry beams of 150 x 230 mm cross-section and 1300 mm length were cast using locally available burnt clay bricks and cement mortar of proportions 1:3 (cement: sand) as bed joint. These masonry beams were externally strengthened with FRP sheets and bars in different patterns. Masonry beams were strengthened in flexure and shear by bonding FRP sheets at soffit and U-wrapping, respectively. These masonry beams were tested for four-point bending and loaded monotonically up to failure. Flexural capacity, deformation, and crack patterns of tested control masonry beams and strengthened masonry beams are compared and discussed. This study demonstrates various failure patterns developed during the four-point bending. The experimental results show that FRP sheets and bars are very effective for increasing the load and deformation carrying capacity. Moreover, the effectiveness of types of CFRP bars (pultruded and hand-layup) on the flexural strength of masonry beams are discussed based on experimental results.

The second section deals with the effectiveness of precast ECC sheets for strengthening of masonry beams by bonding them on tension face as well as both on tension and compression faces like a sandwich beam. Two types of bonding materials have been used, i.e., epoxy and cement mortar for bonding the ECC sheets with masonry beam. The experimental flexural response has been predicted for tension strengthened as well as sandwich beams. All beams were tested under four-point loading systems. The present study results reveal that the application of precast ECC increases the strength and deformability of masonry beams and hence demonstrate its effectiveness as strengthening element for masonry structures.

4.2 Flexural Response of Masonry Beams with Cement Mortar and ECC as Bed Joint

This section deals with experimental descriptions and methodology of the masonry beams casted using cement mortar and ECC as bed joint. This section includes the specimen preparation, experimental test-setup, and result & discussions of the tested masonry beams. The flexural response of masonry beams along with the various failure patterns developed during the experimental test are discussed in this section.

4.2.1 Specimen preparation

A total of forty-four masonry beams of 150 × 230 mm cross-section (width × depth) and 1300 mm length were cast. Out of forty-four specimens, half of the beams were constructed with cement mortar as bed joint and remaining half with the ECC as bed joint. The group of masonry beam specimens is shown in Fig. 4.1. The burnt clay bricks of C1 type (See Chapter 3) were used for casting of masonry beams. The cement mortar of M1 type and Polyester-ECC were used for the construction of masonry beams with cement mortar and ECC as bed joint, respectively. Two layers of burnt clay brick (C1 type) were inserted in each beam as shown in Fig. 4.2. The masonry beams have five brick units in each layer with four mortar joints, each of approximately 20 mm thickness. The thickness of top, bottom and end cover of the beam was maintained as 30 mm with mortar. The beams were cured for 28 days before testing.

These masonry beams were divided into six series. Series #1 having four specimens and remaining all series (Series #2-6) contains eight specimens. Each series consist of two types of specimen, the first type was made with cement mortar as bed joint (Fig. 4.2 a) and the second type constructed with ECC as bed joint (Fig. 4.2b). The description of the masonry beams specimens is presented in Table 4.1. To distinguish the masonry beam with cement mortar as bed joint and ECC as bed joint, the designation ‘CM-X’ and ‘CE-X’ are used, where ‘X’ indicates the specimens described in Table 4.1; ‘CM’ stands for cement mortar as bed joint; ‘CE’ refers to the ECC as bed joint.

Fig. 4.1 Masonry beam specimens

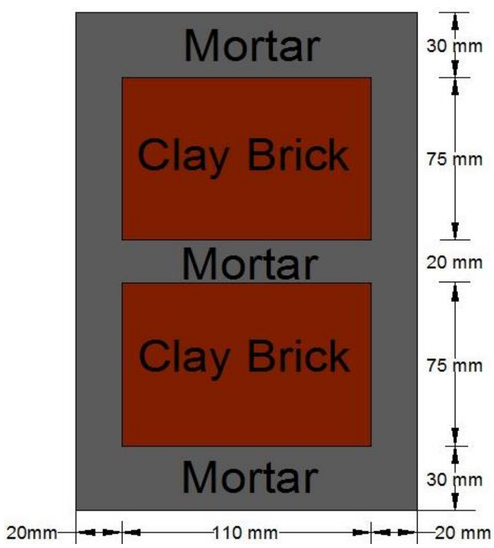

Fig. 4.2 (a) Cross-section of masonry beam with cement mortar as bed

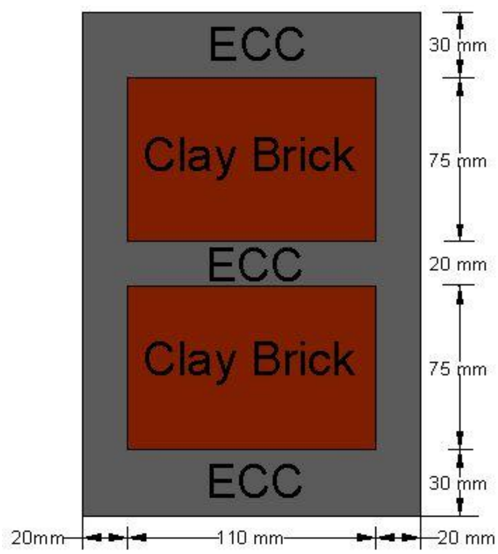

Fig. 4.2 (b) Cross-section of masonry beam with ECC as bed

Table 4.1 Description of beam specimens

Series No.	Specimen ID	Specimen details	No of specimens
1	CM	Control masonry beams with cement mortar as bed joint	2
	CE	Control masonry beam with ECC as bed joint	2
2	CM-CFB	Carbon fiber flexural strengthened masonry beams with cement mortar as bed joint	2
	CM-GFB	Glass fiber flexural strengthened masonry beams with cement mortar as bed joint	2
	CE-CFB	Carbon fiber flexural strengthened masonry beams with ECC as bed joint	2
	CE-GFB	Glass fiber flexural strengthened masonry beams with ECC as bed joint	2
3	CM-CUB	Carbon fiber U-wraping shear strengthened masonry beams with cement mortar as bed joint	2
	CM-GUB	Glass fiber U-wraping shear strengthened masonry beams with cement mortar as bed joint	2
	CE-CUB	Carbon fiber U-wraping shear strengthened masonry beams with ECC as bed joint	2
	CE-GUB	Glass fiber U-wraping shear strengthened masonry beams with ECC as bed joint	2
4	CM-CCB	Carbon fiber continuous U-wraping shear strengthened masonry beams with cement mortar as bed joint	2
	CM-GCB	Glass fiber continuous U-wraping shear strengthened masonry beams with cement mortar as bed joint	2
	CE-CCB	Carbon fiber continuous U-wraping shear strengthened masonry beams with ECC as bed joint	2
	CE-GCB	Glass fiber continuous U-wraping shear strengthened masonry beams with ECC as bed joint	2

5	CM-PRB	Pultruded CFRP bars reinforced masonry beams with cement mortar as bed joint	2
	CM-HRB	Hand lay-up CFRP bars reinforced masonry beams with cement mortar as bed joint	2
	CE-PRB	Pultruded CFRP bars reinforced masonry beams with ECC as bed joint	2
	CE-HRB	Hand lay-up CFRP bars reinforced masonry beams with ECC as bed joint	2
6	CM-NPB	NSM strengthened masonry beams using pultruded CFRP bars with cement mortar as bed joint	2
	CM-NHB	NSM strengthened masonry beams using hand lay-up CFRP bars with cement mortar as bed joint	2
	CE- NPB	NSM strengthened masonry beams using pultruded CFRP bars with ECC as bed joint	2
	CE- NHB	NSM strengthened masonry beams using hand lay-up CFRP bars with ECC as bed joint	2

Series #1

This series consists of four control masonry beam specimens. Out of four, two specimens were constructed with cement mortar as bed joint and remaining two with ECC as bed joint. The schematic diagram of Series #1 specimen is shown in Fig 4.3.

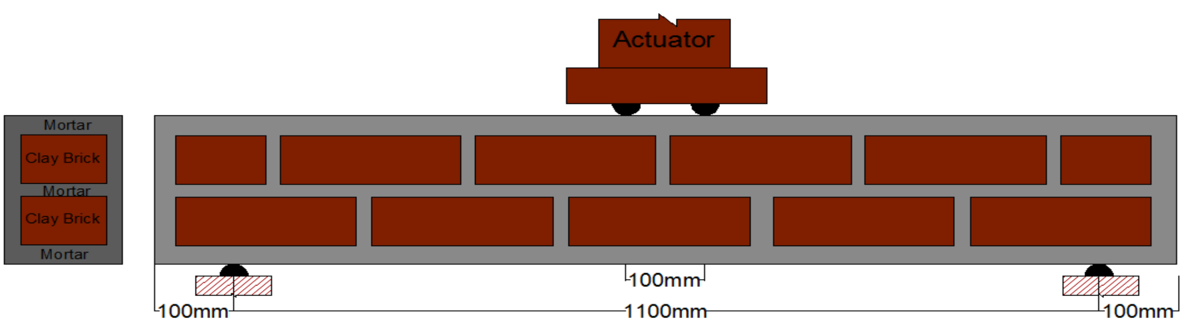

Fig. 4.3 Schematic diagram of Series #1 beam

Series #2

In this series, specimens were strengthened in flexural with one ply of FRP (CFRP and GFRP) as externally bonded with epoxy at the bottom (tension zone) of the beam. To ensure a good bonding with the bottom surface, each beam was cleaned for dust before applying epoxy adhesive. After the application of first epoxy layer on the bottom surface, the fiber fabric was glue to the beam with epoxy and rollers were used for uniform application of epoxy. Epoxy adhesive is allowed to cure for 15 days at room temperature prior to testing. The schematic diagram of Series #2 specimen is shown in Fig. 4.4.

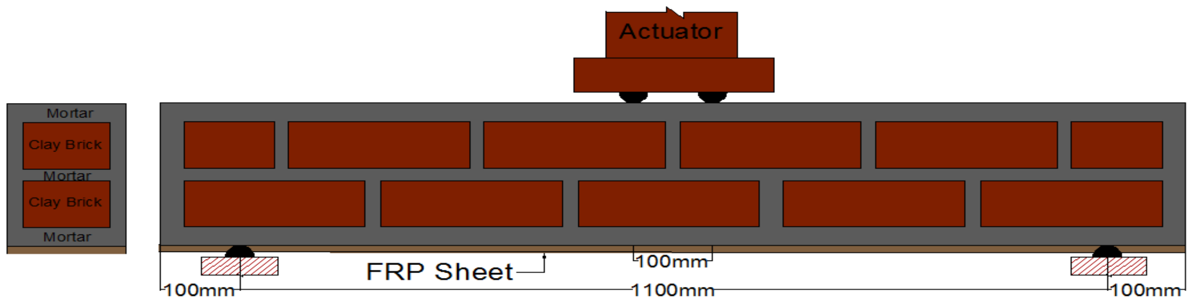

Fig. 4.4 Schematic diagram of Series #2 beam

Series #3

This series specimens were first strengthened in flexure similar to that of specimen of Series #2, further were strengthened in shear by discrete U-wrapping with one ply of 70 mm wide FRP strips at the spacing of 100 mm (i.e., 0.43 d). No FRP shear strips were provided in constant moment zone. The schematic diagram of Series #3 specimen is shown in Fig. 4.5.

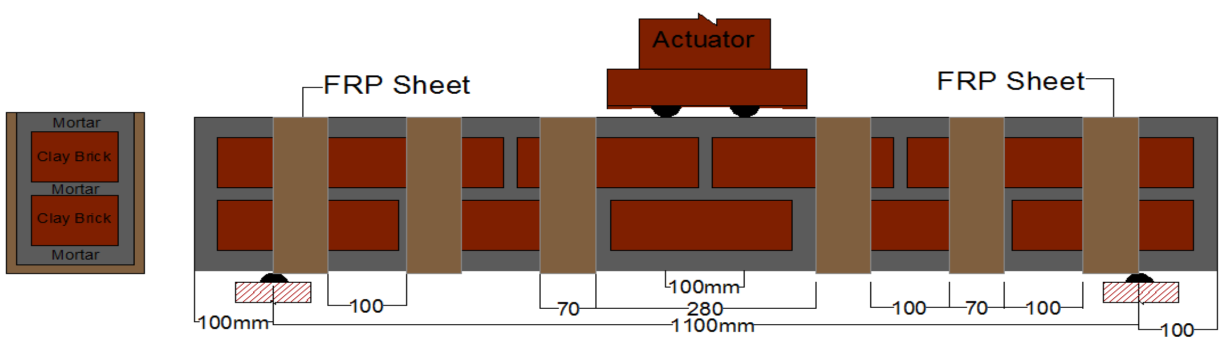

Fig. 4.5 Schematic diagram of Series #3 beam

Series #4

The fourth series consists of four specimens which were first strengthened in flexure similar to that of specimen of Series #2 and then strengthened in shear by continuous U-wrapping with one ply of FRP sheet for the whole length. The schematic diagram of Series #4 beams is shown in Fig. 4.6.

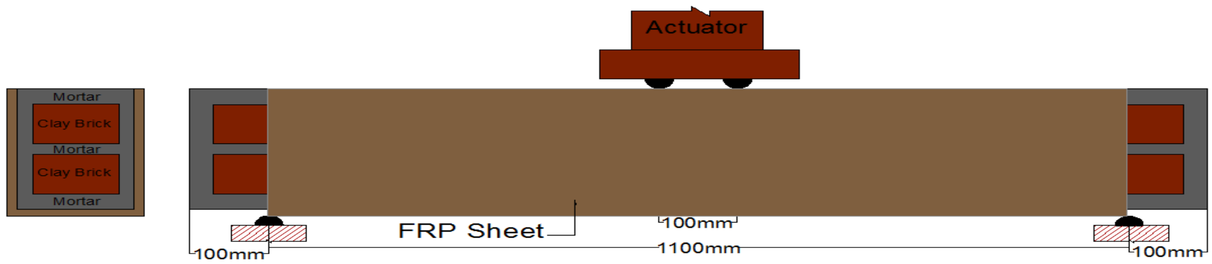

Fig. 4.6 Schematic diagram of Series #4 beam

Series #5

This series consists of eight specimens; four specimens constructed with cement mortar as bed joint and remaining four with ECC as bed joint. These masonry beams were reinforced with three numbers of CFRP bars of diameter 8 mm as shown in Figs 4.7 (a), & (b). Out of four, two specimens were reinforced with pultruded CFRP bars and remaining two with CFRP bars fabricated by hand lay-up process. The schematic diagram of reinforced masonry beams with CFRP bars is shown in Fig. 4.8.

Series #6

In this series, eight masonry beams were constructed; four specimens with cement mortar as bed joint and remaining four with ECC as bed joint. The specimens were cured with wet jute bags for 28 days after the casting. Then, these specimens strengthened with three numbers of near surface mounted (NSM) CFRP bars of diameter 8 mm. Out of four, two specimens were strengthened with pultruded CFRP bars and remaining two with CFRP bars fabricated by hand lay-up process. The surface of CFRP bars manufactured by pultrusion technique was glossy, while the CFRP bars fabricated by hand lay-up process was rough. Grooves of size 1.5 times of FRP bar diameter (12 mm) were cut along the length of masonry beams using marble cutter. Dust was removed from the grooves using the vacuum cleaner. After cleaning of grooves, epoxy is filled half way in the grooves followed by placing the NSM bars and pressing them to allow the epoxy to flow around the bars. Afterwards, grooves were filled completely with epoxy and allowed to cure for 15 days prior to testing of specimens. The schematic diagram of NSM strengthened masonry beams with FRP is shown in Figs. 4.9-4.10.

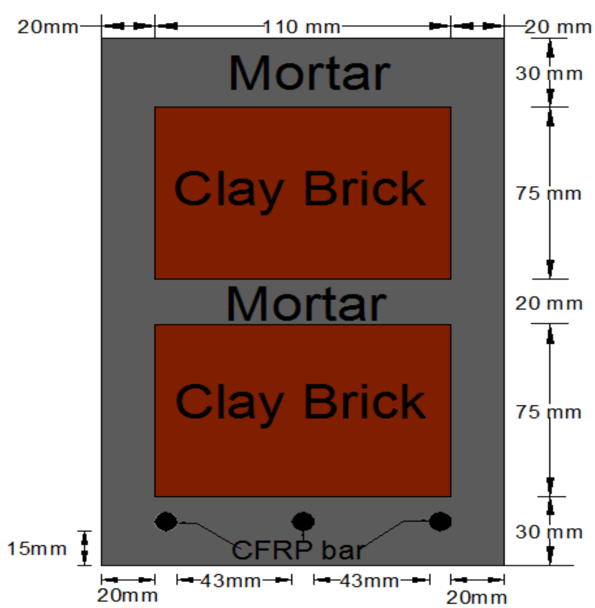

Fig. 4.7 (a) Cross-section of reinforced masonry beam with cement mortar as bed joint

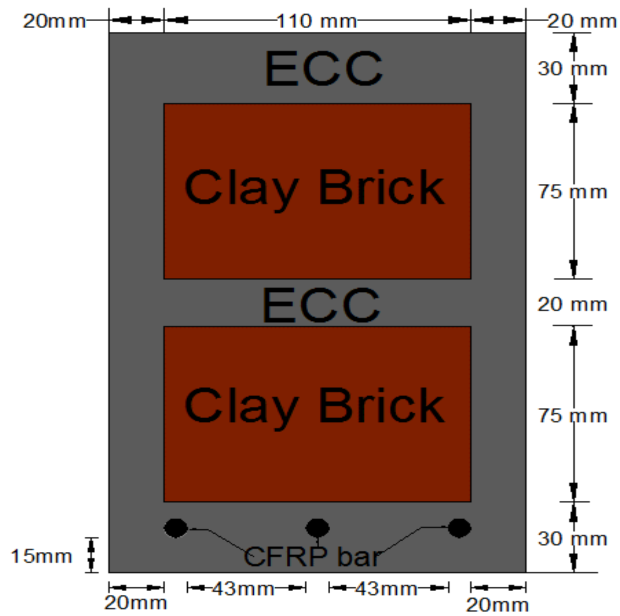

Fig. 4.7 (b) Cross-section of reinforced masonry beam with ECC as bed joint

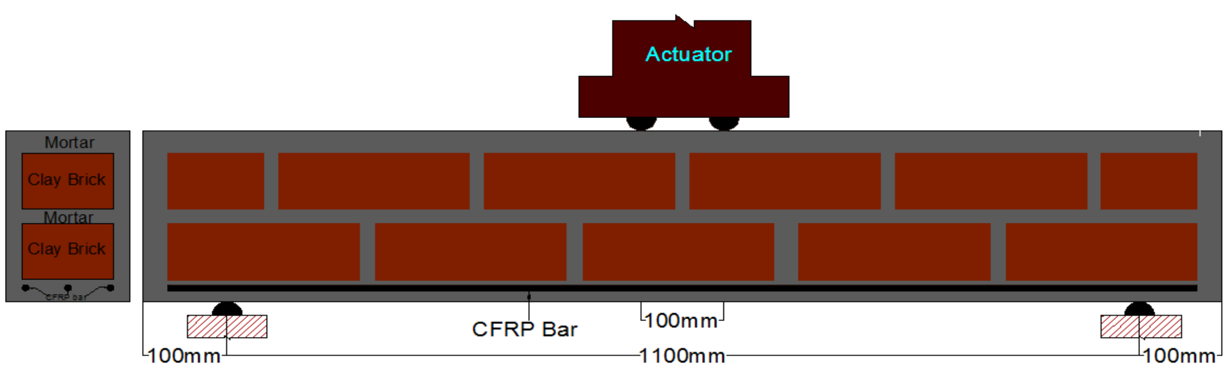

Fig. 4.8 Schematic diagram of Series #5 beam

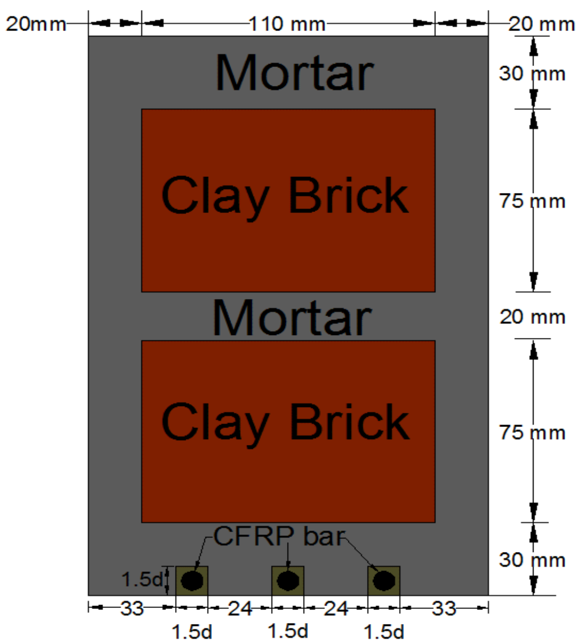

Fig. 4.9 (a) Cross-section of NSM strengthened masonry beam with cement mortar as bed joint

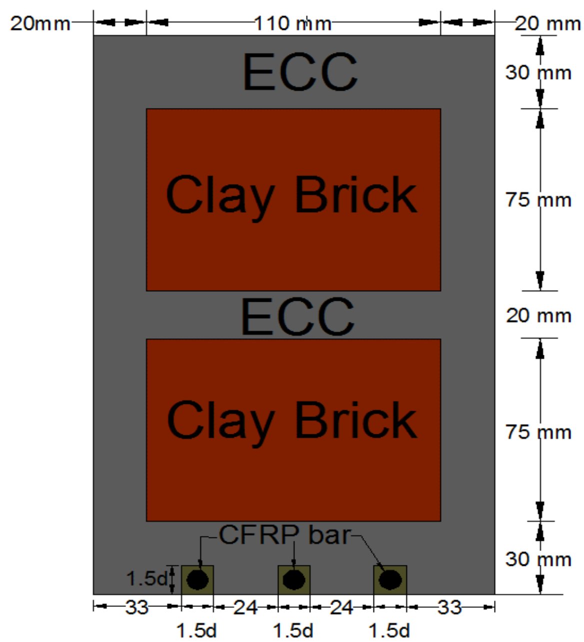

Fig. 4.9 (b) Cross-section of NSM strengthened masonry beam with ECC as bed joint

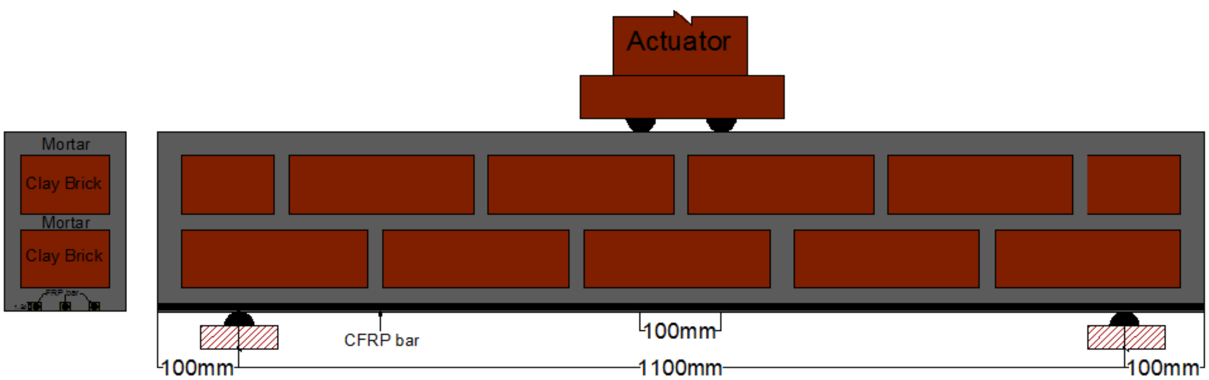

Fig. 4.10 Schematic diagram of Series #6 beam

4.2.2 Experimental test-setup

For the flexural testing, the beams were loaded under four-point bending. Load was applied by means of a 200 kN capacity servo hydraulic Actuator. The load and deflection of the beams were measured through the control system. The specimens were tested of an effective span of 1.10 m with loading span of 100 mm as shown in the schematic diagrams of Section 4.2.1. All specimens were monotonically loaded at a displacement control rate of 0.05 mm per sec till failure.

4.2.3 Result and discussion

Test results of the control, reinforced, and strengthened masonry beams are presented in Table 4.2. Responses and failure patterns of the masonry beams are presented in the following sub-sections.

Table 4.2 Experimental results of tested beams

Series No.	Specimen ID	Average failure load (kN)	Average mid-span deflection (mm)	P_{SB}/P_{CB}*	δ_{SB}/δ_{CB}**	Mode of failure
1	CM	3.58	1.38	-	-	Sudden-flexural
	CE	23.01	12.50	6.43	9.06	Flexural
2	CM-CFB	30.08	8.63	8.40	6.25	Shear
	CM-GFB	28.10	6.67	7.85	4.83	Shear
	CE-CFB	79.34	13.20	3.45	1.06	Shear
	CE-GFB	62.46	12.15	2.71	0.97	Shear
3	CM-CUB	41.21	11.27	11.51	8.17	Shear
	CM-GUB	34.89	12.21	9.74	8.85	Shear
	CE-CUB	70.86	16.68	3.08	1.33	Shear
	CE-GUB	61.25	16.15	2.66	1.29	Shear
4	CM-CCB	77.00	16.99	21.51	12.31	Flexural
	CM-GCB	63.03	16.66	17.60	12.07	Flexural
	CE-CCB	86.80	14.77	3.77	1.18	Flexural
	CE-GCB	85.65	14.25	3.72	1.14	Flexural
5	CM-PRB	48.70	20.34	13.60	14.74	Flexural
	CM-HRB	42.78	12.49	11.95	9.05	Flexural

	CE-PRB	62.25	28.56	2.71	2.29	Flexural
	CE-HRB	60.34	14.45	2.62	1.16	Flexural
6	CM-NPB	47.85	9.79	13.37	7.10	Shear
	CM-NHB	41.32	10.52	11.54	7.62	Shear
	CE- NPB	73.04	11.68	3.17	0.93	Shear
	CE- NHB	66.88	10.35	2.91	0.83	Shear

* P_{SB} = Load carrying capacity of strengthened/reinforced masonry beam

* P_{CB} = Load carrying capacity of respective control masonry beam

**δ_{SB} = Mid-span deflection of strengthened/reinforced masonry beam

**δ_{CB} = Mid-span displacement of respective control masonry beam

Series #1

The control masonry beam with cement mortar as bed joint failed suddenly due to the brittleness of both bricks and cement mortar. The beams failed at an average ultimate load of 3.58 kN and corresponding mid-span deflection of approximately 1.38 mm was observed. It has been observed that flexural cracks developed at the mid span of the beam and tends to fail in a brittle mode as shown in Fig. 4.11.

In the case of control masonry beams with ECC as bed joint, vertical flexural cracks developed in the constant moment zone followed by flexural shear cracks in shear spans as shown in Fig. 4.12. Then the cracks widened in the tension zone after the ECC has yielded, and finally, the rupture of brick at the mid span of the beam occurred. The normal flexural failure was observed in the control beam characterized by yielding of the ECC. The load-deflection response of control masonry beams with cement mortar and ECC as bed joint is shown in Fig. 4.13. The control masonry beam with ECC as bed joint (CE) has almost linear slope up to the cracking load, while after the peak loads, yielding of the ECC occurred. It is clearly shown in Fig. 4.13, that the effect of ECC as bed joint in place of cement mortar has significantly improved the strength and ductility of masonry beam.

Fig. 4.11 Failure mode of control beam with cement mortar as bed joint

Fig. 4.12 Failure mode of control beam with ECC as bed joint (CE)

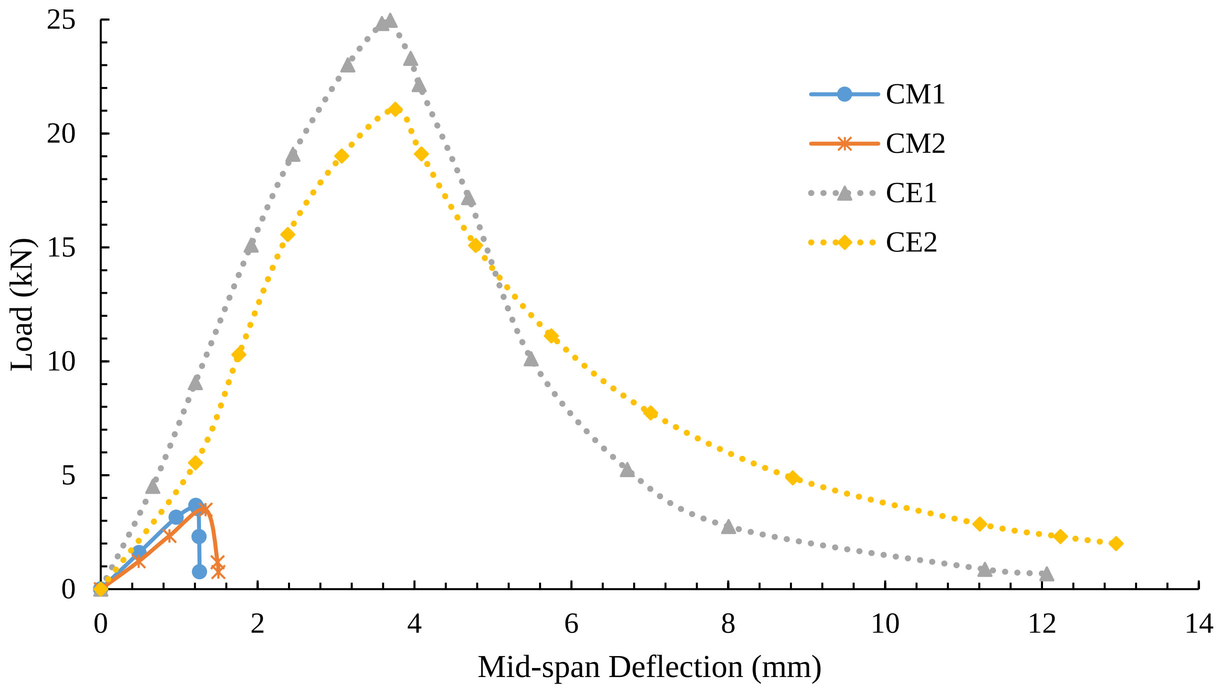

Fig. 4.13 Load-deflection response of Series #1 beams

Series #2

It is observed that in the case of masonry beam with cement mortar as bed joint, cracks have originated in the shear zone from the top and propagated towards the end. After this, the FRP sheet has de-bonded in the tension zone of the beam as shown in Fig. 4.14.

On the other hand, in the case of masonry beam with ECC as bed joint, flexural and shear cracks started at the mid span. Subsequently, new shear cracks were originated from the top and propagated towards the end. After this, the FRP sheet has de-bonded in the tension zone of the beam as shown in Fig. 4.15. The similar response was observed in the remaining specimens of the same series. After having seen this, the beams were strengthened in the shear by U-wrapping (Series #3). The load-displacement response of Series #2 is shown in Fig. 4.16. In Series #2, load-carrying capacity of the beams has increased and failure occurred because of de-bonding of FRP sheet.

Fig. 4.14 Shear failure of Series #2 beam with cement mortar as bed joint (CM-CFB)

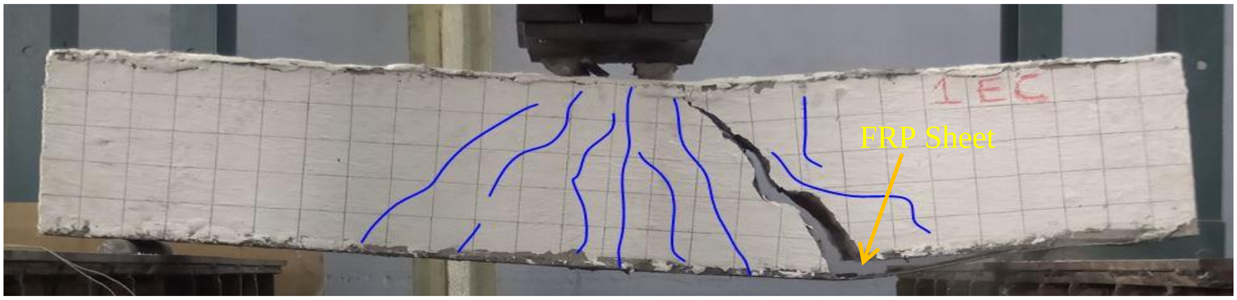

Fig. 4.15 Shear failure of Series #2 beam with ECC as bed joint (CE-CFB)

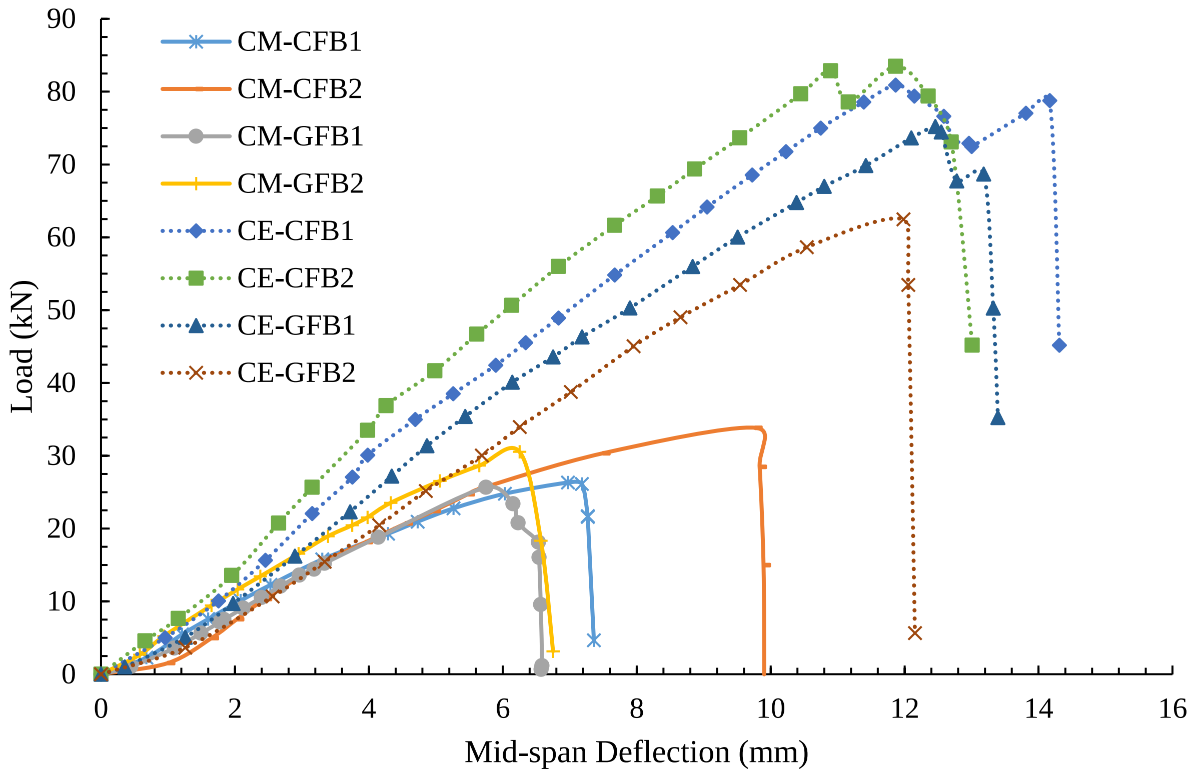

Fig. 4.16 Load-deflection response of Series #2 beams

Series #3

In this series, the primary patterns of cracking were similar to that of the Series #2 beams. In the case of cement mortar as bed joint, the crack developed in the top of the beam and propagated inclined at 45° towards the shear zone. The new shear cracks, followed by widening of the previous shear crack, were formed leading to the separation of FRP from the beam. Finally, the beam has failed in shear due to FRP delamination as illustrated in Fig. 4.17. The similar behavior has been shown in the case of ECC as bed joint. The failure pattern of masonry beam with ECC as bed joint is shown in Fig. 4.18. The load-deflection response of the Series #3 beams is shown in Fig. 4.19. It is seen that the mid-span deflection behavior is erratic which may be due to progressive failure of fibers as the load continuously increasing till the failure. The load carrying capacity of the beam has increased by discrete U-wrapping with respect to Series #2 beams but the mode of failure is shear. Therefore, beams were strengthened by continuous U-wrapping with FRP.

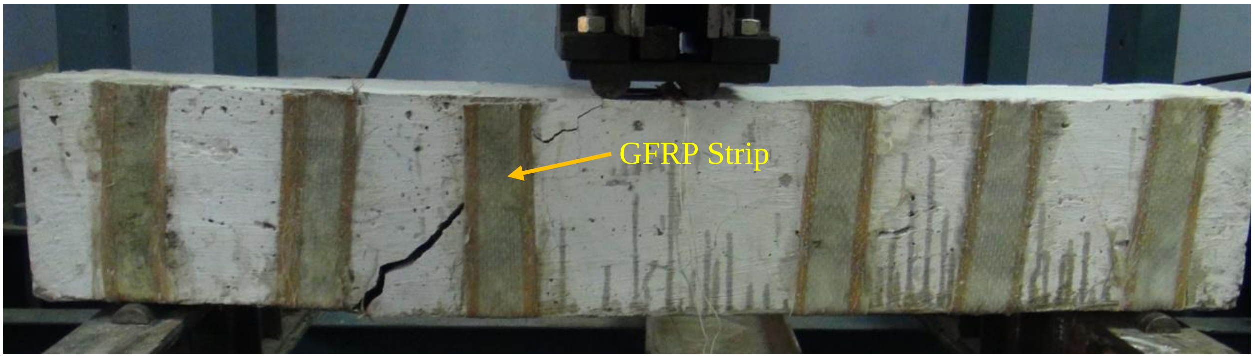

Fig. 4.17 Shear failure of Series #3 beam with cement mortar as bed joint (CM-GUB)

Fig. 4.18 Shear failure of Series #3 beam with ECC as bed joint (CE-GUB)

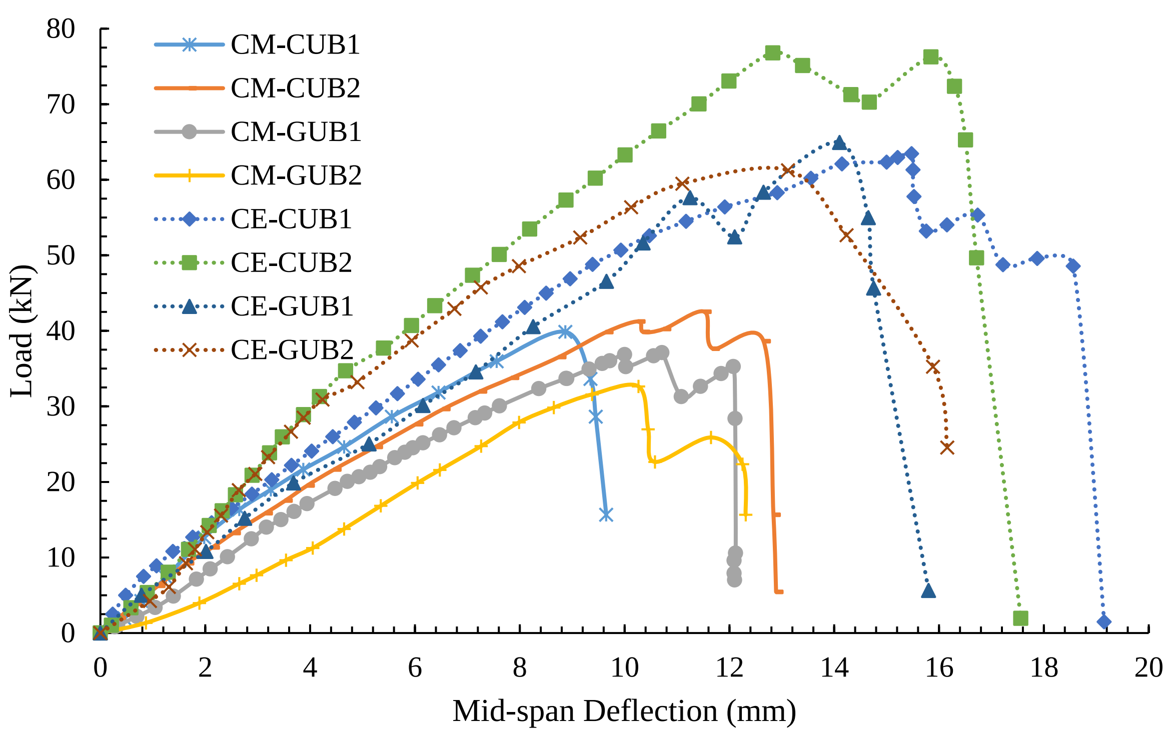

Fig. 4.19 Load-deflection response of Series #3 beams

Series #4

In the case of masonry beam with cement mortar as bed joint, the visibility of crack patterns of the beam with that strengthened by U-wrapping was hindered because of continuous wrapping of FRP. The specimen failed due to masonry crushing at the extreme compression side as shown in Fig. 4.20. Conversely, in the case of masonry beam with ECC as bed joint, flexural cracks developed inside the FRP wrapping, and at the failure load, FRP sheet ruptured as shown in Fig. 4.21. After the rupture of FRP sheets, beams have suddenly collapsed upon the application of further load. This indicates the effectiveness of FRP fabric sheet affected continuously in changing the mode of failure from shear (Series #3 beams) to flexural failure (Series #4 beams). The load-deflection response of Series #4 specimens is shown in Fig. 4.22. It may be noted that the progressive failure of the fiber is observed as the load continuously increasing till the failure. It is observed from the experimental results that strengthened masonry beams with continuous FRP U-wrapping considerably improved the load-carrying capacity of the beam.

Fig. 4.20 Failure mode of Series #4 beam with cement mortar as bed joint (CM-GCB)

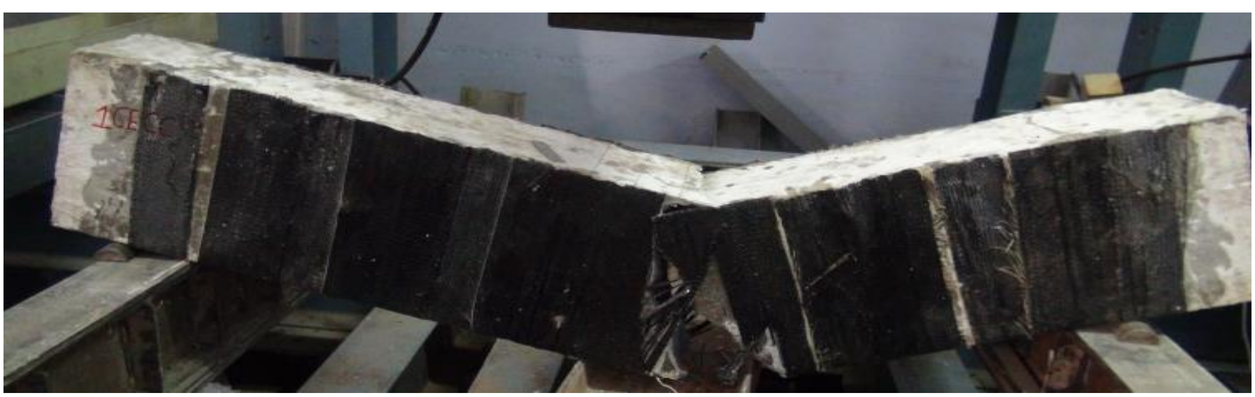

Fig. 4.21 Failure mode of Series #4 beam with ECC as bed joint (CE-CCB)

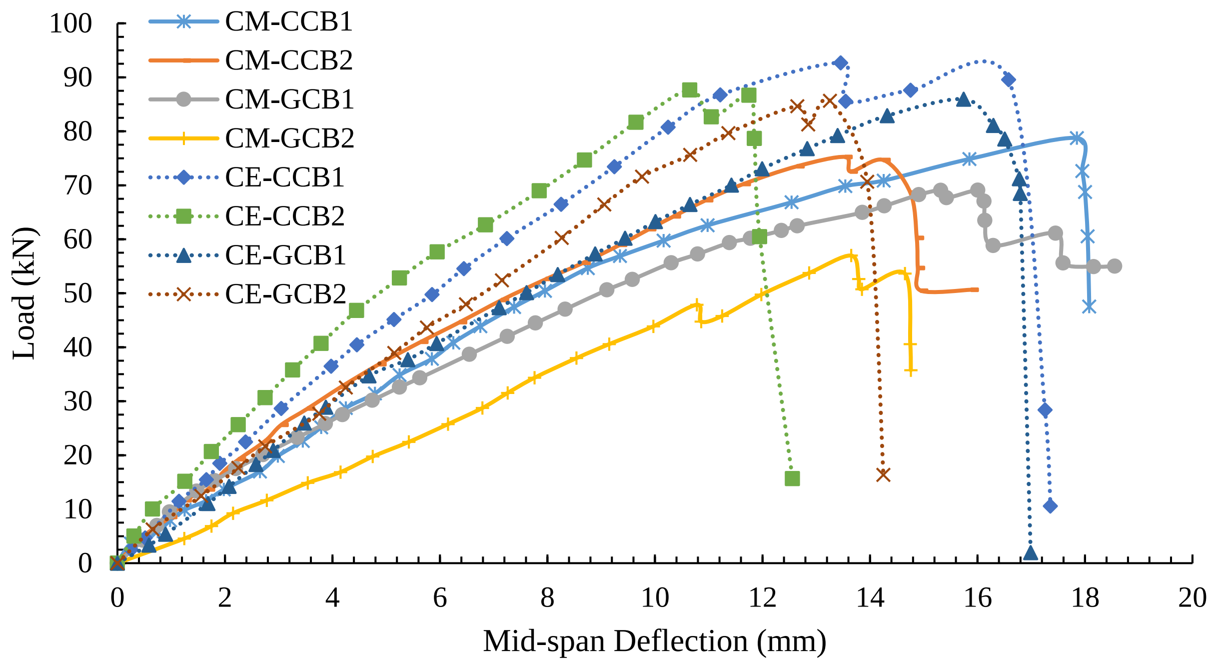

Fig. 4.22 Load-deflection response of Series #4 beams

Series #5

In the reinforced masonry beam with pultruded CFRP bars, the first crack appeared in the vertical direction close to the left side of loading point, as shown in Fig. 4.23. As the load was increased, the cracks widened in the tension zone and propagated towards the compression face. On the other hand, in the case of reinforced masonry beams with hand lay-up CFRP bar, vertical flexural cracks developed in the mid span zone. The normal flexural failure was observed in the specimens. The failure pattern of the reinforced masonry beams with hand lay-up CFRP bar is shown in Fig. 4.24. The similar response was observed in the remaining specimens of the same series. The load-deflection response of the Series #5 specimens is shown in Fig. 4.25. In the reinforced masonry beam with pultruded CFRP bars, large deflection was observed after the peak load due to slippage of CFRP bars, as shown in Fig. 4.25. The slippage occurred in the reinforced masonry beam due to the smooth surface of CFRP bars. In the case of reinforced masonry beam with hand layup CFRP bars, the response of the specimens 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 bars, followed by another load decay. Finally, the rapid drop in the load response was observed as shown in Fig. 4.25.

Fig. 4.23 Failure mode of reinforced beam with pultruded CFRP bars (Series #5)

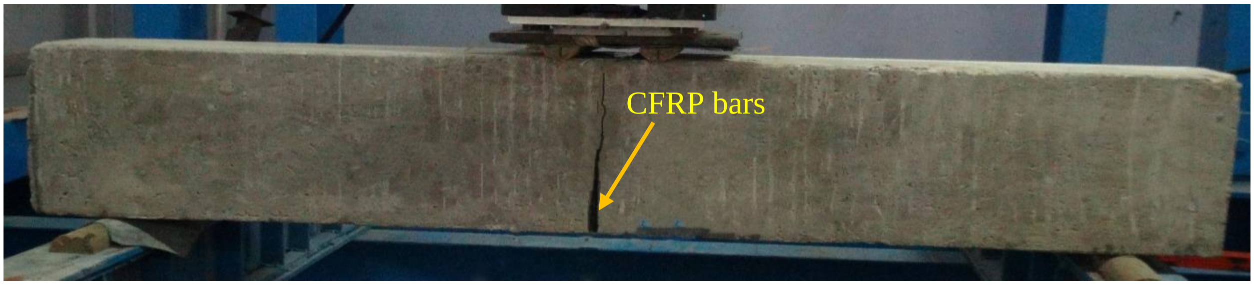

Fig. 4.24 Failure mode of reinforced beam with hand layup CFRP bars (Series #5)

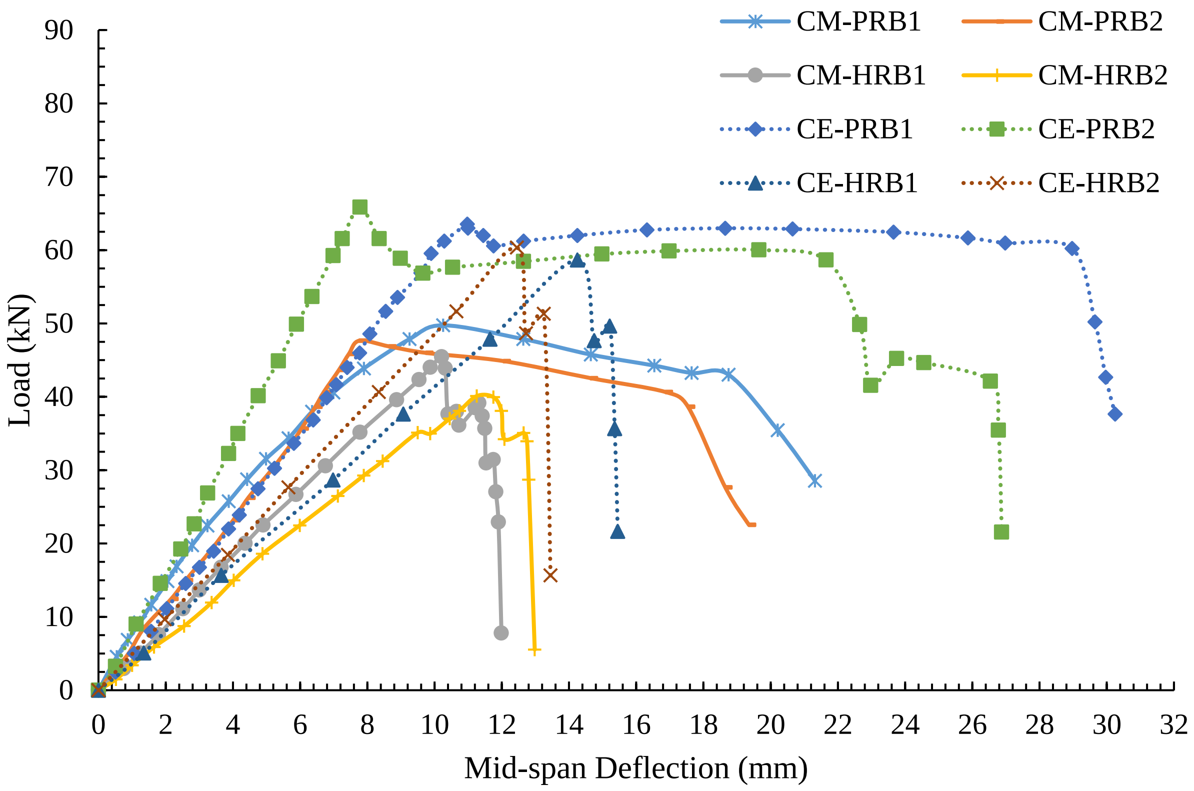

Fig. 4.25 Load-deflection response of Series #5 beams

Series #6

In the NSM strengthened (Pultruded CFRP) masonry beam with cement mortar as bed joint, shear cracks started at the left side of loading point and propagated towards the support point concurrently new shear cracks started in the right side also as shown in Fig. 4.26. The NSM strengthened masonry beams with hand lay-up CFRP bars have shown the similar responses and failed in the shear.

On the other hand, in the case of NSM strengthened masonry beam with ECC as bed joint, primary patterns of cracking were similar to that of the beam with cement mortar as bed joint. The crack developed at the top of the beam at loading point and propagated at an angle of 45° towards the end support. The shear cracks widened as the load increased. Finally, the beam failed in shear as illustrated in Fig. 4.27. The load-deflection response of the Series #6 beams is shown in Fig. 4.28. It was found that the NSM strengthened system applied to masonry beams have significantly increased the load carrying capacity and ductility.

Fig. 4.26 Failure mode of NSM strengthened beam with pultruded CFRP bars

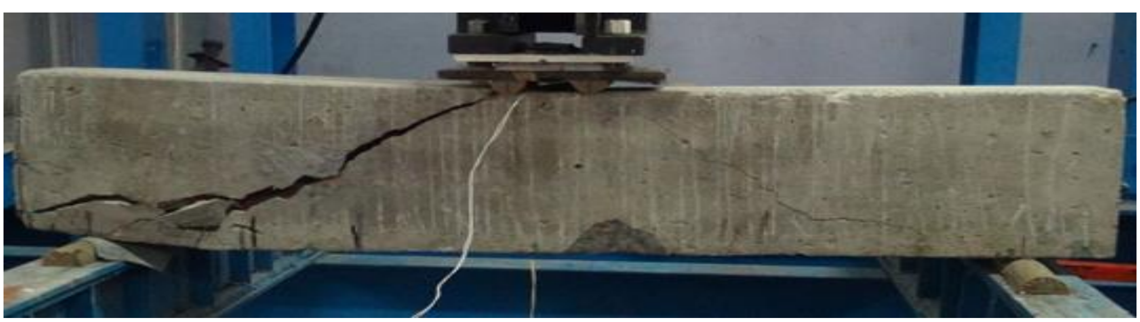

Fig. 4.27 Failure mode of NSM strengthened beam with hand lay-up CFRP bars

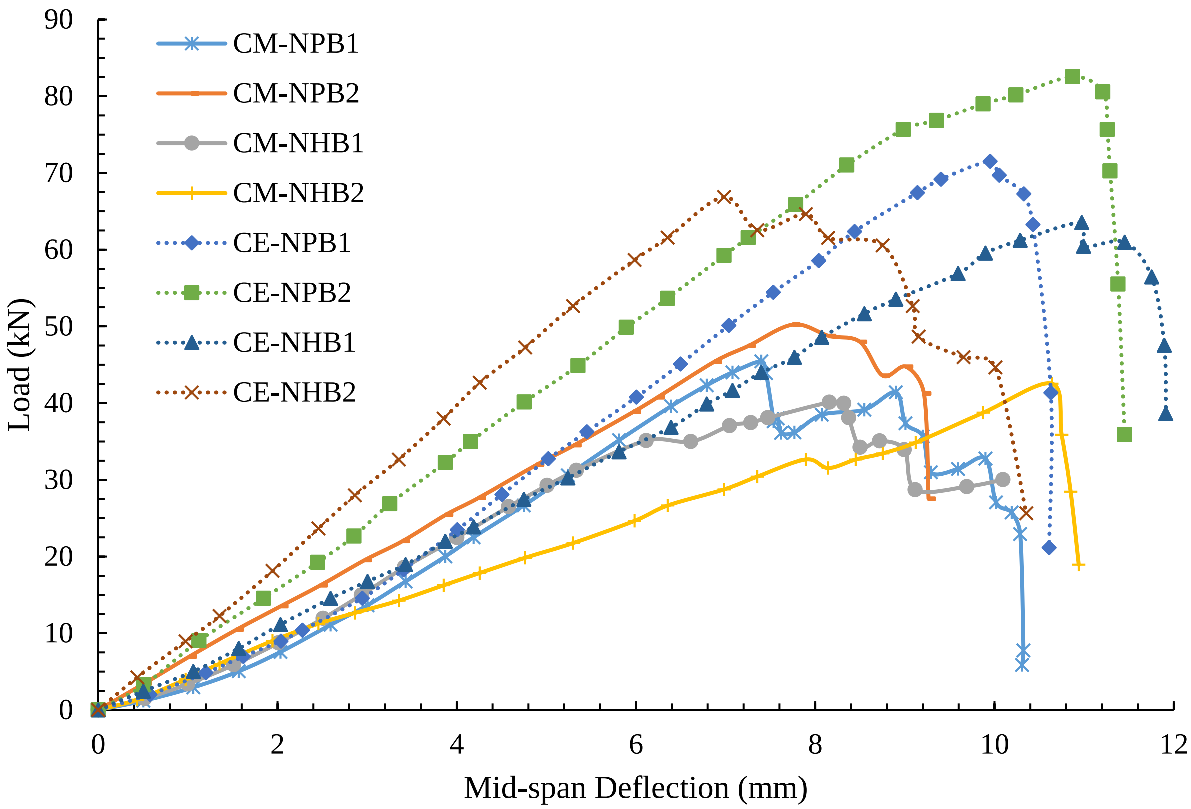

Fig. 4.28 Load-deflection response of Series #6 beams

4.3 Flexural Response of Masonry Beams Strengthened with ECC Sheet

This section demonstrates the effectiveness of precast ECC sheet for strengthening of masonry beams by bonding them on tension face as well as both on the tension and compression faces like a sandwich beam. Two types of bonding materials have been used, i.e., epoxy and cement mortar for bonding the ECC sheet with masonry beam. This section deals with the specimen preparation, installation process, experimental test set-up, and results and discussion of the control and strengthened masonry beams.

4.3.1 Specimen preparation

A total of 11 burnt-clay brick masonry beams of 230 mm (width) × 110 mm (depth) cross-section and 860 mm length were cast. The masonry beams have nine brick units with eight mortar joints, each of approximately 20 mm thickness. Out of the 11 beams, 4 beams were strengthened on the bottom (tension face) with ECC sheet of 35 mm thickness and 4 beams were strengthened on both sides (compression and tension faces) like a sandwich beam with ECC sheet of 35 mm thickness.

The other three beams acted as control beams (i.e., unstrengthened). Two types of bonding materials were used for strengthening purpose i.e., epoxy and cement mortar. The thickness of epoxy and cement mortar were maintained approximately 1 mm and 8 mm, respectively. Portland pozzolana cement and local river sand were used in the mix proportion of 1:3 (cement: sand) for the casting of masonry beams. The material properties of the Portland pozzolana cement and local river sand are described in Chapter 3 (Section 3.3). The burnt clay bricks of C3 type and cement mortar of M1 (See Chapter 3) were used in this study. Polyester-ECC was used for casting of ECC sheets and properties of Polyester-ECC are given in Chapter 3 (Section 3.5). The beams were cured for 28 days before testing. In addition to the masonry beams, two numbers of ECC sheets of size 860 mm (length) × 230 mm (width) × 35 mm (depth) were also tested under 4-point flexural loading to predict the flexural response of ECC sheets.

4.3.2 Installation of ECC sheets on masonry beams

Installation of ECC sheets on the faces of masonry beams was executed using two types of bonding agents resulting in two sets of strengthened beams; (i) tension strengthened; and (ii) sandwich beams. In tension strengthened beam, the bonding agent epoxy/cement mortar was applied on tension face and ECC strip of 35 mm thickness was bonded to the tension face. In the case of sandwich beam, tension as well as compression faces was levelled and applied with specific bonding agent, i.e., epoxy/cement mortar before bonding ECC strip on both the faces. After bonding the ECC strips, the beam specimens were left for curing for 28 days.

4.3.3 Test setup

All beams were tested under four-point loading using servo hydraulic actuator of capacity 200 kN and subjected to monotonic load till failure. The vertical deflection was measured by linear variable differential transducers kept at soffit of the beam at the mid-span. The beams were subjected to a ramp loading at a displacement control rate of 0.05 mm per sec till failure. The schematic of 4-point loading arrangement for beams is shown in Fig. 4.29. This arrangement of 4-point loading ensured desired flexural failure in the test beam.

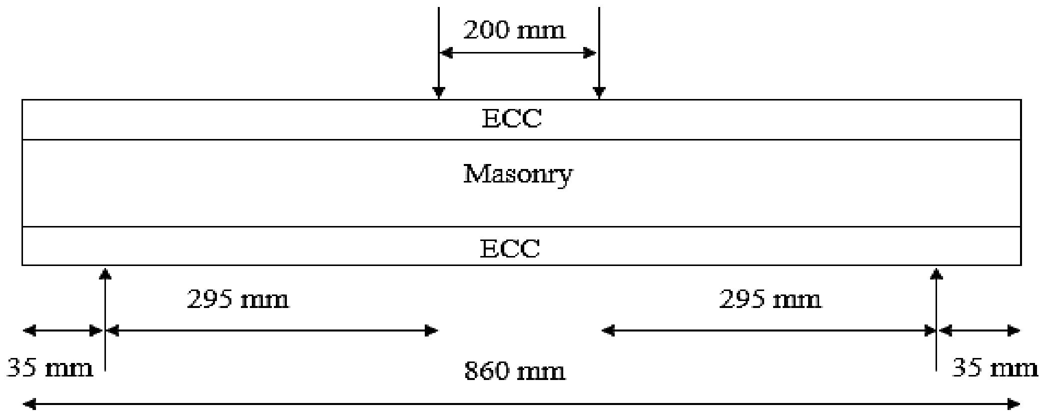

Fig. 4.29 Schematic loading arrangement for beams

4.3.4 Result and discussions

Table 4.3 depicts the average experimental test results along with the descriptions of beams used in this study. As shown in Fig. 4.30, the control beam, i.e., the beam without external strengthening, failed due to rupture of brick units at an average failure load of 2.18 kN. The tension cracks initiated from the bottom tip of left side of loading point and propagated towards the top of the beam. The sudden failure of the control masonry beams was observed. The tension strengthened beam (ET) with epoxy as bonding agent shows higher flexural strength approximately two times of the corresponding beam (CT) with cement mortar as bonding agent. The delamination was the mode of failure in tension strengthened masonry beam with cement mortar as bonding agent as shown in Fig. 4.31. In sandwich beams with epoxy as bonding agent, cracks originated in the flexure zone from the bottom and propagated towards the end as shown in Fig. 4.32. While in sandwich beams with cement mortar as bonding agent, a vertical crack developed near the left side of loading point due to stress concentration and led to flexural failure of the beam as shown in Fig. 4.33. Experimental responses in the form of load versus deflection have been presented in Fig. 4.34. It is shown that the load-carrying capacity and stiffness of ECC strengthened masonry beams has improved significantly.

Table 4.3 Experimental results of masonry beams strengthened with ECC sheet

Beam designation	Beam description	Experimental		P_{SB}/P_{CB}*	δ_{SB}/δ_{CB}**	Mode of failure
		Peak load (kN)	Mid-span deflection (mm)			
M	Masonry control beam of depth 110 mm	2.18	0.99	-	-	Sudden-flexural
ECC	ECC control beam of depth 35 mm	0.65	2.66	-	-	Flexural
ET	Epoxy bonded tension strengthened beam with ECC thickness 35 mm on tension face	7.70	2.80	3.53	2.83	Flexural
CT	Cement mortar bonded tension strengthened beam with ECC thickness 35 mm on tension face	3.90	2.30	1.79	2.32	Delamination
ECT	Epoxy bonded Sandwich beam with ECC thickness 35 mm on both faces	11.25	2.23	5.16	2.25	Flexural
CCT	Cement mortar bonded Sandwich beam with ECC thickness 35 mm on both faces	9.58	2.32	4.39	2.34	Flexural

* P_{SB} = Load carrying capacity of strengthened masonry beam

* P_{CB} = Load carrying capacity of control masonry beam

**δ_{SB} = Mid-span deflection of strengthened masonry beam

**δ_{CB} = Mid-span displacement of control masonry beam

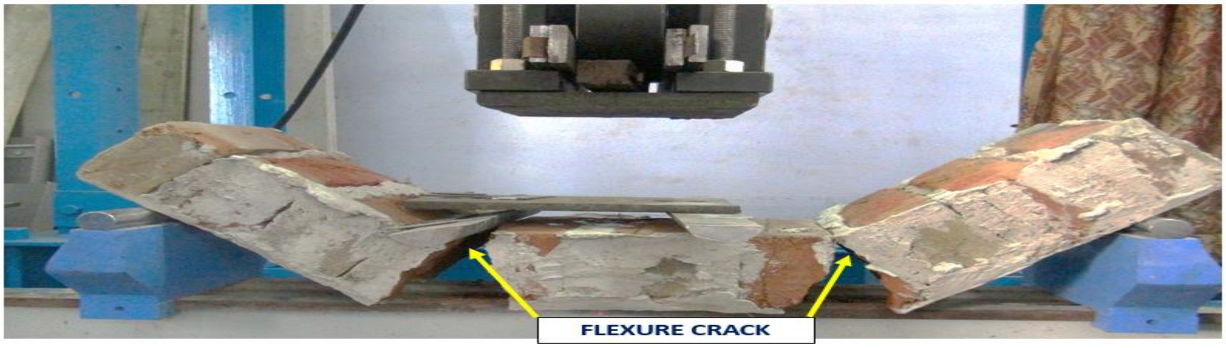

Fig. 4.30 Failure of control masonry beam

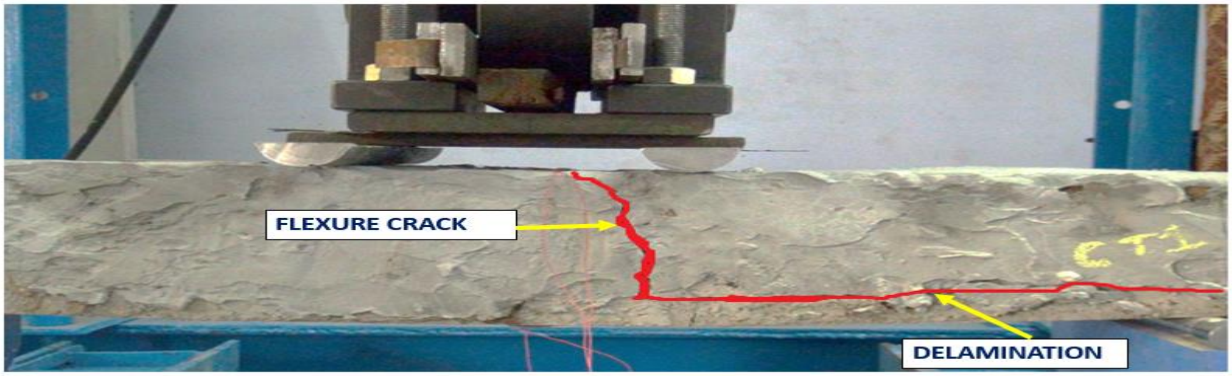

Fig. 4.31 Delamination of tension strengthened masonry beam with cement mortar as bonding agent

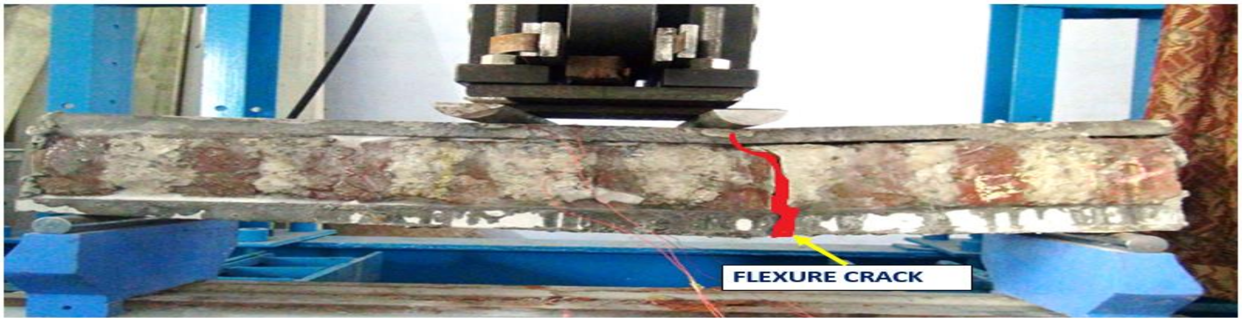

Fig. 4.32 Failure of sandwich beam with epoxy as bonding agent

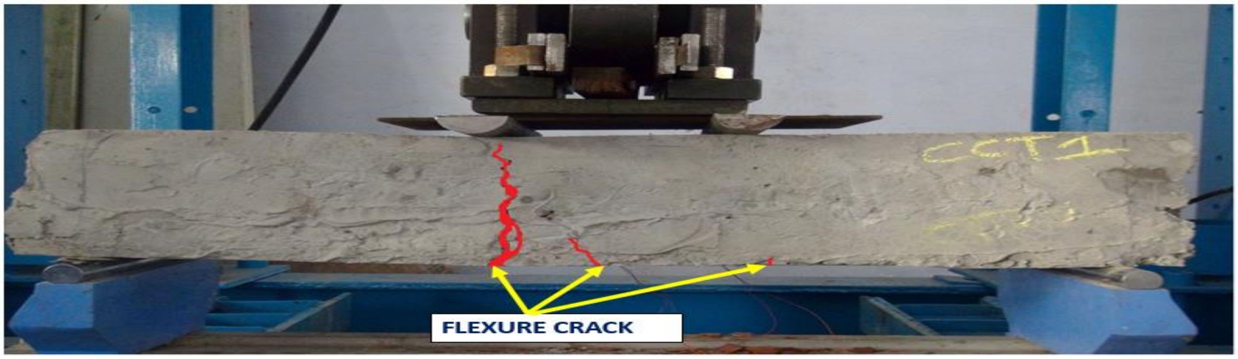

Fig. 4.33 Failure of sandwich beam with cement mortar as bonding agent

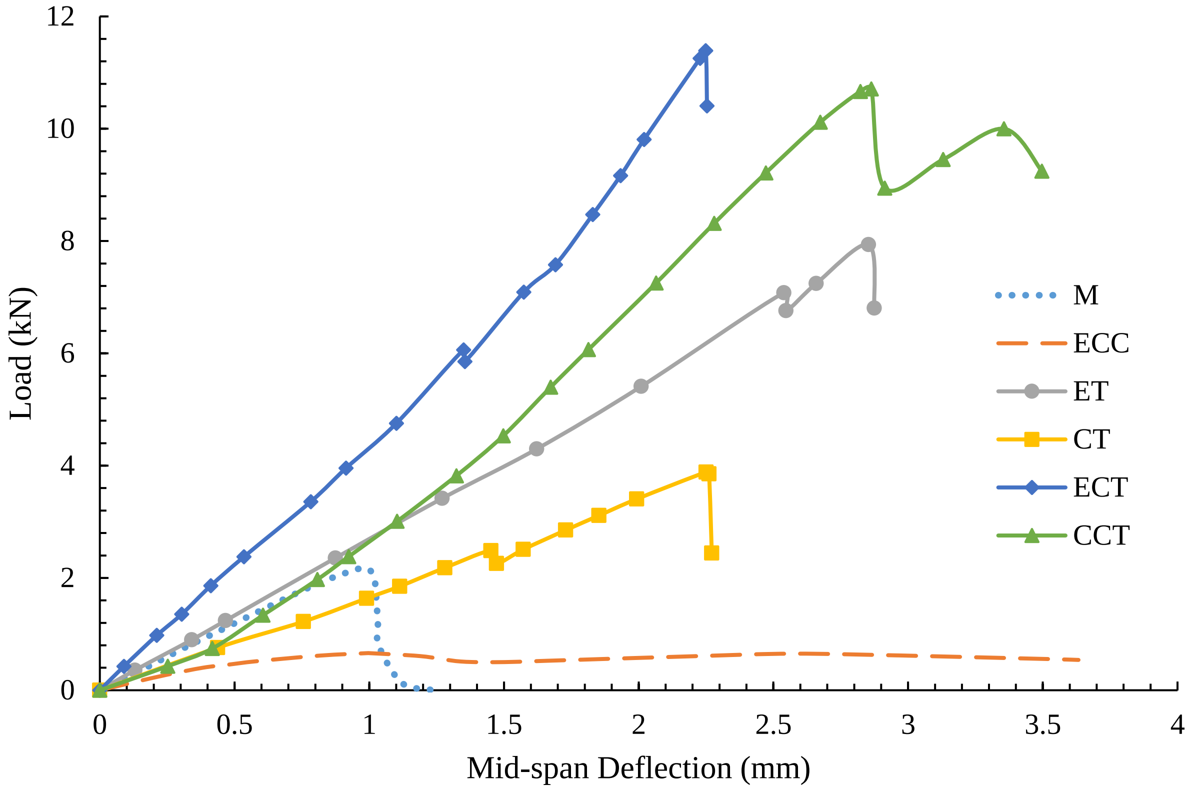

Fig. 4.34 Load-deflection response of control and strengthened masonry beams

4.4 Concluding Remarks

The experimental results of masonry beams strengthened with FRP and ECC shows the increase in flexural performance in terms of load capacity in comparison with unstrengthened/control masonry beams. The following concluding remarks are made based with the results of this chapter:

- Load carrying capacity of control masonry beams with ECC as bed joints is found to be about 6 times of that of masonry beam with cement mortar as bed joints.
- Masonry beams with ECC as bed joints exhibit ductile performance, and ductility has increased by 9 times of that of masonry beam with cement mortar as bed joint. Therefore, ECC could be used in replacement of cement mortar.
- Masonry beams strengthened with fabric sheets demonstrate a drastic improvement in their load carrying capacity and ductility.
- Load carrying capacity of flexural strengthened masonry beam with one ply of carbon fabric is found to be about 8 times of that of control masonry beam.
- The continuous U-wrapping along with flexural strengthening is more effective technique, which has increased the load carrying capacity of the beam about 21 times of that of control beam.
- Use of continuous CFRP/ GFRP wrapping for shear strengthening changes the mode of failure from undesirable shear failure to the most desirable flexural failure.
- Reinforced masonry beams with three CFRP bars in the tension zone demonstrated a drastic improvement in their load carrying capacity and ductility. Load carrying capacity has increased by 2.5 times of that of unreinforced masonry beams with ECC as bed joint.
- The load carrying capacity as well as ductility of masonry beams increases significantly when reinforced with CFRP bars.
- The NSM strengthening technique using CFRP rods is very effective in enhancing the flexural strength of masonry beams.
- NSM strengthened masonry beams with ECC as bed joint has improved their load carrying capacity, almost three times of unstrengthened masonry beam with ECC as bed joint.
- For a given bonding agent of particular thickness, the load carrying capacity of sandwich beam is higher in comparison to the corresponding tension strengthened beam.

- Epoxy is observed to be better bonding agent over cement mortar especially for sandwich beams with respect to the load capacity, flexural stiffness, and deformability.
- Epoxy bonded beams have higher flexural load carrying capacity compared to the cement mortar bonded beams.
- Load carrying capacity of epoxy bonded sandwich beam with ECC sheet is found to be about 5 times of that of unstrengthened masonry beam.