Malaysian
Journal Of Civil
Engineering

Full Paper

Flexural Capacity Assessment of Brick Aggregated Pre-cracked RC Beam Strengthened with Carbon Fiber Polymer

Article history
Received
22 June 2018
Received in revised form
21 November 2018
Accepted
2 January 2019
Published online
1 April 2019

Niaz Md Mamun[a], G. M. Sadiqul Islam[b]* & Md Jahangir Alam[b]

[a]Department of Disaster & Environmental Engineering, Chittagong University of Engineering & Technology (CUET), Chittagong – 4349, Bangladesh
[b]Department of Civil Engineering, Chittagong University of Engineering & Technology (CUET), Chittagong 4349, Bangladesh

*Corresponding author
gmsislam@cuet.ac.bd

Abstract

Ageing and improvements to design code has led to many existing RC structures made of locally available brick aggregates are now found structurally deficient and are in need of rehabilitation. This research emphases on flexural capacity assessment and investigation of failure modes of Carbon Fiber Reinforced Polymers (CFRP) strengthened brick aggregated RC beams. Flexural performance of the RC beam specimens are evaluated using four point bending method. Six RC beams (initially cracked) with CFRP strengthening were tested by varying (i) type of CFRP, (ii) reinforcing area, (iii) anchorage type; and (iv) number of CFRP layers. Two beams were tested as control specimens. Unidirectional carbon fiber sheet (Tow Sheet) and individually hardened continuous fiber strands woven into sheet form (Strand Sheet) were used. Simple flexure failure was obtained for unstrengthened RC beams while end plate and interfacial debonding were observed for the initially cracked CFRP strengthened RC beams. Strengthening of pre-cracked beams using Strand Sheet gave better performance compared to Tow sheet. Overall flexural strength improvement of CFRP strengthened beams varied from 12% to 34% with respect to unstrengthened beams depending on strengthening methods.

Keywords: CFRP, brick aggregate, pre-cracked, flexural capacity, tow sheet, strand sheet

1.0 INTRODUCTION

Concrete primarily consist of cement, aggregates and water. Crushed stone and sand are generally used as coarse and fine aggregates. These are mainly filler material but increase the sturdiness of concrete (Neville, 2011). Hence, the aggregates particularly coarse aggregate plays an important role in the strength characteristics of concrete (Al-Oraimi *et al*., 2006). The coarse aggregates are usually derived from natural sources but in Bangladesh and parts of West Bengal, India where natural rock deposits are scarce as well as costly; burnt-clay bricks are widely used as alternative of stone aggregate. Use of crushed brick (brick aggregate) concrete is quite common here in construction of rigid pavement, small-to medium-span bridges and culverts, even building up to six stories (Effat, 2016). Concrete with compressive strength around 20 MPa can easily be achieved by using crushed normal strength brick and following the usual practice of concrete-making. Having less unit weight of brick chips aggregate the concrete made with this would result a less dead load to the structure which is also an added benefit (Rashid *et al*., 2008).

During early 70's, immediate after independence lots of structure were built using brick aggregate in Bangladesh. Many of those buildings are currently being used as industry and require improving safety margin by strengthening the foundation and the structural members. Usually strengthening of existing concrete structures may require carrying higher design loads, improvement for strength loss due to deterioration, poor initial design and construction deficiencies or due to lack of maintenance (FIB Bulletin 14, 2001). In many case the failure of a structure initiate from flexural members such as slab or beam; hence failure of beam or slab is a major issue.

The most common material used in FRP strengthening is Continuous Fiber Sheet (CFS) method using FRP sheet (Mirmiran *et al*., 2004). Use of CFRP sheets has been gained interest in recent years because of its high strength to weight ratio, high stiffness, light weight, flexibility and also due to corrosion resistance (Lacasse *et al*., 2001, ACI, 2002). However, despite having high reinforcing effect, the continuous fiber sheet method has limitations to be taken care of such as quality, application period, cost, and ease of handling (Kobayashi *et al*., 2009). CFRP strip method has some limitations such as small bonding area, low reinforcing effect compared to CFS method.

To overcome these CFRP strand sheet was introduced which contains bunch of individually hardened continuous fiber strands and has certain features such as sufficient resin matrix impregnation, high fiber mass per unit area, decrease in application failure, high reinforcing effect and overlap splice same as CFS method (Kobayashi *et al*., 2009). An experiment (Komori *et al*., 2012) showed that interfacial fracture energy of concrete is higher than usual value of CFS when strand sheet is used with different adhesive. The study also showed that effective bond length increases with the number of strand sheet layers.

The load carrying capacity of CFRP increase with number of layers of carbon fiber sheets up to six sheets (Shahawy *et al*., 1996; Shehata *et al*., 2001 and Toutanji *et al*., 2006). Studies (Smith and Teng 2002; Buyukozturk and Yu, 2006 and Obaidat, 2011; Hollaway, 2011; Zhang *et al*., 2012) have been performed to explain each premature debonding failure mode; however, the exact mechanism for the premature bond failures has not yet been established due to numerous influencing factors affecting the bond strength at the FRP-concrete interface. Various anchor systems such as bolts, mechanical anchors, or U-shaped sheets have been investigated as end anchors for the EB system (Hollaway and May, 1999; Teng *et al*. 2002).

Over the years numerous researches of FRP strengthening system have been conducted on virgin RC beams. Only a few researches are performed on pre cracked RC beams (Arduini and Nanni, 1997; Buyukozturk and Hearing, 1998; Jayaprakash *et al*., 2008). Common observed failures are due to debonding of FRP plate or ripping of the concrete cover in virgin beam specimens (Teng *et al*., 2003). Intermediate crack debonding and end peeling always initiate at flexural or shear crack in a strengthened member (Ueda *et al*., 2012). These failure modes are sometimes more critical in pre-cracked beam specimens. Interfacial shear and normal stress concentration at FRP cut-off points and at flexural cracks along the beam causes premature failure modes (Esfahani *et al*., 2007). However, no studies have been conducted on strengthening of brick chips aggregated concrete structural members.

This study worked on brick aggregated high strength pre-cracked beams subsequently strengthened with CFRP materials. Four point bending test was carried out to evaluate the strength enhancement and failure mechanism. Beam specimens with adequate shear reinforcement were fabricated in the laboratory to ensure flexural failure. Two forms of unidirectional CFRP material viz. flexible fabric (tow sheet) and rigid (strand sheet) were used. Beams were strengthened by varying number of plies, addition of anchorage and variation in thickness of adhesive paste. The aim of this study is to evaluate the strength enhancement/recovery and deflection of pre-cracked beams using these CFRP materials. Comparison of cost effectiveness of these two types of materials was also studied.

2.0 MATERIALS

2.1 Concrete and Reinforcing Steel

Concrete mix design with normal weight aggregate (crushed brick aggregate) was conducted as per American Concrete Institute (ACI-211, 2009). Trial mixtures were prepared to obtain target strength of 35 MPa at 28 days considering a slump value of 100-125 mm. All the aggregates brought to the saturated and surface dry (SSD) condition before mixing. The mix proportion used is 375 kg of Ordinary Portland Cement, 680 kg of sand and 900 kg of crushed brick chips aggregate to produce 1 m^3 of fresh concrete. Polycarboxylic Ether (PCE) based superplasticizer was used (0.6% of cement content) to achieve high target strength at desired slump. For every trial mixer a 0.04 m^3 volume concrete was prepared using a concrete mixer.

Appropriate quantity of crushed brick aggregate (SSD), fine aggregates (SSD) and cement, were first dry mixed for a period of 2 minutes. The superplasticizer was mixed thoroughly with the mixing water and added to the mixer. After mixing, the workability of concrete was determined using slump cone. Cylinder specimens having 150mm diameter and 300mm height were prepared for compressive strength test. The specimens prepared were tested after 7 and 28 days curing under water. Once the target slump was achieved all the beams were casted from a single batch of concrete mix. The beam specimens were wet cured by covering with jute bag for 28 days. From the same concrete samples, standard cylinder specimens (φ150 mm×300 mm) were also tested in the laboratory to verify the concrete compressive strength. The average compressive strength of concrete cylinder was found to be 39.4 MPa at 28 days.

Two 12-mm deformed steel bars were placed as flexural steel while two 10-mm rebar served the hanger purpose. Average ultimate tensile strengths of the 12-mm and 10-mm rebar were measured 624.5 MPa and 663.4MPa, respectively.

2.2 CFRP Reinforcements

Both sheet and pre-cured CFRP materials were used. Uni-directional CFRP strand sheet and Tow sheet were used. Table 1 gives the properties of CFRP materials (Forca Towsheet Catalogue, 2015).

Table 1 Properties of CFRP materials

Properties	CFRP Sheet (fabric)	CFRP Strand Sheet
Fiber areal weight (g/m^2)	200	610
Fiber density (g/cm^3)	1.8	1.8
Design thickness(mm)	0.111	0.339
Design tensile strength (N/mm^2)	3400	4340
Tensile modulus (N/mm^2)	2.45×10^5	2.45×10^5

2.3 Adhesive

FB-E7S (SH), epoxy based adhesive paste was used for CFRP strand sheet while FR E3P (SH) an epoxy based resin was used for bonding the CFRP fabrics with the concrete. The material properties are shown in Table 2 based on the Nippon Steel Composite Co Ltd. technical data sheet.

Table 2 Properties of Adhesive

Properties	Adhesive paste FB-E7S (SH)	Epoxy Based Resin FR-E3P (SH)
Main: Hardener(weight ratio)	4:1	2:1
Flexural Strength (N/mm²)	1.8	>40
Tensile Strength (N/mm²)	35.8	>30
Usage (gm/m²)	1300	600

3.0 EXPERIMENTAL METHODS

3.1 Design and Fabrication of Beams

Eight identical rectangular beams dimensioning 1016mm × 203.2mm×152.4mm were fabricated. The specimen parameters details are given in Figure 1. The required moment capacity (16.72 kN-m) and the material strengths were known to design the beam. The required x-section and reinforcement were obtained from those known data. The beams were designed in such a manner that it does not act as a deep beam (beams with clear spans less than or equal to 4 times the total member depth).

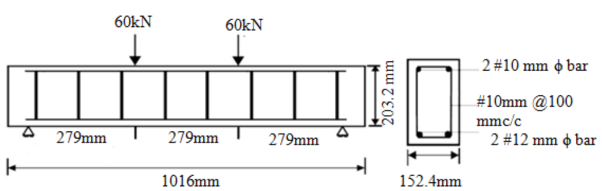


Figure 1 Geometry, arrangement of reinforcement and load of the tested beams

The required reinforcement was calculated considering minimum reinforcement and tension failure mode. Each beam specimen consists of two steel bars of 10mm diameter in compression zone while two bars of 12mm diameter at tension zone. 10 mm bar was used as stirrups and placed at 100 mm spacing throughout the beam. Shear reinforcement was provided more than minimum requirement to ensure flexural failure rather than shear.

Table 3 Categorization of beam specimens

Designation of specimen	No. of specimens	Remarks
Control Beam	2	Used as a control beam.
BTS-1, BTS-2, BTS-3	3	Beams were strengthened with Tow sheet
BSS-1, BSS-2, BSS-3	3	Beams were strengthened with Strand sheet

Depending on the use of CFRP materials, specimens are classified in two groups and designated as BTS and BSS. Categorization of beam specimens is shown in Table 3. The Control Beams (CB) were without application of CFRP materials. Each of the BTS and BSS group contained three specimens. All the strengthened specimens were pre-cracked before strengthening.

3.2 Application of CFRP Reinforcement

Debonding implies ample loss of composite action between concrete and FRP. This prevents full utilization the benefits of FRP-concrete system and may lead to failure before the design load is reached (Buyukozturk and Yu, 2006). Debonding may occur in the strengthened beam due to inappropriate surface preparation, therefore additional attention is required for this step. Surface of the beam specimens was grinded uniformly to remove undulations or irregularities using angle grinder. The sharp edges of exposed aggregate were rounded to radius of at least 10 mm. Then the embedded dust particles were removed by air blow and the beam surface was dried properly to apply the CFRP composites.

Figure 2(a) Surface preparation of beam specimen

Figure 2(b) Application of epoxy based resin

Figure 2(c) Application of putty filler on beam surface

Figure 2(d) Placing of tow sheet

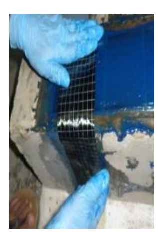


Figure 2(e) Installation of end anchorage

Figure 2(f) Demonstration of strengthening on an existing beam

Figure 2 (g) Applying expoxy adhesives

Figure 2(h) Beam specimens after strengthening

Initially, epoxy based primer was applied to concrete body of group BTS with an approximate thickness of 1 mm using brush. Then putty filler was applied on it to make smooth and also fill the pores, if present. Steel scrapper was used to fill up the pores appeared. After that, saturated resin was applied at an appropriate thickness of about 1 mm with roller. The CFRP materials were applied after cutting at desired shape and dimensions. Then another layer of resin was gently applied on the applied CFRP material over the concrete. Ribbed roller was used to squeeze out the excessive resin. For the BSS group, the epoxy adhesive was applied to the surface to fill the pores with epoxy based adhesive using scrapper. Strand sheets were measured and cut into desired shape and gently pressed to the concrete substrate. After strengthening the flexural area, CFRP strip shear reinforcement was applied to the specimens using epoxy resin in two layers.

3.3 Four Point Bending Test Setup

All the eight (8) beams are tested under simply supported end conditions. 'Four Point Bending' method was applied for testing. In this system load application was symmetrical. The span was divided into three equal parts (Figure 2). The testing of beams was performed using Universal Testing Machine (UTM). Load was applied to the beam with hydraulic jack and the data was recorded from load cell. Three dial gauges were placed to record deflection, one at the midpoint and other two were placed at the two loading points.

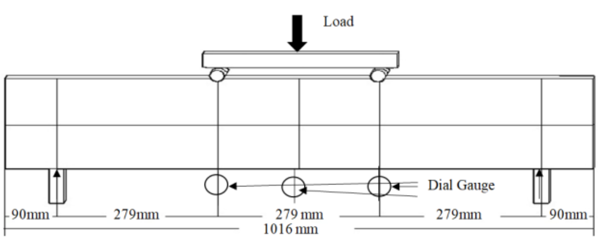


Figure 3 Four-point bending test setup showing location of dial gauge on the beam

Two control beams were tested after 28 days of curing to observe the safe load and the ultimate load. The remaining six beams are loaded and initial crack load were determined.

Figure 4(a) Reinforcement placed in the mould

Figure 4(b) Specimen after surface finishing

Figure 4(c) Test setup of beam

4.0 RESULT AND DISCUSSIONS

4.1 Preloading and Failure Pattern

The beam specimens to be strengthened were preloaded up to initial crack formation. The ultimate strength of RC beams strengthened with FRP is affected by the initial load at the time of strengthening. A beam strengthened at a higher level of load will produce a lower ultimate strength than a beam strengthened at a lower level of load (Wenwei and Guo, 2006). For control beams, 50 kN and 53 kN loads for initial cracks were noted. Their mean value (51.5 kN) was used to form initial cracks in other six beams. The cracks were observed and marked. Figure 5 shows some the beams with initial cracks. The midpoint deflection is ranged between 1.0-1.1mm which is similar to the midpoint deflection of control beams. After that beam was strengthened and categorized.

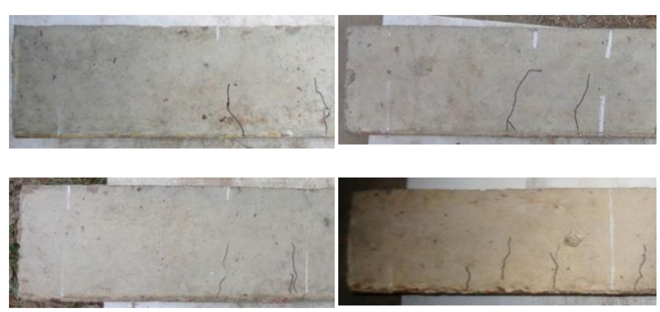


Figure 5 Preloaded beams with initial cracks marked

4.2 Strengthening of Beam Specimen using CFRP

4.2.1 Subgroups BTS (Strengthened with Tow sheet)

Three beams BTS-1, BTS-2 and BTS-3 were strengthened using CFRP fabric (tow sheet). The distinguishable feature of the beam was the method of strengthening. Strengthened beams were subjected to four point bending again. The beam was loaded at equal increment of load up to ultimate failure. BTS-1 beam failed due to plate debonding of the FRP from the concrete substrate at an ultimate load of 155 kN with midpoint deflection recorded as 6.8 mm. Results show that BTS-1 sustained 12.3% higher ultimate load than failure load of the control beams. Deflection recorded at loading points were 5.6 mm and 5.55 mm respectively. Figure 6 shows that cracks were visible at the flexural zone of the beam.

The second beam (BTS-2) was strengthened for flexure similarly as the previous beam, but end anchorage was provided to prevent end plate debonding. The anchorage strip width was 80 mm (adopted from Jayaprakash *et al.,* 2008). It was wrapped around the beam as U-strip maintaining 0/90 degree angle to the longitudinal axis of the beam at both ends. Figure 7(a) demonstrates the position of U-strip generally applied after 50 mm from support end (90-40 mm).

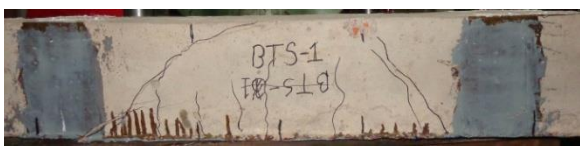


Figure 6 Beam BTS-1 after failure

After preloading as shown in Figure 7, the beam clearly failed due to flexure at an ultimate load of 170 kN with midpoint deflection of 7.125 mm. Application of anchorage restrained the beam to fail due to end plate debonding and change the failure mode into plate interfacial debonding. Arduini and Nanni (1997) reported similar results. Deflections of loading points were 6.2 mm and 6.1 mm respectively.

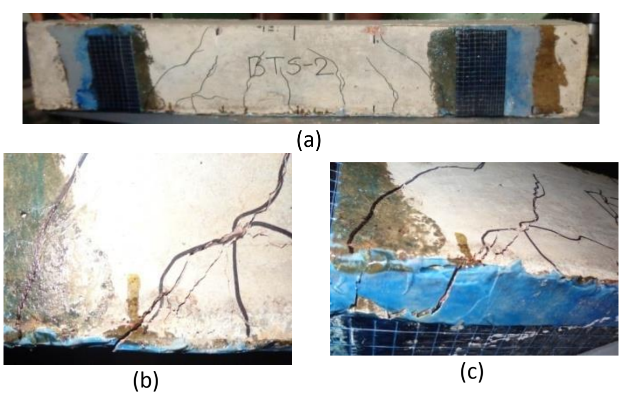


Figure 7 (a) Beam BTS-2 after failure (b) magnified view of the front (c) Magnified view of the cracks at bottom

BTS-3 beam specimen was strengthened with 2 layers of CFRP sheets and under loading, similar test preparation was found at the research of Sobuz *et al.*, 2011. The beam failed due to insufficient flexural strength by end plate de-bonding (shown in Figure 8) at an ultimate loading of 163 kN with relatively less deflection value of 4.8 mm at midpoint. Results indicate that additional layer of FRP sheet reduced the deflection almost 30% than the previous two beam, but absence of end anchorage lead the failure into debonding mode. Reduction of deflection also indicates that BTS-3 showed better stiffness than the previously tested beams.

Figure 8 Beam specimens BTS-3 with after ultimate failure

4.2.2 Subgroups BSS (Strengthened with Strand Sheet)

Beam specimen BSS-1 was loaded similarly as BTS-1, but it showed greater strength and less deflection than BTS-1. As shown in Figure 9, the beam failed due to crushing of concrete and debonding of the FRP from the concrete substrate at an ultimate load of 166 kN with midpoint deflection of 3.71 mm. Deflection recorded at loading points were 3.45 mm and 3.51 respectively. Comparing to BTS-1 this beam showed better load carrying capacity and also better stiffness property.

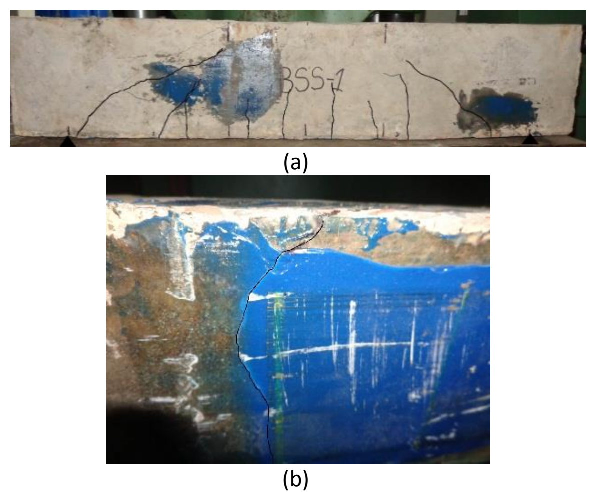


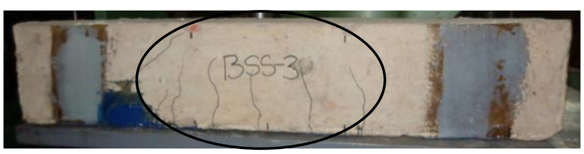
Figure 9 (a) Flexural shear cracks (marked) of BSS-1 after failure; (b) Magnified view of cracks at bottom span

BSS-2 was strengthened similarly as BTS-2, after strengthening the soffit of the beam with strand sheet; CFRP U-wrap was applied at both ends as anchorage. Application of end anchorage restricted end plate debonding. However, the beam failed due to crushing of concrete in compression zone and due to inadequate flexural strength (Figure 10). The beam failed at an ultimate load of 185 kN with a midpoint deflection of 5.5mm. Deflection at loading points was recorded as 5.08 and 5.02 mm respectively. Results show that this beam attained higher strength and also minimum deflection when compared to other specimens. Garden and Hollaway (1998) reported less deflection with end anchorage system.

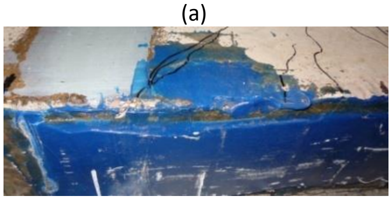
Figure 10 Ultimate failure of BSS-2 with flexural-shear crack formation

BSS-3 was strengthened in a different pattern, strand sheet was applied similarly as on the beam before, but adhesive thickness was increased at both ends 1.5 times higher than BSS-1 and BSS-2. The beam sustained a relatively higher ultimate load than BSS-1 and yet failed due to end plate debonding with an ultimate load of 171 kN with a midpoint deflection of 4.54 mm (Figure 11). The beam attained higher strength than BSS-1 yet failed due to end plate debonding.

In general, the test results showed that strength recovery of the CFRP strengthened specimens were varied ranging from 12% to 34%. Application of FRP reinforcement enhanced flexural capacity of initially cracked beams but failed due to premature de-bonding before reaching its full capacity. By adding the CFRP strips the distribution of cracks were less compared to the specimen with no CFRP strip. Thus it implies that addition of CFRP strips not only increased strength but also affected the crack distribution. De-bonding at the end plate was observed with concrete cover debonding. Installation of end anchor strip modified the origin of crack propagation pattern from the support.



(a)



(b)

Figure 11 (a) Ultimate failure of BSS-3 with end plate de-bonding; (b) Magnified view at the failure zone

4.3 Load - Deflection Profile

The load-deflection behavior of control beams and beams strengthened with different CFRP materials are shown in Figure 12. Initially all the beams behaved similarly as of control beams with the internal steel reinforcing bar carrying the most of the tensile force in the section. The additional tensile force is carried by the FRP system and thus increase in load capacity of the member is achieved.

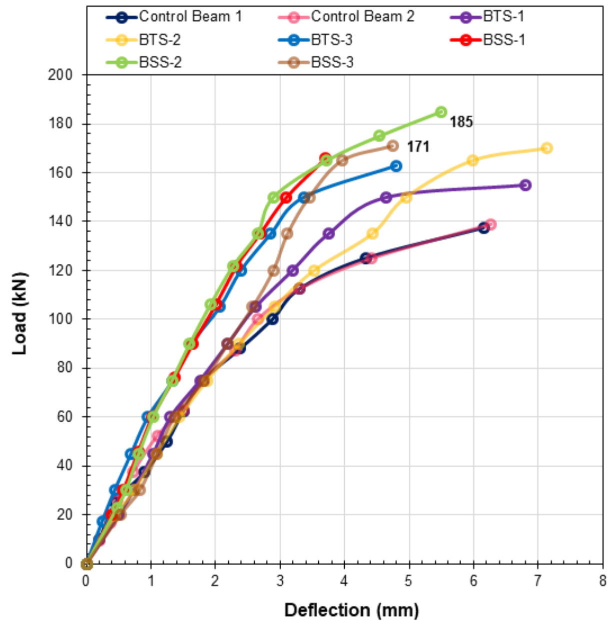


Figure 12 Load-Deflection profile of beam specimens

Eventually, the FRP strengthened beams failed. The failure patterns which are observed on the CFRP strengthened beams are dissimilar to the failure pattern of classical reinforced concrete control beams. The strengthened beams acted in a linear elastic fashion almost up-to failure.

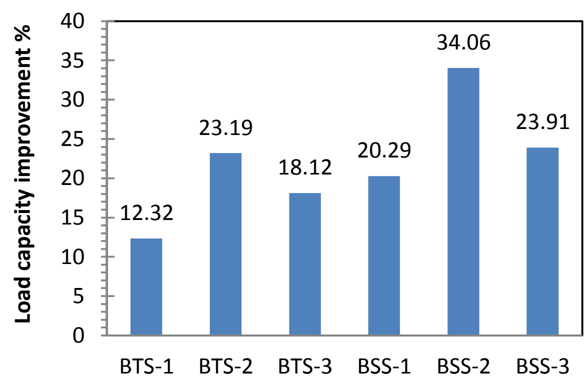


Figure 13 Improvement of load capacity with respect to control beam

From the test result given in Figure 13, strengthened beams attained relatively higher load when compared to control beams. Initially beam specimen BTS-1, BTS-2 and BSS-3 showed similar behavior as control beams whereas BSS-1, BSS-2 and BTS-3 gave relatively different load-deflection pattern. Beam specimen BTS-1, BTS-2 and BSS-3 showed similar behavior as control beam, up-to the yielding of internal reinforcing steel. Due to presence of FRP reinforcement in the bottom BTS-1 carried additional load up-to 155 kN of ultimate load, due to U-wrap at both end, BTS-2 attained higher load than BTS-1. Beam BSS-3 also initially showed similar behavior as control beam, however, after yielding of internal reinforcing steel, load-deflection behavior of BSS-3 altered due to additional FRP reinforcement with higher adhesive thickness. The results also indicated that specimen BSS-1, BSS-2 and BTS-3 showed better stiffness than other beams.

4.4 Cost Analysis with Respect to Strengthening

Material cost is calculated for individual strengthened options. Total cost of materials varied depending on the strengthening techniques applied. Parameters related to cost including area of strengthening, type of strengthening, type of material used. The dimension of tow sheet/strand sheet applied at the soffit of the beam (700mm×100mm) and U-strips (500mm × 80mm) was same for all the beam specimens. Figure 14 gives a relation between strength enhancement and associated cost. Comparatively higher material cost was required for BSS group because of higher price of strand sheet.

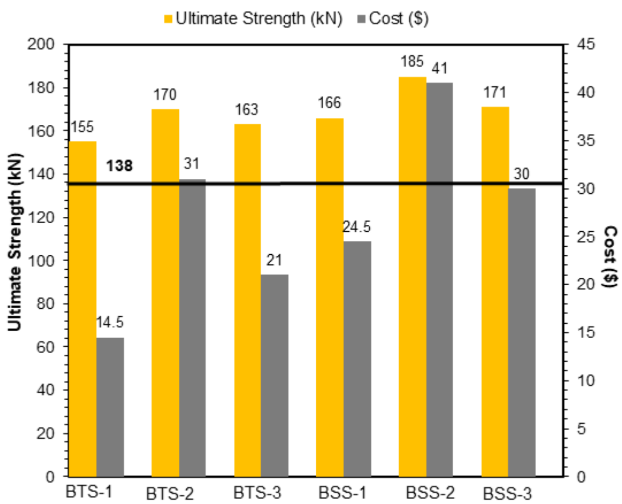


Figure 14 Cost vs strength for different strengthening option

Considering the lowest (155 kN) and highest (185 kN) strength enhancement with BTS-1 and BSS-2 the cost of material increased 2.8 times for 22% higher strength enhancement from the control beam strength. Therefore, CFS method could be chosen when budget is an issue and Strand sheet with U-strip is better option for higher strength enhancement.

5.0 CONCLUSION

The experimental results indicated that use of externally bonded uni-directional CFRP composite system significantly increases flexural strength of rectangular pre-cracked RC beam. However, the usual strengthening system failed to control de-bonding of FRP at support. The following conclusions are drawn based on experimental investigation and analysis of brick aggregated pre-cracked rectangular RC beams:

- due to the material property, strength enhancement and easier installation, strand sheet is more attractive and effective than tow sheet for similar strengthening work;
- beams strengthened with strand sheet gave less deflection with higher load carrying capacity in comparison to tow sheet;
- RC beams strengthened with FRP plate overlay end peels before reaching its full capacity. The spacing and number of CFRP strips affects the flexural capacity enhancement of pre-cracked RC beams. Installation of anchorage at the end zone of FRP plate prevents the failure due to end plate de-bonding;
- lower deflection was obtained with end anchorage. It also modified the failure mode from flexure to shear and prevented end plate de-bonding;
- as with the strand sheet, additional layer of tow sheet aided to attain higher strength with less deflection;
- effect of adhesive thickness was found insignificant on failure mode of FRP overlay. Greater thickness would favour stress redistribution and raise the ultimate load; and
- strengthening with strand sheet is preferable where cost is not a major issue.

Acknowledgements

The financial support (Project No.: CUET/DRE/2014-15/CE/009) provided by the University Grants Commission of Bangladesh is gratefully acknowledged. The authors are grateful to the strength of Materials Laboratory, Department of Civil Engineering, Chittagong University of Engineering & Technology and Prof. Dr. Mahmood Omar Imam of this department for experimental support. Humble gratitude extended to Mr. Akira Kobayashi, Nippon Steel Composite Co. Ltd and Prof. Tamon Ueda, Hokkaido University, Japan for their kind support to obtain CFRP materials.

References

[1] ACI Committee 440. 2002. *Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*. American Concrete Institute, Farmington Hills, Michigan, USA.

[2] Al-Oraimi, S. K., Taha, R., & Hassan, H. F. 2006. The Effect of the Mineralogy of Coarse Aggregate on the Mechanical Properties of High-strength Concrete. *Construction and Building Materials*, 20(7): 499-503.

[3] Arduini, M., & Nanni, A. 1997. Behavior of Precracked RC Beams Strengthened with Carbon FRP Sheets. *Journal of Composites for Construction*, 1(2): 63-70.

[4] Buyukozturk, O., & Hearing, B. 1998. Failure Behavior of Precracked Concrete Beams Retrofitted with FRP. *Journal of Composites for Construction*, 2(3): 138-144.

[5] Effat, S. 2016. The Characteristics of Brick Aggregated Concrete on a Basis of Dry Density and Durability. *Malaysian Journal of Civil Engineering,* 28(1): 50-58.

[6] Esfahani, M. R., Kianoush M. R., & Tajari, A. R. 2007. Flexural Behaviour of Reinforced Concrete Beams Strengthened by CFRP Sheets. *Engineering structures*, 29(10): 2428-2444.

[7] FIB Bulletin 14, Technical Report. 2001. *Externally Bonded FRP Reinforcement for RC Structures*. International Federation of Structural Concrete.

[8] Garden, H. N. and Hollaway, L. C. 1998. An Experimental Study of the Influence of Plate End Anchorage of Carbon Fiber Composite Plates Used to Strengthen Reinforced Concrete Beams. *Composite Structures*, 42(2): 175-188.

[9] Hollaway, L. C. 2011. Key Issues in the Use of Fiber Reinforced Polymer (FRP) Composites in the Rehabilitation and Retrofitting of Concrete Structure. *Service Life Estimation and Extension of Civil Engineering Structures.* Abington Hall (Cambridge): Woodhead Publishing Ltd.

[10] Jayaprakash, J., Abdul Samad, A. A., Anvar Abbasovich, A., & Abang Ali, A. A. 2008. Shear Capacity of Precracked and Non-precracked Reinforced Concrete Shear Beams with Externally Bonded Bi Directional CFRP strips. *Construction and Building Materials*, 22(6): 1148-1165.

[11] Kobayashi, A., Sato, Y. and Takahashi, Y. 2009. Basic Characteristics of FRP Strand Sheets and Flexural Behavior of RC Beams Strengthened

with FRP Strand Sheets. *The Second Official Regional Conference of International Institute for FRP in Construction for Asia-Pacific Region*, *Seoul, Korea*, *December 9-11, 2009*.

[12] Komori, A., Taniguchi, K., Nakamura, S., Yamaguchi, K. and Hino, S. 2012. Experimental Study on Strengthening Effect of CFRP Strand Sheet on RC Beams Applied with Several Kinds of Adhesives. *Third Asia-Pacific Conference on FRP in Structures*, *Hokkaido University, Japa*n, *February 4-6, 2012.*

[13] Lacasse, C., Labossiere, P., & Neale, K. W. 2001. FRPs for the Rehabilitation of Concrete Beams Exhibiting Alkali-aggregate Reactions. *Proceedings of 5th International Symposium on Fibre-Reinforced (FRP) Polymer Reinforcement for Concrete Structures*, 1: 35-43.

[14] Mirmiran, A., Shahawy, M., Nanni, A. and Karbhari, V. 2004. *NCHRP Report 514: Bonded Repair and Retrofit of Concrete Structures Using FRP Composites-Recommended Construction Specifications and Process Control Manual.* Transportation Research Board, Washington, DC.

[15] Neville, A. M. 2011. *Properties of Concrete*. 5th Edition. Essex, Pearson Education Limited. Essex, England.

[16] Obaidat, Y. 2011. Structural Retrofitting of Concrete Beams using FRP-debonding Issues. Doctoral Thesis: Lund University, Lund, Sweden.

[17] Rashid, M. A., Hossain, T., and Islam, M. A. 2008. Higher Strength Concrete using Crushed Brick as Coarse Aggregate. *Indian Concrete Journal*, 82(10): 18.

[18] Shahawy, M. A., Arockiasamy, M., Beitelman, T. and Sowrirajan, R. 1996. Reinforced Concrete Rectangular Beams Strengthened with CFRP Laminates. *Composites Part B: Engineering,* 27(3): 225-233.

[19] Shehata, I. A. E. M., Cerqueira, E. C., Pinto, C. T. M., & Shehata, L. C. D. 2001. *Strengthening of RC Beams in Flexure and Shear using CFRP Laminate.* Thomas Tetford London, 97-106.

[20] Smith, S. T. and Teng, J. G. 2002. FRP-strengthened RC Beams. Review of Debonding Strength Models. *Engineering Structures*, 24(4): 385-95

[21] Sobuz, H. R., Ahmed, E., Uddin, M. A., & Sadiqul, N. M. 2011. Structural Strengthening of RC Beams Externally Bonded with Different CFRP Laminates Configurations. *Journal of Civil Engineering (IEB)*, 39(1): 33-47.

[22] Teng, J. G., Zhang, J. W., and Smith, S. T. 2002. Interfacial Stresses in Reinforced Concrete Beams Bonded with a Soffit Plate: a Finite Element Study. *Construction and Building Materials*, 16(1): 1-14.

[23] Teng, J. G., Smith, S. T., Yao, J. and Chen, J. F. 2003. Intermediate Crack-induced Debonding in RC Beams and Slabs. *Construction and Building Materials*, 17: 447-62.

[24] Toutanji, H., Zhao, L., & Zhang, Y. 2006. Flexural Behavior of Reinforced Concrete Beams Externally Strengthened with CFRP Sheets Bonded with an Inorganic Matrix. *Engineering Structures*, 28(4): 557-566.

[25] Ueda, T., Zhang, D., & Furuuchi, H. 2012. Towards Rational Design Method for Strengthening of Concrete Structures by External Bonding. *Civil Engineering Dimension*, 14(3): 196-204.

[26] Wenwei, W. and Guo, L. 2006. Experimental Study and Analysis of RC Beams Strengthened with CFRP Laminates under Sustaining Load. *International Journal of Solids and Structures*, 43(6): 1372-1387.

[27] Forca Towsheet Catalogue. 2015. Nippon Steel and Co Ltd., Japan.