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Procedia Engineering 77 (2014) 123 – 130
Procedia Engineering
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Fourth International Symposium on Infrastructure Engineering in Developing Countries, IEDC 2013

Behaviour of Reinforced Concrete Beams Strengthened by CFRP Wraps with and without End Anchorages

Asad ur Rehman Khan[a,]*, Shamsoon Fareed[a]

[a]*NED University of Engineering & Technology, Karachi-75270, Pakistan*

Abstract

Use of Carbon Fibre Reinforced Polymer (CFRP) strips as externally bonded reinforcement, is a technically sound and practically efficient method of strengthening and upgrading reinforced concrete (RC) members. Externally bonded CFRP strips help in improving the structure performance by reducing deflections and/or cracking and increasing ultimate strength. The ultimate capacity of the strengthened beam is controlled by either compression crushing of concrete, rupture of CFRP and flexural shear cracking induced de-bonding atconcrete-CFRP interface. Present study deals with the use of externally bonded CFRP wraps instead of strips to strengthen RC beams in flexure with and without end anchorages. Six beams strengthened with CFRP wraps at bottom with and without anchorages, were tested with different a/d ratios. It was observed that use of CFRP wraps resulted in significantly increasing the stiffness and ductility of the RC beams along with increasing load carrying capacities of the strengthened RC beams with end anchorages.

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Peer-review under responsibility of the Accounting Research Institute, Universiti Teknologi MARA.

Keywords: Beams; CFRP; shear span to depth ratio; strengthening

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* Corresponding author. Tel.:+92-21-99261261-8; fax:+92-21-99261255
E-mail address: asadkhan@neduet.edu.pk

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Selection and peer-review under responsibility of the Department of Urban and Infrastructure Engineering, NED University of Engineering and Technology
doi:10.1016/j.proeng.2014.07.011

1. Introduction

Reinforced concrete structures have enabled the vast world-wide construction of infrastructures. Strengthening of RC structure may be required due to modifications in design standards/codes or in usage of structure. Therefore, all these may result in a need to strengthen an existing or new structure.Many construction methodologies that are being practised are of importance now but they were ignored previously, resulting in distress and hence require strengthening.

Nomenclature

CFRP	Carbon Fibre Reinforced Polymer
a/d	shear span to depth ratio

Carbon Fibre Reinforced Polymer (CFRP) materialsare becoming increasingly popular for strengthening of reinforced concrete (RC) structures in flexural and shear. There are several advantages of using CFRP as externally bonded material over conventional steel such as high strength to weight ratio, outstanding durability in a variety of environment, ease and speed of installation, flexibility in application techniques, electromagnetically neutral, outstanding fatigue property and low thermal conductivity. FRP plates or sheets can easily be bonded to the exterior of reinforced concrete members using the wet lay-up procedure with an epoxy resin/adhesive. The FRP sheets or plates are generally bonded to the tension faces of flexural elements to increase their bending capacity, or to their side faces to increase the shear capacity.

Chahrour et al[1] studied the flexural response of reinforced concrete strengthened with end-anchored partially bonded CFRP Strips. It was found that the end-anchored partially bonded CFRP strips significantly enhanced the ultimate capacity of the control beam and performed better than the fully bonded strip with no end-anchorage. Al-Amery et al [2] investigated the combined shear-flexural strengthening of RC beams. It was found that a significant improvement in the beam strength upto 95% is gained due to the use of CFRP strips to anchor the CFRP sheets. It was found that the dominant mode of failure observed in the beams with strips was a ductile flexural failure with excessive yielding of internal steel prior to the rupture of CFRP sheets and crushing of the concrete.Alagusundaramoorthy et al[3] studied the flexural behaviour of RC beams strengthened with CFRP sheets or fabric. It was found that the flexural strength was increased up to 58% on concrete beams strengthened with anchored CFRP sheets.

Shear failures in reinforced concrete beams are characterized as brittle and catastrophic as they give no warning of impeding failure. Strengthening in flexure results in thereduction of the shear capacity of the beam.It is common in Pakistan to change building usage from residential to commercial in developing trading zones of urban areas. Such buildings may have to strengthen to cater for the additional superimposed loads caused by this change. In this study the flexural behaviour of reinforced concrete beams strengthened with externally bonded CFRP wraps has been studied with varying shear span to depth ratio (a/d). It was found that the RC beams wrapped with CFRP at bottom and extended on sides provided with and without ends anchorages, improved the structural performance in terms of stiffness, ductility and load carrying capacity.

2. Experiment program

In this study six (06) rectangular reinforced concrete beams having width of 152.4 mm, depth of 203.2 mm and length of 1828.8 mm were tested. The beams were divided in to two groupsof three beams based on the shear span to depth ratio (a/d) used. Group 1 beams were tested with a/d ratio of 3.4 and those of Group 2 were tested with a/d ratio of 2.5. One beam in each group served as control specimen,while other two were strengthened with CFRP wraps, one without end anchorage and other with end anchorage. All beams used in this study have 3#4 (12.7 mm) bars in the bottom 2#3 (9.52 mm) bars at the top. Twenty three (23) stirrups of #3 (9.52 mm) bars spaced at 75 mm c/c. The reinforcement detail of all six beams is shown in Fig. 1. In strengthened RC beams of each group, CFRP wraps were applied at the bottom of the beam such that they were extended 50 mm at both sides of the beams. One beam was without end anchorages (Fig. 2) while the other was with end anchorages wrapped all along the cross-section of the beam (Fig. 3). CFRP wraps used in the study has a width of 500 mm and thickness of 1.2 mm. Properties of materials used in reinforced concrete beams along with that of CFRP wraps are shown in Table 1. The nomenclature of the beam is shown in Table 1. All the beams were tested under four point bending. Deflections and crack initiation were noted and monitored upto failure.

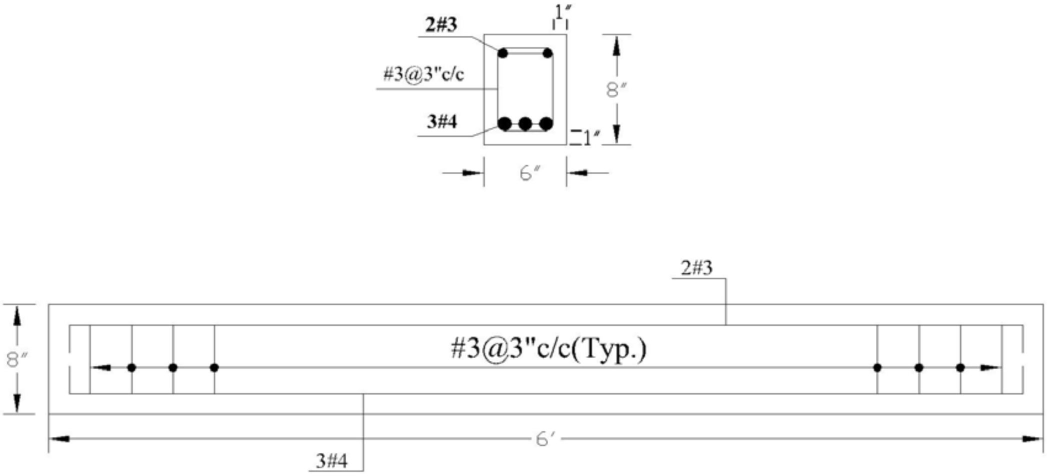

Fig. 1: Typical Beam Reinforcement

Fig. 2: Typical Wrapping Scheme - CFRP at bottom and extended on sides

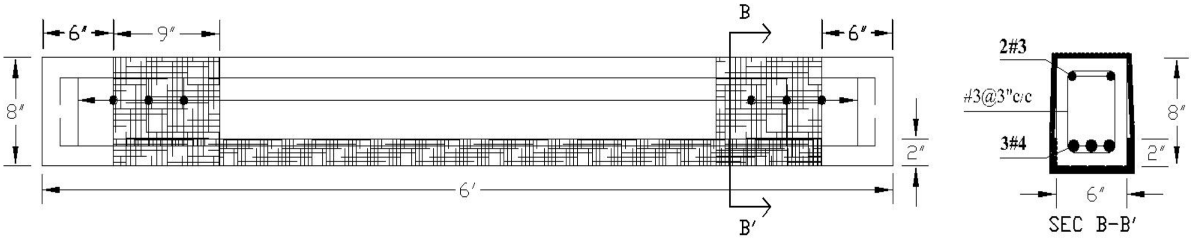

Fig. 3: Typical Wrapping Scheme - CRFP at bottom and extended on sides with end anchorages

Table 1: Material properties used

	Compressive strength (MPa)	*Yield Strength (MPa)*	*Tensile strength (MPa)*
Concrete	40	-	-
Reinforcement	-	413	-
CFRP	-	-	4100

Table 2: Nomenclature of the beams

Nomenclature	*Description Of Beam*	*a/d*
CB-1	Control beam	3.4
WSB-1	RC strengthened beam with CFRP at bottom and extended 50 mm (2 in.) on sides without end anchorage	3.4
WSAB-1	RC strengthened beam with CFRP at bottom and extended 50 mm (2 in.) on sides with end anchorage	3.4
CB-2	Control beam	2.5
WSB-2	RC strengthened beam with CFRP at bottom and extended 50 mm (2 in.) on sides without end anchorage	2.5
WSAB-2	RC strengthened beam with CFRP at bottom and extended 50 mm (2 in.) on sides with end anchorage	2.5

3. Results and Discussion

Results of the experimental investigations are presented and discussed in terms of ultimate load carrying capacities, failure modes and deflection curves (Table 3 and Fig.s 4 to 8).

3.1 Ultimate Load and Failure Modes

The first crack load, ultimate load and failure modes of control and strengthened RC beams are summarized in Table 3. Fig.s 4 to 6 shows different failure modes of beam observed in the tests. The control specimen CB-1 failed in flexure due to yielding of steel followed by crushing of concrete in compression zone with wide flexural cracks at the bottom (Fig. 4). The beam failed in compression at an ultimate load of 103.1 kN. The Beam WSB-1 failed in flexure at ultimate load of 113.7kN, due to yielding of steel followed by crushing of concrete in compression zone with evenly distributed cracks throughout the flexural span. The beam WSB-1 carried an additional load of 10.3% and first crack initiated in the beam at a load 11.9% more than that of control beam CB-1 which was 67 kN. Beam WSAB-1 also failed in flexure and sequence of failure was yielding of steel followed by crushing of concrete in compression zone with evenly distributed fine cracks in flexure zone. The closely spaced fine cracks were observed before failure and the beam failed when concrete on compression side reached its ultimate capacity. The ultimate load carrying capacity of the beam was found to be 120.3 kN (16.7% higher than CB-1) and first crack appeared at a load of 81 kN which was 20.9% higher than that of CB-1 and 8% more than that of WSB-1.

Control beam CB-2, with a/d ratio of 2.5, failed at an ultimate load of 141.75 kN in flexure due to yielding of steel followed by crushing of concrete in compression zone with wide flexural cracks at the bottom. Beam WSB-2 failed at ultimate load of 149.5 kN, carrying 5.4% additional load as compared to the control beam CB-2, in shear-tension due to rupture of concrete at web shear zone. Extension of the wraps at sides of the beam resulted in delayed crack initiation along with crack width reduction and enhanced the stiffness of the beam. First crack in WSB-2 initiated at 75 kN which was 36.4% more than the first crack load of CB-1 which was 55 kN. Failure was sudden and brittle and occurred due to the debonding of CFRP at bottom and the sides of the beam with a portion of concrete up to the height of the wrap was debonded from the beam as shown in Fig. 5. It was observed that the CFRP tore away from the end of the beam along with the chunks of weak concrete, exposing the reinforcement at some parts of the beam as the shear and normal stresses near the support exceeded the critical limit. Beam WSAB-2 failed in shear-compression due to excessive diagonal cracking in web shear zone. The ultimate load carrying capacity of the beam was found to be 171.3 kN, 20.8% more than the control beam. Crack initiation was also delayed and the first crack was initiated at a load of 98.7 kN, 79.5% and 31.6% more than the control beam CB-2 and WSB-2 respectively. Enhanced stiffness of the beam was observed but a change in crack width and incursion was observed particularly in web shear zone which can be attributed to wrapping of end anchorages all along the cross-section. As a result a weak compression zone was formed between the point load and the reaction created by confinement provided by the fully wrapped end anchorages as shown in Fig. 6. The cracks in web shear zone penetrated earlier than flexural cracks hence decreasing the effective area of concrete in resisting compression and the beam thus failed suddenly between point load and anchorage. The effectiveness of end anchors was prominent in increasing ultimate load capacity of this beam as compared to WSB-2 because of lesser a/d ratio.

Table 3: Experimental Results

BEAM	FIRST CRACK LOAD (kN)	CRACK PATTERN	ULTIMATE LOAD (kN)	FAILURE MODE
CB-1	67	Wide flexural cracks	103.1	Flexure failure due to yielding of steel followed by crushing of concrete in compression zone with wide cracks.
WSB-1	75	Wide flexural cracks	113.7	Flexure failure due to yielding of steel followed by crushing of concrete in compression zone with fine cracks evenly distributed in flexure zone.
WSAB-1	81	Due to CFRP wrapping at bottom and sides the appearance of cracks was delayed	120.3	Flexure failure due to yielding of steel followed by crushing of concrete in compression zone with evenly distributed fine cracks in flexure zone.
CB-2	55	Diagonal shear cracks in web zone	141.8	Flexure failure due to yielding of steel followed by crushing of concrete in compression zone.
WSB-2	75	Flexural cracks approached faster than diagonal cracks in web shear zone	149.5	Shear-Tension failure due to rupture of concrete at web shear zone
WSAB-2	98.7	Diagonal shear cracks in web shear zone approached faster than flexural cracks	171.3	Shear-Compression failure of concrete due to diagonal cracks in web shear zone

Fig. 4: Failure of control Beam in Compression with wide Flexure cracks

Fig. 5: Shear Failure of beam with de-bonding of CFRP along with concrete

Fig. 6: Diagonal shear compression failure

3.2 Load-Deflection curves

Load-deflection curves of the Group 1 are shown in Fig. 7 while that of Group 2 in Fig. 8. It can be seen from both Fig.s that the strengthened beams were stiffer as compared to the respective control beams. This difference becomes more prominent in the post cracking region of the load-deflection curves and is more pronounced in Group 2 beams where initial cracking load of beam CB-2 is lesser than CB-1. It can also be noticed from both the figures that load-deflection curves of strengthened beams with end anchorages are stiffer as compared to the beams without end anchorages. The curves for the strengthened beams showed identical response in the initial stage of loading but as the load increases beams without end anchorages starts to deflect more due to excessive cracking at the ends and tendency of the wraps to debond prematurely. This effect is more pronounced in Group 2 beams as can be seen in Fig. 8. Enhanced ductility of the strengthened beams with anchorages can also be noticed in Fig.s 7 and 8. This is also attributed towards the end anchorages which prevented premature debonding of the wraps at the ends due to excessive shear and peeling stresses as the ends.

4. Conclusions

Following conclusions can be drawn from the study of RC beams strengthened with CFRP wraps along the length with and without end anchorages:

1. RC beams wrapped with CFRP at bottom and extended on sides provided with and without ends anchorages, improved the structural performance of the beams in terms of stiffness, load carrying capacity and ductility.
2. RC beams strengthened with CFRP were found to have fine cracks evenly distributed along the span and higher first crack load as much as 20.9% in WSAB-1 and 79.5% in WSAB-2 than that of their respective control beams.

3. Ultimate load carrying capacities of the strengthened beams increased up to a maximum of 16.7% over respective control beam in Group 1, where as it increased up to a maximum of 20.8% in Group 2.
4. Strengthened beams tested at smaller a/d ratio were found to fail in shear- tension and shear- compression in spite of having adequate shear stirrups to resist shear. Difference of failure modes in strengthened beams with smaller a/d ratio is due to the presence of end anchorages. However, beams tested at higher a/d ratio failed in flexure as expected.

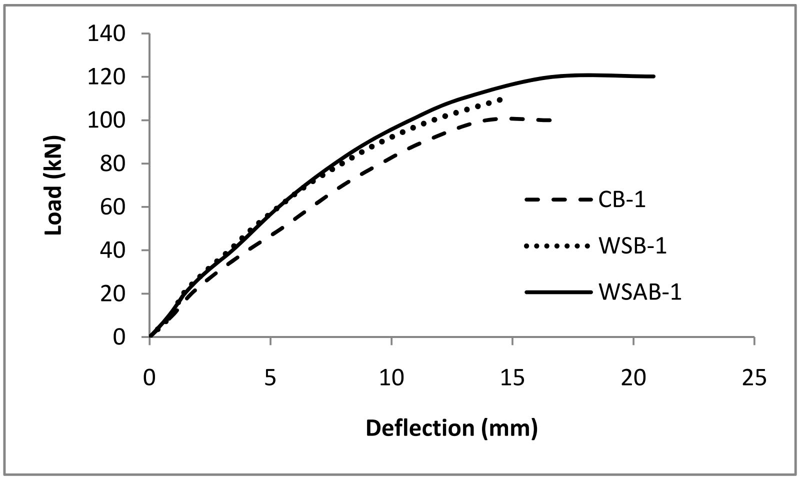

Fig. 7: Load Deflection Curve for beams with a/d=3.4

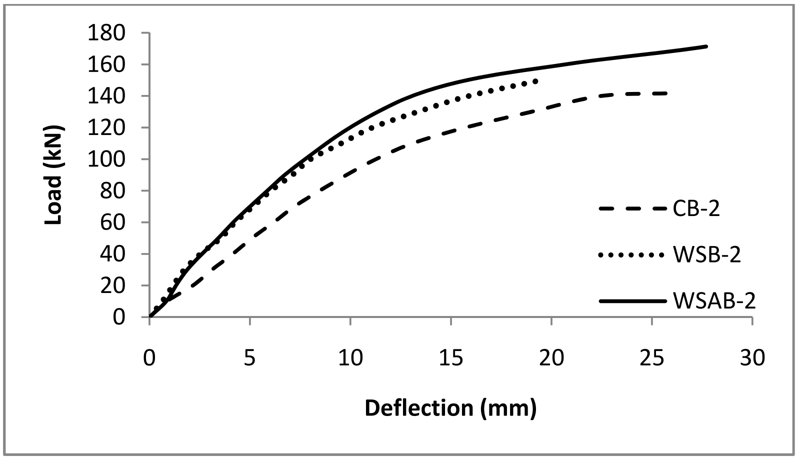

Fig. 8: Load Deflection Curve for beams with a/d=2.5

Acknowledgement

The authors are indebted to the Department of Civil Engineering, NED university of Engineering & Technology, its undergraduate students (ArsalanShaikh, Syed Saadat Salman Shah, Syed RummaanAhmed , Imran Khan, AsadYousuf, AnasAjaz) and University itself for pursuit of this work.

References

[1] Ali Chahroun and KhaledSoudki (2005) Flexural Respounce of Reinforced Concrete Beams Strengthened with End-Anchored Partially Bonded Carbon Fiber-Reinforced Polymer Strips. *Journal of Composite for Construction.*9(2), 170–177.

[2] Al-Amery and Riadh Al-Mahaidi (2006) Coupled flexural-shear retrofitting of RC beams using CFRP straps. Riyadh, *Composite Structures*, Vol. 75, pp. 457-464.

[3] Alagusundaramoorthy.P.;Harik. I.E,M.ASCEabdChoos C.C. (2003) Flexural Behaviour of RC beams strengthened with Carbon Fiber Reinforced Polymer Sheets or Fabric, *Journal of Composite for Construction.*Vol. 7, No. 4, November 2003, pp. 292-301.