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PERFORMANCE OF RC BEAMS STRENGTHENED FOR SHEAR AND FLEXURE USING DIFFERENT SCHEMES OF U-SHAPED CFRP ANCHORAGES AND/OR STRIPS[*]

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Abstract– Deficiencies of RC structures can be overcome by strengthening/retrofitting using different strengthening methodologies. This paper emphasises the effectiveness of externally applied U-shaped CFRP anchorages/strips on the performance of RC beams of relatively low compressive strengths (approximately 21 MPa). Three types of the beams were cast based on the shear reinforcement detailed as containing "no shear reinforcement", "minimum shear reinforcement" and "adequate shear reinforcements" as suggested in ACI 318-08. All beams were provided adequate flexural reinforcement as recommended by ACI 318 to fail the beams in flexure. U-shaped CFRP anchorages and strips were bonded to the beams in the predominant shear and flexural loading regions and tested under four-point bending condition by varying shear span-to-depth ratio (*a*/*d*) as 2.46 and 3.38. Different strengthening schemes (including CFRP anchorage alone and in combination with CFRP strips) as well as the effect of U-shaped CFRP anchorages applied over full and partial applied beam depth was also the parameter of investigation in the current study. Results showed that externally bonded U-shaped anchorages applied along the beam span and at the ends together with CFRP strips improved the deformability, strength and performance of RC beams by transforming failure manner from brittle to ductile. Moreover, use of partial depth anchorage is beneficial to attain higher load in comparison to the full depth anchorages, particularly anchorage height equal to 3/4 of the beam depth is found to be most suitable.

Keywords– Carbon fibre reinforced polymer, Reinforced concrete beams, Shear span to depth ratio

1. INTRODUCTION

In recent years, several researchers focused on the use of Fibre Reinforced Polymers (FRP) as an external strengthening material for reinforced concrete (RC) structures. Developments in the field of FRP have confirmed it as an efficient construction material and therefore, it is gaining attention [1]. The other strengthening techniques are discussed in [2]. According to the capacity design criterion of RC members, shear mode of failure is never appreciated and recommended as shear collapse implies a sudden and brittle failure. The need of strengthening of RC beams in shear may arise due to several reasons including lack of adequate shear reinforcement. Therefore, substantial attempts have been made to improve the shear mode of failure with the application of FRP on the RC members, which result in FRP anchorages being able to improve the sectional capacity of the rectangular beams, particularly for those having lesser shear capacity than the flexure or those requiring extra load capacity [3, 4]. According to many published test data [5-19], failure mechanism of RC beam strengthened in shear with externally bonded anchorages is different in comparison to the beam reinforced with internal stirrups, and is primarily governed by the anchorage efficiency and the anchorage bond instead of the tensile strength of the anchorage material. Beside this,

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strengthening by FRP does not allow the attachment of FRP fabric as a closed hoop covering the full cross-section of the members in the existing structures, which causes a problem for anchorage. This is why, the potential use of external anchorage is in the form of U-shape, although no sufficient results are reported in the literature to conclude the effectiveness of externally bonded CFRP anchorages in increasing the shear resistance [4].

In spite of this, the practical use of CFRP anchorages as an external reinforcement is an efficient and comprehensive strengthening technique, which upgrades the structural deficiencies and the deterioration of RC members. Besides this, it also improves the structural performance by reducing the deflection and cracking as well as by increasing the ultimate strength controlled either by the concrete crushing or the localised concrete failure due to the stress concentration at the anchorage ends or the rupture of composite anchorages or debonding of the CFRP caused by the flexural shear crack-induced [20, 21].

It is an observation that the RC structures built in the coastal regions of Pakistan deteriorate earlier than their predictable life due to the harsh marine and coastal environment. Department of Civil Engineering, NED University of Engineering and Technology (NEDUET) realized the importance of this issue and initiated research in this domain. The current investigation is part of the initiative taken by the Department of Civil Engineering, NEDUET, to explore the promising use of CFRP in strengthening and /or retrofitting of the un-cracked and pre-cracked beams. Low strength concrete was selected keeping in mind the limited literature available on the application of FRP materials on the low strength concrete structural elements. In addition, typical concrete used in the local construction in Pakistan of low strength (usually in the order of 21 MPa) and CFRP as a strengthening material has been selected for the reason that its applications is not appropriately explored in Pakistan.

2. EXPERIMENTAL PROGRAM

Sixteen (16) RC beams were cast by using concrete of a typical mix proportion of cement, fine and coarse aggregate as 1:2:4 and water cement (w/c) ratio of 0.6. The cross sectional area of all the beams was 150×200 mm, whereas the length was 1800 mm. Beams were divided into three series “A”, “B” and “C”: Series “A” was comprised of six (6) RC beams, Series “B” of six (6) and Series “C” of four (4) beams respectively. In each series, beams were distributed into two groups namely, “A1” and “A2”, “B1” and “B2”, “C1” and “C2” based on the variation in shear span as 550 mm and 400 mm (i.e. a/d ratio of 3.38 and 2.46) respectively. These particular a/d ratios have been selected intentionally (particularly a/d ratio of 2.46) to fail the RC beam in shear as RC beams tested to $a/d \leq 2.5$ ratio usually fail in shear [22]. Also, each group was comprised of one control beam. Nomenclature of control and strengthened RC beams is shown in Table 1.

In Series “B”, control beams were also strengthened using U-shaped CFRP end anchorages in shear span. Casting, curing and strengthening of the beams was carried out in Material Testing Laboratory of the Department of Civil Engineering, NED University of Engineering and Technology. All the beams were cured for 28 days prior to strengthening and testing.

a) Details of control and strengthened RC beams

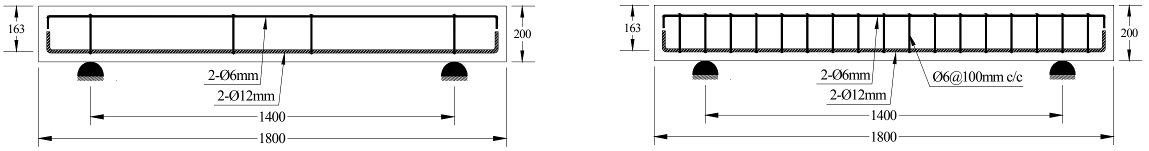
Series “A” was divided into two groups: “A1” and “A2”. Beams of Series “A” were reinforced with two 12 mm diameter deformed bars at the bottom and two 6 mm diameter mild bars at the top. Beams of group “A1” contained no shear reinforcement; whereas all beams of group “A2” were detailed in shear with a minimum amount of shear reinforcement as 6 mm diameter mild bar spaced at 150 mm continuously all over the beam span. Beams of Series “B” and Series “C” were divided into two groups “B1”, “B2” and “C1”, “C2” respectively. Beams of series “B” and “C” were reinforced with two 12 mm diameter deformed bars placed at the bottom, whereas two 10 mm diameter mild bars were placed at the top as a main flexural and hanger reinforcements. In order to detail the beams for shear, 6 mm diameter mild bar was used, which was spaced at 100 mm continuously all over the beam length. In order to strengthen the beams, CFRP anchorages were applied to the bottom as well as on the sides of the beams according to the guidelines provided by the manufacturer. It is worth mentioning that the designing of all beam was based on ACI 318-08 [23]. Mechanical properties of concrete, reinforcement and CFRP material are shown in Table 2. Reinforcement details of the beams are shown in Fig. 1, whereas Fig. 2 to Fig. 4 show the strengthening schemes used for beams of series “A”, “B” and “C” respectively.

Table 1. Nomenclature of control and strengthened RC beams

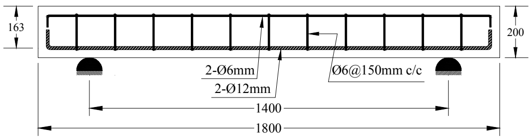
Series	Nomenclature	Shear span	Description
“A”	A1-0	550 mm (*a*/*d* = 3.38)	Control Beam without shear reinforcement
	A1-1		RC Beam containing no shear reinforcement and strengthened with CFRP anchorages in shear span only
	A1-2		RC Beam containing no shear reinforcement and strengthened with CFRP anchorages in shear span and CFRP strip
	A2-0	400 mm (*a*/*d* = 2.46)	Control Beam with minimum transverse reinforcement
	A2-1		RC Beam containing minimum shear reinforcement and strengthened with CFRP anchorages in shear span and CFRP strip
	A2-2		Beam having transverse reinforcement and strengthened with CFRP strip and CFRP anchorages in shear span
“B”	B1-0	550 mm (*a*/*d* = 3.38)	Control beam with shear span a = 550 mm
	B1-1		Control beam (B1-0) strengthened with CFRP strip and full depth anchors (anchorage height = 200 mm)
	B1-2		Beam strengthened with CFRP strip and Partial depth anchors (anchorage height = 150 mm)
	B1-3		Beam strengthened with CFRP strip and Partial depth anchors (anchorage height = 100 mm)
	B2-0	400 mm (*a*/*d* = 2.46)	Control beam with shear span a = 400 mm
	B2-1		Control beam (B2-0) strengthened with CFRP strip and full depth anchors (anchorage height = 200 mm)
	B2-2		Beam strengthened with CFRP strip and Partial depth anchors (anchorage height = 150 mm)
	B2-3		Beam strengthened with CFRP strip and Partial depth anchors (anchorage height = 100 mm)
“C”	C1-0	550 mm (*a*/*d* = 3.38)	Control beam with shear span a = 550 mm
	C1-1		Pre-cracked by loading up to 70% of ultimate load from C1-0 and strengthened with CFRP strip and full depth anchors
	C2-0	400 mm (*a*/*d* = 2.46)	Control beam with shear span a = 400 mm
	C2-1		Pre-cracked by loading up to 70% of ultimate load from C2-0 and strengthened with CFRP strip and full depth anchors

Table 2. Material properties

Materials	Material properties	Series “A”	Series “B”	Series “C”
Concrete	Compressive strength, $f_c^/$ (MPa)	28	20.7	20.7
Steel	Long. steel yield strength, f_y (MPa)	445	415	415
	Long. steel diameter (mm)	12	12	12
	Stirrup steel yield strength, f_y (MPa)	318 (Mild)	318 (Mild)	318 (Mild)
	Stirrup diameter (mm)	6	6	6
CFRP strip	Thickness (mm)	1.4	1.4	1.4
	Width (mm)	50	50	50
	Ultimate tensile strength (MPa)	2500	2500	2500
	Young's modulus (GPa)	150	150	150
CFRP anchorages	Thickness (mm)	0.117	0.117	0.117
	Ultimate tensile strength (MPa)	3800	3800	3800
	Young's modulus (GPa)	240	240	240

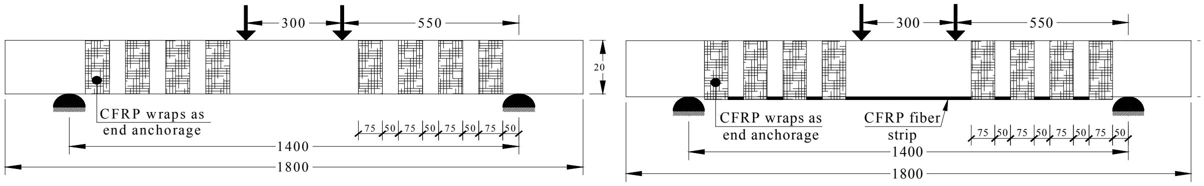


(a) Series "A" (Group: A1) (b) Series "A" (Group: A2)

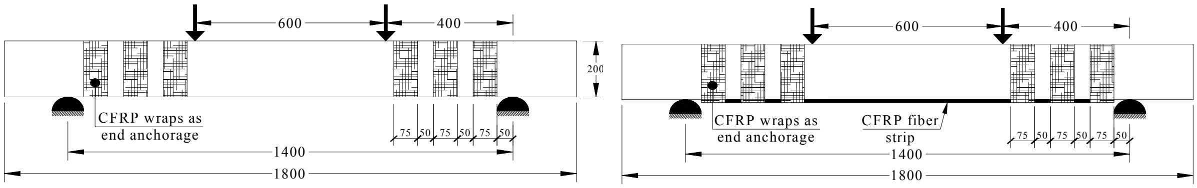


(c) Series "B" and Series "C"

Fig. 1. Reinforcement details of the RC beams

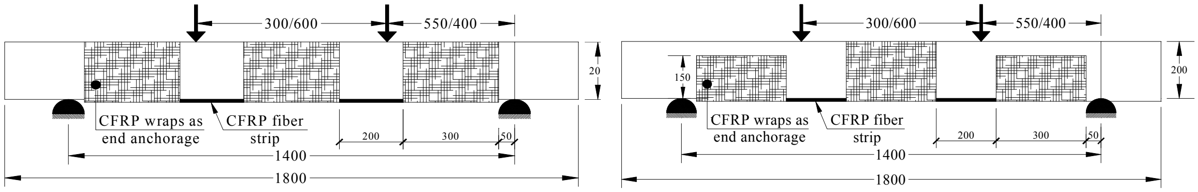


i- Beam A1-1 ($a/d = 3.38$, where $a = 550$ mm) ii- Beam A1-2 ($a/d = 3.38$, where $a = 550$ mm)

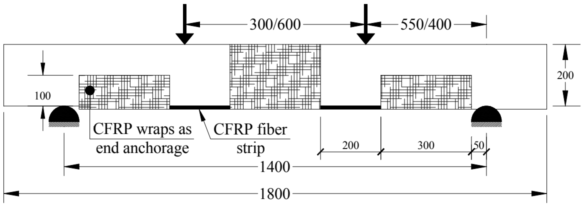


iii- Beam A2-1 ($a/d = 2.46$, where $a = 400$ mm) iv- Beam A2-2 ($a/d = 2.46$, where $a = 400$ mm)

Fig. 2. Typical strengthening scheme of the beams of Series "A"



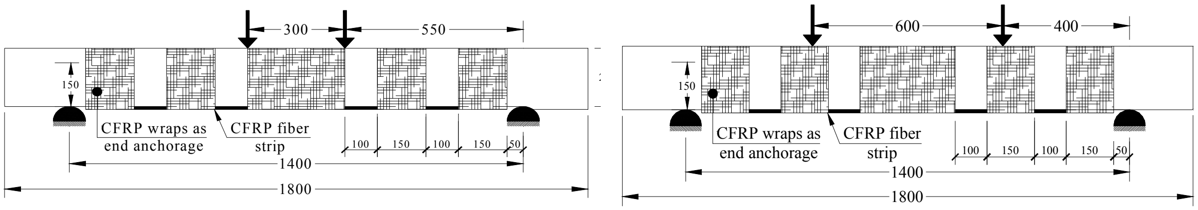
i- Beam B1-1 and B2-1* ii- Beam B1-2 and B2-2*



iii- Beam B1-3 and B2-3*

(*a = 550 mm for beam B1-1, B1-2 and B1-3 and a = 400 mm for Beam B2-1, B2-2 and B2-3)

Fig. 3. Typical strengthening scheme of the beams of Series "B"



i- Beam C1-1(a/d = 3.38, where a = 550 mm) ii- Beam C2-1(a/d = 2.46, where a = 400 mm)

Fig. 4. Typical strengthening scheme of the beams of Series "C"

All RC beams were tested under four point bending condition as simply supported beams with shear loading span (a) as mentioned in Table 1. Mid-span deflections were recorded using displacement gauges. All the measurements were continuously monitored and recorded up to failure.

3. RESULTS AND DISCUSSION

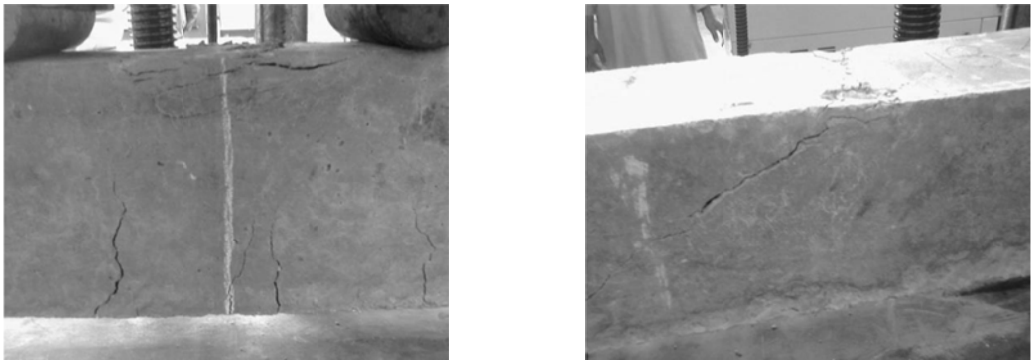
Experimental results are described in the succeeding section in the form of load carrying capacity, mode of failure, load-deflection patterns and the performance factors of control as well as strengthened RC beams.

a) Load carrying capacities and modes of failure

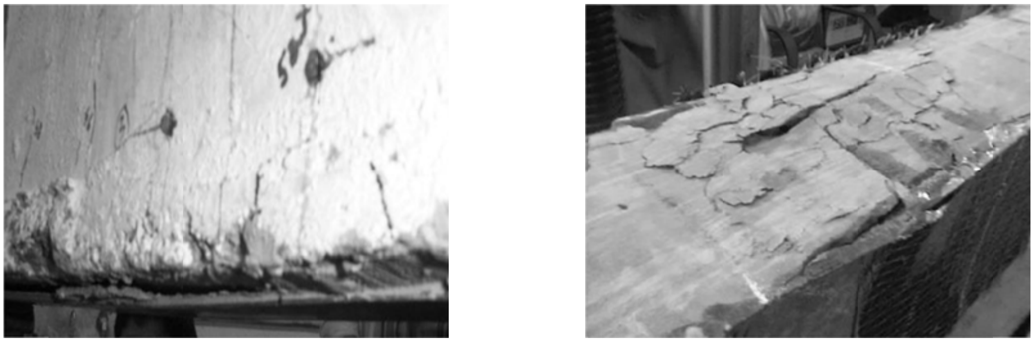
Ultimate loads along with the failure modes of control and strengthened RC beams are presented in Table 3 and Fig. 5.

Beams A1-1 and A2-1 of Group "A" (having no and minimum shear reinforcement, respectively) strengthened by CFRP anchorages only, attained higher load than the control beam and failed in the expected flexure mode of failure. These beams were deficient in shear but failed in flexure failure manner due to the enhancement of the shear capacity of the beams. This enhanced shear capacity of the beam resulted in the transformation of brittle mode of failure into the ductile mode of failure. Failure of the beams A1-1 and A2-1 in flexure led the authors to strengthen the beams in shear in a similar fashion of beams A1-1 and A2-1, but also apply the CFRP strips to observe the beams behavior. The aim of applying CFRP strip was to increase the flexural resistance of the beams. It can be seen from results that use of U-shaped CFRP anchorages and strip together only enhanced the load carrying capacity of the Beams A1-2, A2-2, A1-1 and A2-1, but was not effective in producing desired flexure mode of failure. Beams already had sufficient amount of flexural reinforcement and the additional application of CFRP strip caused the beams A1-2 and A2-2 to fail after debonding of the CFRP strip in flexure and shear zone, respectively. Failure of the beam A2-2 also confirmed the fact that this a/d is shear critical and caused the beam to fail in shear according to Kani [22].

The effect of a/d has also been observed in Group "B". Control Beam B1-0 tested to failure with a/d = 3.38 failed in flexure, whereas control Beam B2-0 failed in shear. The a/d ratio of the beam B2-0 was 2.46. Irrespective of the failure modes of the control beams, all beams of sub group "B1" and "B2" were strengthened by bonding CFRP anchorages and strips in similar fashion by using CFRP strips but variable CFRP anchorages depths (Fig. 3). Test results of strengthened beams showed that variation in the anchorage depths had no influence on the mode of failure and all beams of sub group "B1" failed in flexure and most of the beams of sub group "B2" failed in shear. Results presented in Table 3 show that the application of partial depth CFRP anchorages is more suitable than full depth anchorages, particularly the load carrying capacity of those RC beams in which CFRP anchorages applied to 3/4 depth are found to be highest, irrespective of the shear loading span. The same behavior was observed in the pre-cracked beams of Group “C”, i.e. use of CFRP strip further increased the flexural capacity and failure mode could not be transformed to ductile, though beams were detailed for shear as recommended in ACI 318-08 [23]. After strengthening, failure of the pre-cracked Beam C1-1 was flexure similar to the control; however, failure of Beam C2-1 was mixed flexure and shear failure. This mixed failure occurred after the development of the new flexural cracks that appeared in the pure flexural zone after exceeding 92.3 kN load, but the failure was due to excessive shear cracking in shear span leading to the failure of concrete at end anchorages. During the testing of Beam C1-1, it was observed that cracks appeared during initial loading of the beams opened up and they later on extended towards the compression zone and ultimately led to failure.



(a) Flexure (b) Shear



(c) Debonding in flexure zone (d) Tension steel yielding followed by crushing of concrete

(e) Debonding of end anchorage due to shear failure of concrete

Fig. 5. Different failure modes for un-strengthened and strengthened RC beams

Table 3. Experimental failure loads and failure modes

Series	Nomenclature	Loading span	Experimental failure load (kN)	% Increase in the ultimate load after strengthening	Failure mode of the strengthened beam
"A"	A1-0	550 mm (*a*/*d* = 3.38)	36.5	-	Shear failure
	A1-1		45	23.3%	Flexure failure
	A1-2		57.5	57.5%	Flexure after debonding of CFRP strip in flexure zone
	A2-0	400 mm (*a*/*d* = 2.46)	38.85	-	Shear failure
	A2-1		47.5	22.3%	Flexure failure
	A2-2		55	41.6%	Shear failure
"B"	B1-0	550 mm (*a*/*d* = 3.38)	79	-	Flexure failure
	B1-1		105	32.9%	Flexure failure
	B1-2		115	45.6%	Flexure failure
	B1-3		107	35.4%	Flexure failure
	B2-0	400 mm (*a*/*d* = 2.46)	93	-	Shear failure
	B2-1		97	4.3%	Shear failure
	B2-2		130	39.8%	Flexural shear failure
	B2-3		117	25.8%	Shear failure
"C"	C1-0	550 mm (*a*/*d* = 3.38)	68	-	Tension steel yielding
	C1-1		101	48.5%	Tension steel yielding followed by crushing of concrete
	C2-0	400 mm (*a*/*d* = 2.46)	92.3	-	Shear failure
	C2-1		117	26.8%	Debonding of end anchorage due to shear failure of concrete

b) Load-deflection patterns

Figures 6 to 8 show the comparison of the load-deflection behavior for the control and strengthened beams of all groups with/without CFRP strips and U-shaped anchorages at the mid-span and ends.

Load-deflection patterns of all the beams of Group "A" (Refer to Fig. 6) strengthened with CFRP strips are stiff in comparison to the corresponding control beams. As mentioned in the preceding section, all strengthened beams attained added load in the range of 22% to 57% in comparison to the corresponding control beams. U-shaped anchorages applied in the shear span aided in improving the ductility of the strengthened RC beams, which expected to be sudden and brittle in control beams. U-shaped anchorages increased the ductility alongside the enhancement of shear capacity of the beam section in addition to the shear resistance offered by the concrete in the form of end anchorages.

Load-deflection patterns for the beams of series "B" are shown in Fig. 7. A sudden drop is observed in the load carrying capacity of the beams due to either delamination of CFRP strips or anchorages resulted by the excessive shear, flexure or mixed flexure-shear cracking. Excessive flexural cracking in the beams of sub-group "B1" was observed; however, in the beams of sub-group "B2", excessive shear, flexure or mixed flexure-shear cracking has been observed due to variable height of end anchorages.

The comparison of load-deflection patterns in Fig. 8 showed that the load-deflection patterns for all the strengthened beams are stiff in comparison to the corresponding control beams. All pre-cracked strengthened beams carried aided load in comparison to the corresponding control beams as U-shaped anchorages provided at the ends and at mid span helped in increasing the flexural capacity, shear capacity and ductility of the section. U-shaped anchorages also prevented premature failure that may occur due to the de-boning of CFRP strips thereby improving the performance as compared to the respective control beams.

c) Performance factor (PF)

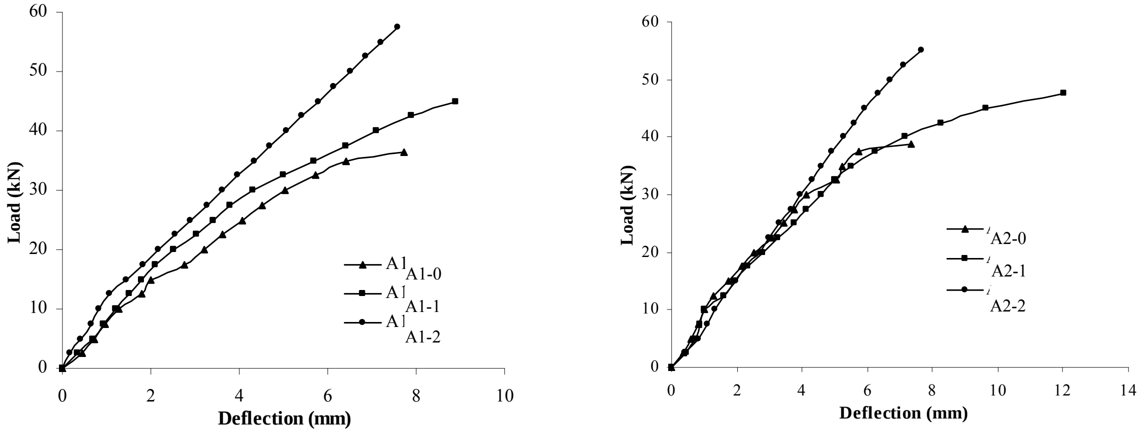
Deformability and strength are two important factors that define performance of any structure.In fact, both factors need to be optimized while selecting materials, design parameters and detailing [15].

Strength and deformability are related to the serviceability and ultimate limit state for strengthened RC beams. Serviceability limit state is the stage when the compressive strain of the concrete reaches the linear behaviour, i.e. at a strain of 1000 μm/m. Several tests demonstrated that this is an appropriate value, after which non-linear structural performance is assumed to initiate. Deformability factor (DF) and strength factor (SF) are explained as follows [15]:

$$DF = \frac{Deflection\ at\ Ultimate\ State}{Deflection\ at\ \varepsilon_c = 1000\ \mu m/m} \tag{1}$$

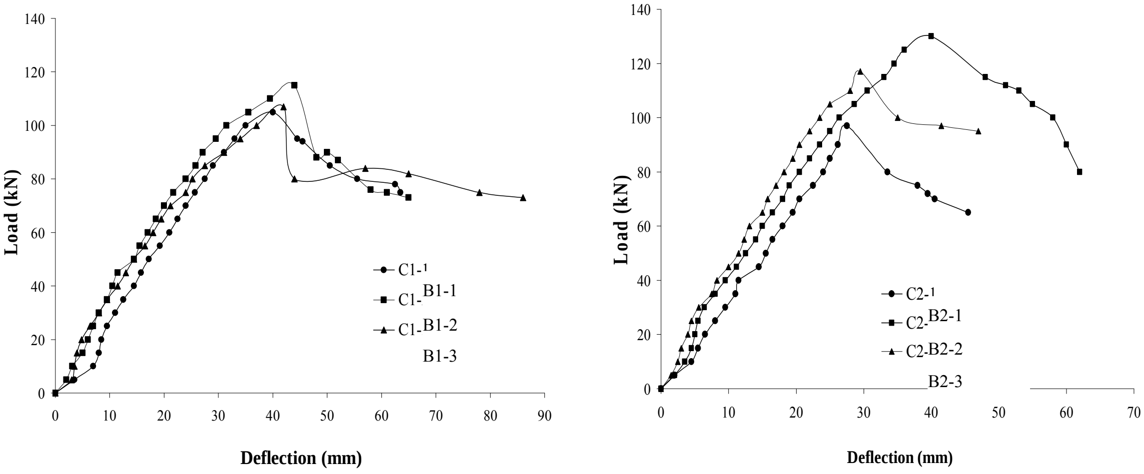
$$SF = \frac{Load\ \ at\ Ultimate\ State}{Load\ \ at\ \varepsilon_c = 1000\ \mu m/m} \tag{2}$$

The overall structural performance of the strengthened beam is evaluated by a global factor defined as Performance factor (PF), which is defined by Spadea et al. [15] as:



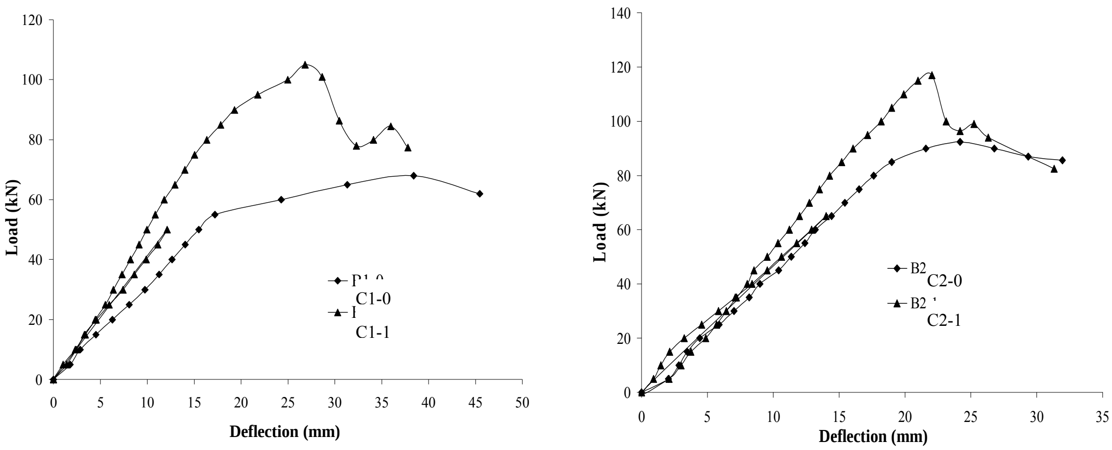
(a) Beam A1-0, A1-1 and A1-2 (b) Beam A2-0, A2-1 and A2-2

Fig. 6. Load – deflection patterns for Series “A”



(a) Beam B1-1, B1-2, and B1-3 (b) Beams B2-1, B2-2 and B2-3

Fig. 7. Load – deflection patterns for Series “B”



(a) Beam C1-0 and C1-1 (b) Beam C2-0 and C2-1

Fig. 8. Load – deflection patterns for Series "C"

$$PF = DF \times SF \tag{3}$$

The calculated performance factors (PFs) for the control and strengthened RC beams are presented in Table 4, which shows that a properly designed exterior anchorage system can significantly enhance the performance features in the form of strength and deformability.

By looking at the Table 4 for the PF of Group "A" beams, it can be seen that PFs for all the beams are higher than their respective control beams except for the beam A2-2. This can be attributed to the fact that this beam failed in shear which is a brittle mode of failure and therefore has low DF which resulted in overall low PF. Enhancement in PFs of beams A1-1, A1-2 and A2-1varied from 3.6% to 22.6% whereas reduction in PF of beam A2-2 is 22.6%.

Table 4. Performance factors (PF)

Series	Beam	Shear span	DF	SF	PF
"A"	A1-0	550 mm (*a*/*d* = 3.38)	1.9	1.46	2.77
	A1-1		2.069	1.5	3.1
	A1-2		1.75	1.64	2.87
	A2-0	400 mm (*a*/*d* = 2.46)	1.78	1.295	2.3
	A2-1		1.28	2.19	2.82
	A2-2		1.29	1.37	1.78
"B"	B1-1	550 mm (*a*/*d* = 3.38)	1.45	1.31	1.91
	B1-2		1.98	1.53	3.03
	B1-3		2.02	1.53	3.11
	B2-1	400 mm (*a*/*d* = 2.46)	1.41	1.49	2.1
	B2-2		1.52	1.3	1.97
	B2-3		1.51	1.38	2.08
"C"	C1-0	550 mm (*a*/*d* = 3.38)	2.64	1.24	3.26
	C1-1		2.31	1.31	3.03
	C2-0	400 mm (*a*/*d* = 2.46)	1.27	1.09	1.38
	C2-1		1.21	1.17	1.42

Performance factors (PFs) for the beams of sub-group "B1" are similar except for Beam B1-1. This is due to the fact that this beam had been strengthened after testing to failure as un-strengthened control beam and therefore, it has low deformability and strength factors as compared to the other beams. PFs for all the beams of sub-group "B2" are in the same range with almost comparable deformability and strength factors.

In the case of Group "C", PFs of control and strengthened beams were again found to be comparable with 7% reduced performance in the case of beam C1-1 and 3% enhancement in the case of beam C2-1.

It can be seen from the performance comparison of control and strengthened beam that PF proposed by Spadea et al. [15] is a rational and valid parameter to evaluate and assess the structural implications on deformability and strength brought about by externally bonded CFRP strips and external anchorages used in strengthening of RC structural members.

4. CONCLUSION

The following conclusions are drawn from current investigations:

1. Ultimate load carrying capacities of the strengthened RC beams were increased by as much as 57 % for series "A", 46% for series "B" and 48% for series "C" over respective control beam.
2. Shear span to depth ratio (a/d) is the major influencing parameter in terms of failure modes before and after strengthening. This fact, should, therefore, be kept in mind while strengthening the beams, especially where a/d ratio is expected to be less than or equal to 2.5.
3. Height of end anchorages does not affect the load carrying capacities and failure modes in predominant flexural loading regions. In predominant shear loading regions full depth anchorages are recommended to avoid premature and brittle failure modes.
4. U-shaped anchorages provided at ends and at mid-span improved the structural performance of the RC beams strengthened with externally bonded CFRP strips through enhanced strength and greater ductility as can be seen in the case of all the strengthened beams.
5. Properly placed U-shaped anchorages at plate cut-off points and along the span were shown to be effective in optimizing the deformability and strength characteristics of CFRP strengthened RC beams in flexure and shear as is reflected by the performance factor calculated for each beam. Maximum performance enhancement (22.6%) was observed in series "A" beams. They also played their role in transformation of failure mode from brittle to ductile.

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