



Ductility Behaviour of Concrete Beams with Flexural Steel-CFRP Composite Reinforcement

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Abstract. Structural engineers always strived for enhancing the performance of Reinforced Concrete flexure members of the structures incorporating ductility and strength in materials, viz. concrete and reinforcing steel. In the present work, composite of steel and carbon fiber reinforced polymer is used as flexure reinforcement. The composite reinforcement was fabricated in the laboratory by sandwiching woven carbon fiber fabric between steel flats with adhesive. Four concrete beams, one with conventional rebars, and three with the composite as longitudinal reinforcement were cast and suitably cured with water. Experimental results and the structural response of four beams, one of them reinforced with conventional deformed rebars and three with steel-CFRP composite as longitudinal reinforcement have been discussed in this research. Tests were conducted on the beams, supported on two rollers at 1400 mm centre-to-centre, applying two equal symmetrical concentrated loads with a shear span of 400 mm. The deflection at mid-span, deflection ductility ratio, and load-carrying mechanism of the beams with composite reinforcement have been discussed and compared with the beam having longitudinal conventional deformed rebars. The flexural ductility of the beams reinforced with the steel-CFRP composite as flexural reinforcement is found comparable with the beams reinforced with conventional deformed steel rebars.

Keywords: Beam · Ductility · Carbon fibre reinforced polymer (CFRP) · Composite · Shear span

1 Introduction

Fibre-reinforced polymer (FRP) has become an important additional construction material (1) in retrofitting to improve the performance of existing and damaged structural members; and (2) to economize the design of new structures, to carry quasi-static and impulsive loading (Anas et al. 2021a; Anas et al. 2021b; Anas et al. 2020; Anas et al. 2021c, d; Anas and Alam 2021; Anas and Alam 2022a, b; Anas et al. 2022a, b, c, d, e, f, g; Tahzeeb et al. 2022; UI Ain et al. 2022). To enhance the flexural and shear resistance of the beams, shear walls, columns, and slabs, FRP is being extensively used externally

(Bruno et al. 2007). Owing to higher tensile strength and much better resistance in comparison to steel, the carbon-FRP has been widely used in the form of longitudinal rebars in the beams (Demers 1998; El-Hacha et al. 2001; Lieping et al. 2006; Zhao et al. 2007; Aslam et al. 2015; Cao et al. 2015; Cao and Ma 2015; Wang et al. 2019; Deng et al. 2021). Steel undergoes corrosion and affects the durability performance of the reinforced concrete (RC) structures. CFRP does not corrode but its modulus of elasticity is low and it lacks ductility. Low modulus of elasticity, poor ductility, and currently high cost are considered its disadvantages. A good combination of steel and CFRP makes a composite in which one material provides what other material lacks is suitable for rebars to be used in the concrete structure. Due to the high ductility of steel bars and to improve the ductility of the composite system, many researchers adopted additional steel bars inside beams reinforced with FRP (Denvid et al. 2010). In this study, the idea of Aiello and Ombres (2002) was followed by sandwiching CFRP layers, woven carbon fibre fabric, between two mild steel strips to make full-size steel-carbon FRP reinforcement which was fabricated in the laboratory manually and utilized as new longitudinal reinforcement in lieu of steel rebars inside beams. It is worth mentioning that the same materials (Woven carbon fibre, 2-part epoxy impregnation resin, and steel strips) were used by Faris and Alam (2013). Cao et al. (2017) experimentally tested the flexural performance of five expansive concrete and five conventional Portland cement concrete beams. The expansive concrete (EC) beams were reinforced with a hybrid CFRP enclosure and steel rebars. It was concluded that the EC beams with hybrid reinforcement gave the best performance with regards to the ductility and mechanical properties considered. Hollaway and Head (2001) and Zhou et al. (2013) discussed the application of carbon-FRP wrapping for strengthening the structural members and got reduced maximum displacement and width of the flexural cracks.

To examine the mechanical properties of steel-carbon FRP composite longitudinal reinforcement, standard specimens of the composite have been made and tested in this research. Four reinforced concrete beams were tested, one was reinforced with the conventional steel rebars as a reference beam and the remaining three were reinforced with steel-carbon FRP composite as longitudinal flexural reinforcement.

2 Longitudinal Steel-CFRP Composite Reinforcement

To manufacture the longitudinal steel-CFRP reinforcement, following three-material were used:

- Woven carbon fibre fabric, CFRP (SikaWrap®-300C)
- 2-part epoxy impregnation resin Adhesive, (Sikadur®-330) and 1-part hardener
- Strips of mild steel

Two types of longitudinal steel-CFRP reinforcement were fabricated manually:

- 1- Steel-CFRP composite reinforcement with two layers of CFRP and 16 mm wide steel flats of gross cross-sectional area 80 mm².
- 2- Steel-CFRP composite reinforcement with five layers of CFRP and 20 mm wide steel flats of gross cross-sectional area 120 mm².

3 Steel-CFRP Composite Fabrication

The procedure used to fabricate the longitudinal steel-CFRP reinforcement in this study was as follows:

- 1- A full-size mild steel plate has been cut to get a number of 2000 mm blocks, 16 mm and 20 mm wide steel strips using a cutting machine.
- 2- To increase the anchorage of this new composite longitudinal reinforcement in the concrete beam, all strips have been bent at 90° at the ends.
- 3- Following the instruction of the manufacturing company, hardener and resin have been precisely weighed by sensitive balance and thoroughly mixed together using a drill mixer, Fig. 1.
- 4- Using a brush, the adhesive was applied to the prepared steel strips after removing all dust and varnish, Fig. 2.
- 5- The woven carbon fiber fabric which has been already cut to the required size is put onto the adhesive. This step has been completed using a plastic roller rolling along the fabric to remove all excess epoxy and air to get a better bond between the fiber and the steel strip.
- 6- The final step in the procedure of preparing the longitudinal specimens of the composite was to put the second steel strip onto the fibre after applying the adhesive. Parallel clamps were tightened to hold the three components of the specimen together, Fig. 3.

4 Concrete Beams Details

Four concrete beams have been cast. Table 1 shows the complete details of beams considered in this study. The first letter in the designation of a beam represents the type of longitudinal reinforcement used as *S* or *C* (*S*: steel bar reinforcement, and *C*:



Fig. 1. Sensitive balance.



Fig. 2. Using a brush to apply The Sikadur®-330.

composite reinforcement), the first numeral is either the diameter of steel bar or width of composite reinforcement, the next digit represents the number of carbon-FRP layers and the last digit denotes the number of longitudinal rebars used in the beam.

The beams are of 240 mm × 160 mm in dimensions. The span of the beam is 1400 mm, Fig. 4 and Fig. 5. The reference beam namely, S10-2 was provided with two steel rebars of 10 mm diameter, while the other three beams were provided with steel-carbon FRP rebars for instance, C16-2-2; two steel-CFRP reinforcement of width 16 mm, each with two layers of CFRP. C16-2-3 means, there are three reinforcements of steel-CFRP composite reinforcement of width 16 mm and each with two layers of CFRP. C20-5-2 means two reinforcements of steel-CFRP composite reinforcement of width 20 mm and each with five layers of CFRP.

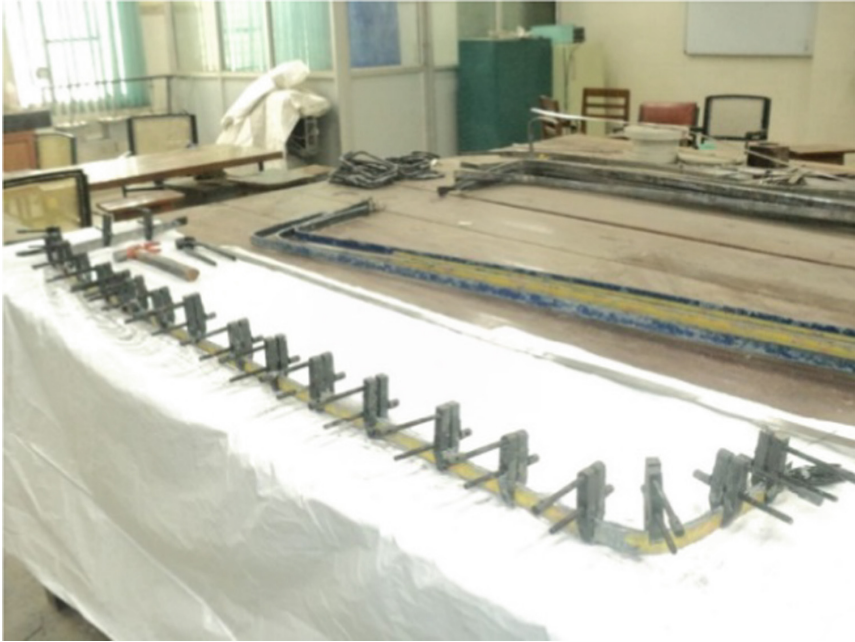


Fig. 3. Parallel clamps to prepare the longitudinal reinforcement.

Table 1. Beams details

Beams designation	Bar type	No. of CFRP layers in each specimen	Diameter or Width of bar of specimen (mm)	Bar Area (mm ²)
S10-2	Steel bar	—	10	79
C16-2-2	Steel-CFRP	2	16	80
C16-2-3	Steel-CFRP	2	16	80
C20-5-2	Steel-CFRP	5	20	120

5 Description of Beams

Six cylindrical specimens of 150 mm diameter and 300 mm height were cast for finding the concrete compressive and tensile strength. The average 28-day compressive strength of concrete was 25 MPa and the average tensile strength from split tests was 3.45 MPa. For all beams, two deformed (HYSD) 10 mm diameter steel rebars have been used as longitudinal reinforcement on compression face. Steel deformed bar of diameter 10 mm was used as two legged stirrups at a spacing of 100 mm centre to centre only in shear spans of the beam, Fig. 4.



Fig. 4. Reinforcement cages of beams.

6 Arrangement of Loading on Beam

Figure 5 shows the loading arrangement beams were tested with. Under four-point loading with two roller supports at 1400 mm centre-to-centre and with shear span of 400 mm, the flexural tests were conducted. Beam testing machine of 500 kN capacity was used to test all the beam specimens at a rate of loading of 2 mm/min (displacement control). Linear variable differential transducer (LVDT) inbuilt with the machine was utilized to measure the mid-span deflection of the beam.

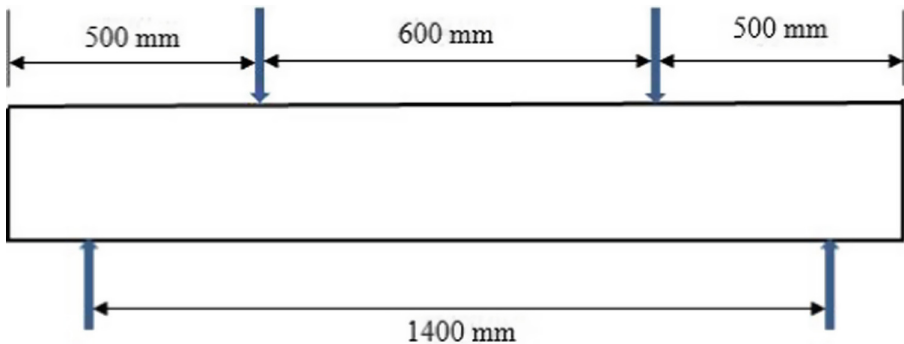


Fig. 5. Arrangement of loading on beam.

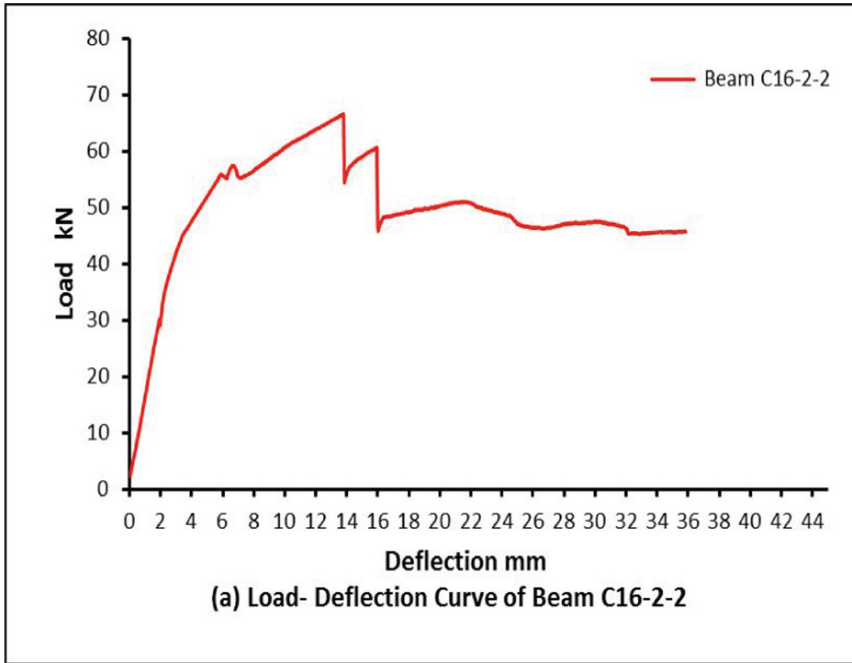


Fig. 6. Load-deflection curve for beam C16-2-2.

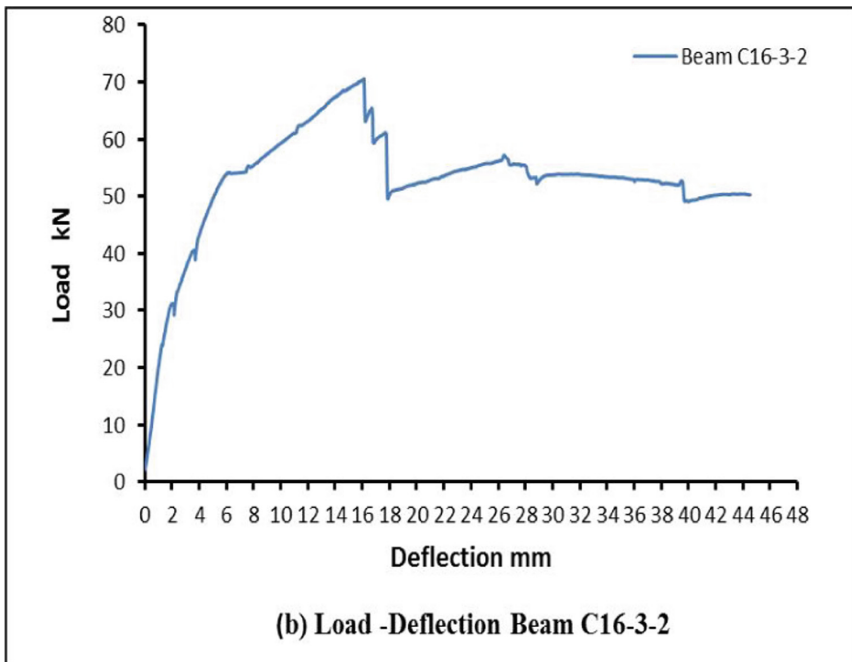


Fig. 7. Load-deflection curve for beam C16-3-2.

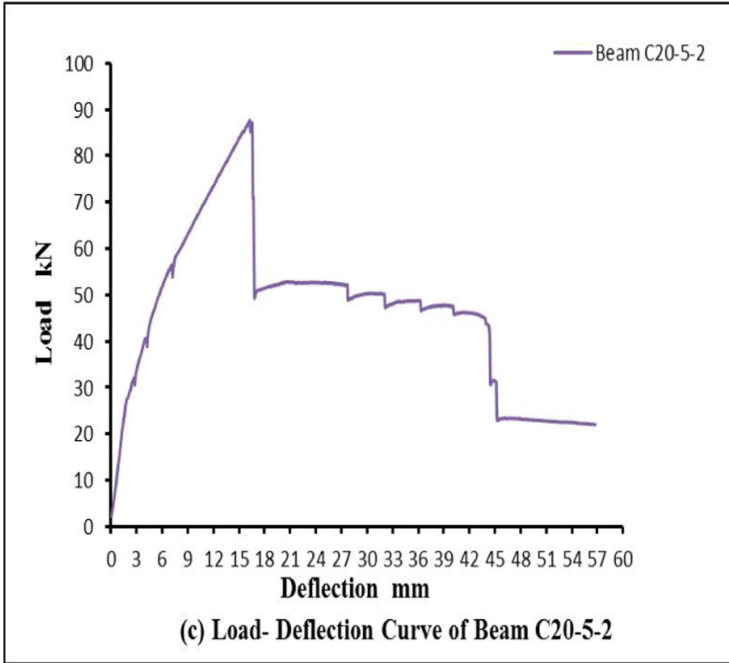


Fig. 8. Load-deflection curve for beam C20-5-2.

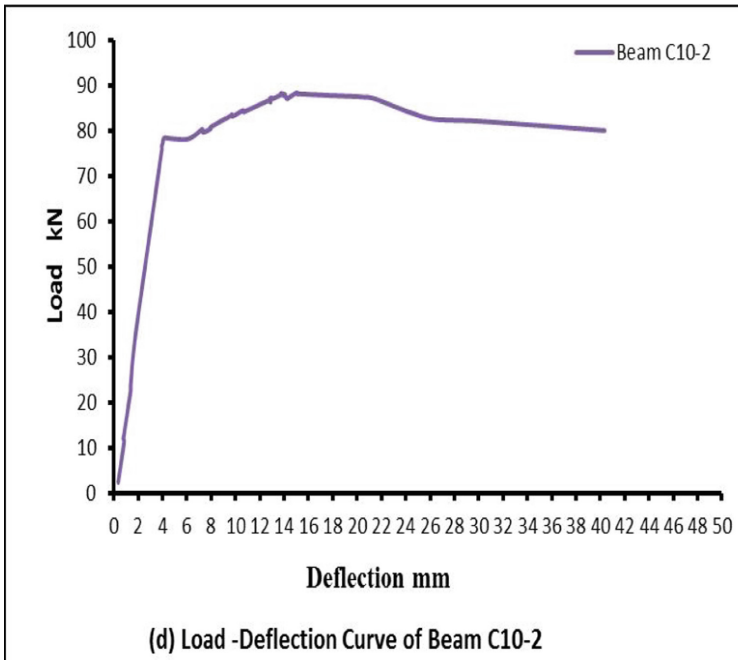


Fig. 9. Load-deflection curve for beam C10-2.

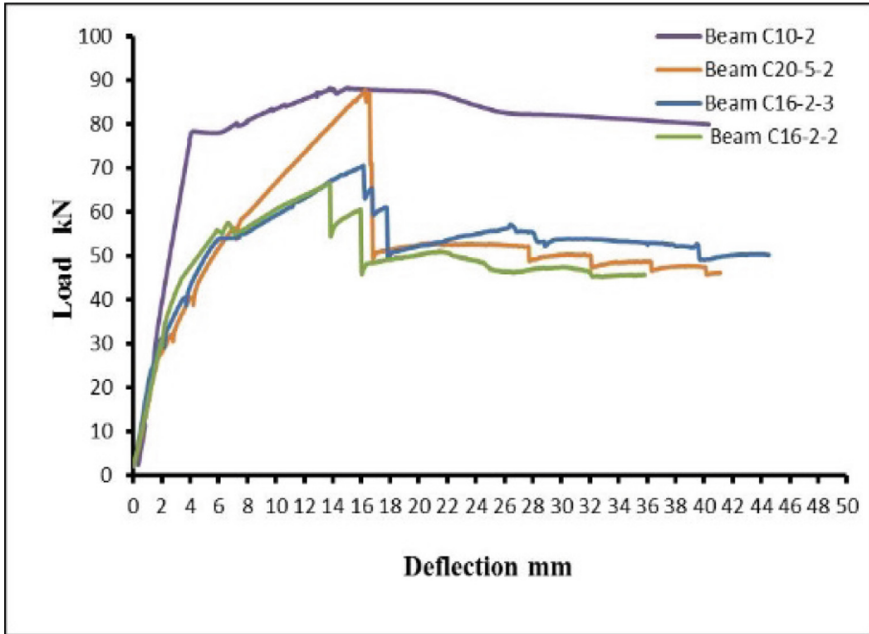


Fig. 10. Load-deflection curves for all beams.

7 Flexural Ductility of Beams

Figures 6, 7, 8, 9 and 10 show the load–deflection curves of the beams tested. Before the rupture of the CFRP laminate of steel-CFRP composite reinforcement, it is clear from these figures that the performance of beam C20-5-2 is comparable with that of beam S10-2 in flexural ductility and ultimate flexural strength, except the former beam experienced a drop in flexural strength when the CFRP laminate ruptured. Moreover, all the beams reinforced with steel-CFRP composite displayed as much flexural ductility as that of beam S10-2 but with lower flexural strength. After the rupture of the CFRP, it could be seen that there was significant amount of ductility remained with the beam owing to the un-ruptured steel strips of the composite reinforcement before the ultimate breaking of the strips. So the role of steel strips was to prevent the catastrophic collapse of the beam after fracture of CFRP laminate of the composite reinforcement. In addition, steel strips contributed along with CFRP laminate as a composite to augment the load carrying capacity of beams.

To discuss the flexural ductility of beams reinforced with steel-CFRP composite quantitatively, Spadea et al. (2001) and Denvid et al. (2010) and many other researchers used the deflection ductility as a criterion. It is the ratio of mid span deflection at ultimate to that at yielding of the reinforcement.

$$\text{Deflection ductility} = \frac{X_m}{X_y} \quad (1)$$

where, X_m = mid-span deflection at failure, and X_y = mid-span deflection at yielding of the steel reinforcement. Reaching to the yield, the stiffness of the hybrid FRP RC member, RC beam which consists of both FRP and steel re-bars, decreases substantially and the load-deformation curve of the beam becomes nonlinear. Therefore, the yield deflection (X_y) can be measured accordingly (Bruno et al. 2007). In this research, similar response was displayed by the beams reinforced with steel-CFRP longitudinal reinforcement, Figs. 6, 7, 8, 9 and 10. Thus, X_m and X_y were measured and used to calculate ductility ratio of the beams as shown in Table 2. It can be seen from Table 2, and Figs. 6, 7, 8, 9 and 10 that the ductility ratio increases with increasing stiffness of the specimens reinforced with steel-CFRP composite reinforcement. The ductility ratio of the specimens reinforced with steel-CFRP is found to be 65% to 80% of the ductility ratio of the beam S10–2. It is worth mentioning that the increase in ductility ratio resulted from increasing amount of steel strips and CFRP laminate used as flexural reinforcement.

Table 2. Ductility ratio of beams

Identification of beams	X_y (mm)	X_m (mm)	$\frac{X_m}{X_y}$	Ductility ratio
S10-2	4	(41)	(10.25)	1.00
C16-2-2	2	13.50	6.75	$(6.75/10.25) = 0.65$
C16-2-3	2.1	16.00	7.61	$(7.61/10.25) = 0.74$
C20-5-2	2	16.40	8.20	$(8.2/10.25) = 0.80$

8 Conclusion

Experimental findings and structural response of the beams with steel-CFRP composite as flexural reinforcement have been discussed and compared with the reference beam with deformed steel bars as flexural reinforcement. Tests results show that the beams reinforced with the composite reinforcement do not lose their ductility and show a good margin of flexural ductility compared to the beam with conventional deformed steel bars. To express the flexural ductility quantitatively, the ductility ratio is found to be increasing with the increase of stiffness of steel-carbon FRP composite reinforcement, however, it stayed less than its peer beam reinforced with conventional steel rebars. The ductility ratio of the beams reinforced with steel-CFRP composite is found 65% to 80% of that of the peer beam (S10–2) provided with two bars of conventional steel. It is inferred that the steel of composite reinforcement contributed effectively to prevent the catastrophic collapse of the beams in addition to its role to augment the flexural ductility and capacity of beams. This research suggests that the use of the CFRP in the form of bar or sheet along with conventional deformed rebars or on the tension surface is useful to enhance flexural resistance without sacrificing the ductility of the flexure member.

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