Acta Technica Napocensis: Civil Engineering & Architecture Vol. 56, No. 2 (2013)
Journal homepage: http://constructii.utcluj.ro/ActaCivilEng
Special Issue: First International Conference for PhD Students in Civil Engineering, CE-PhD 2012.

Flexural Performance of Reinforced Concrete Beams Strengthened with Composite Materials

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(Accepted 28 August 2013; Published online 2 October 2013)

Abstract

Carbon fiber-reinforced polymer (CFRP) composite materials have proven to be a viable alternative to traditional materials in strengthening reinforced concrete (RC) structures. In this context, the current paper presents an experimental investigation regarding the flexural behavior of five RC beams from which one was used as a control specimen and the other four were preloaded until flexural cracks appeared, unloaded and then strengthened with either a single CFRP laminate or a pair of them. Bending was induced by two different loading schemes until failure of the composite system occurred. The following aspects of the flexural responses of the tested beams are analyzed: failure types and crack patterns, strain distributions in the composite material and displacement profiles. Final observations have confirmed the efficiency of the composite strengthening system and revealed possible ways in which the system's performance can be improved.

Rezumat

Materialele compozite din polimeri armați cu fibre de carbon (PAFC) s-au dovedit a fi o alternativă viabilă la materialele tradiționale folosite in ranforsarea structurilor din beton armat. În acest context, studiul de față prezintă o investigație experimentală privind comportarea la încovoiere a grinzilor de beton armat ranforsate cu laminate din PAFC. S-a încercat un număr de cinci grinzi dintre care o grindă a fost folosită ca reper iar celelalte patru au fost încărcate până la apariția fisurilor din încovoiere, descărcate și ranforsate cu un laminat sau două din PAFC. S-au folosit două scheme de încărcare iar încovoierea s-a efectuat până la cedarea sistemului compozit. Au fost analizate următoarele aspecte ale răspunsului la încovoiere: modurile de cedare și tiparele de fisurare, distribuția deformațiilor unitare în materialul compozit, precum și deplasările verticale ale elementelor structurale. Rezultatele au confirmat eficiența sistemului de ranforsare bazat pe materiale compozite și au indicat moduri posibile de îmbunătățire ale performanței acestuia.

Keywords: composite materials; flexural strengthening; CFRP; reinforced concrete beams; experimental study.

1. Introduction

Interest in the durability of buildings is a constant preoccupation for the engineering environment. In this context the studies regarding the use of composite materials have appeared, determined by a

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series of factors such as ageing of structures, more stringent design requirements, construction errors or the need for seismic retrofitting. Strengthening reinforced concrete (RC) members by bonding external fiber-reinforced polymer (FRP) plates or sheets has proven to be an effective method for upgrading structural performance under both service and ultimate load conditions [1,2]. Due to economic and environmental reasons it is preferable to repair or strengthen concrete structures rather than to replace them totally.

Today, a significant part of the composite materials used for strengthening are carbon based. Considering all reinforcing fiber materials used to produce FRPs, the carbon fibers have the highest specific modulus and specific strength which provide a great stiffness to the system, being an ideal choice to be applied in structures sensitive to weight and deflection [3,4]. Compared with steel, carbon fibers can be five times lighter and present a tensile strength eight to ten times higher.
Research has demonstrated that applying carbon-fiber-reinforced polymer (CFRP) laminates to reinforced concrete beams can increase the stiffness and maximum load of the beams. Further observations proved that the application also delays the cracking moment and mitigates the development of cracks [5]. In a study by Toutanji et al. [6], beams retrofitted with CFRP laminates displayed an increased ultimate load up to 170% as compared to the control beams. Although strength had increased, it was pointed out that ductility and serviceability constraints limited the percentage increase to about 40%.

Most of the investigations carried out on reinforced concrete members strengthened in flexure have indicated that externally bonded reinforcement technique cannot fully utilize the strength of the fiber-reinforced polymer composites [7]. Brittle failure due to premature FRP debonding and concrete cover separation has been the most common type of failure [8]. The debonding mechanism results in the loss of the composite action between the concrete and FRP laminates and initiates when high interfacial shear and normal stresses exceed the strength of concrete. Brena et al. [9] reported that because of brittle failures, the strength utilization ratios of plates were sometimes as low as 15-35%, depending on their cause of debonding.

The objective of the current investigation was to study the flexural performance of real-scale reinforced concrete beams retrofitted with CFRP laminates. Even though many studies have been conducted until now, a significant part of the tests were realized on small scale specimens due to high costs involved. The following aspects of the flexural response of the tested beams were analyzed: failure types and crack patterns, strain distributions in the composite system and displacement profiles.

2. Experimental program

The experimental work consisted in testing under four-point bending five simply supported beams, extensively instrumented with focus on their flexural behavior. All beams had the same geometry and internal longitudinal and transversal reinforcement.

One of the beams was used as a control beam (reference specimen) and was tested without the application of a strengthening system while the other four were preloaded until flexural cracks appeared and then retrofitted with carbon fiber (CFRP) laminates. Two CFRP systems were used for strengthening, consisting of one or two laminates applied on the tensioned face of the element. The retrofitted beams were then loaded until failure and the results were processed and compared.

2.1 Test beam details and materials

All of the tested specimens had a total length of 4500 mm and a clear span of 4000 mm with a cross section of 200 by 400 mm. For flexural reinforcement two 12 mm steel bars were positioned at the top and bottom of each beam. As for shear reinforcement, 12 mm steel stirrups were placed every 200 mm along the length of the beam. The concrete had a compressive strength of 36 MPa and the steel reinforcement, type B500 S, had a yielding strength of 500 MPa and a modulus of elasticity of 200 GPa.

Structural damage was induced by preloading the beams before the retrofitting procedure, using the same test setup as in the loading phase. The preload, which represented approx. 40% of the maximum load of the control beam, produced between 9 and 11 permanent flexural cracks and a maximum vertical deflection of 2 mm.

Reference beam B00-REF had no external reinforcement attached and was designed to fail in flexure like any conventional RC beam. The remaining four specimens were strengthened by applying one or two CFRP laminates. The composite strips were identical in size, 50 mm wide and 1,4 mm thick, and were bonded on the tension face of the beam (Fig. 1). No external anchorage system was installed on top of the composite system.

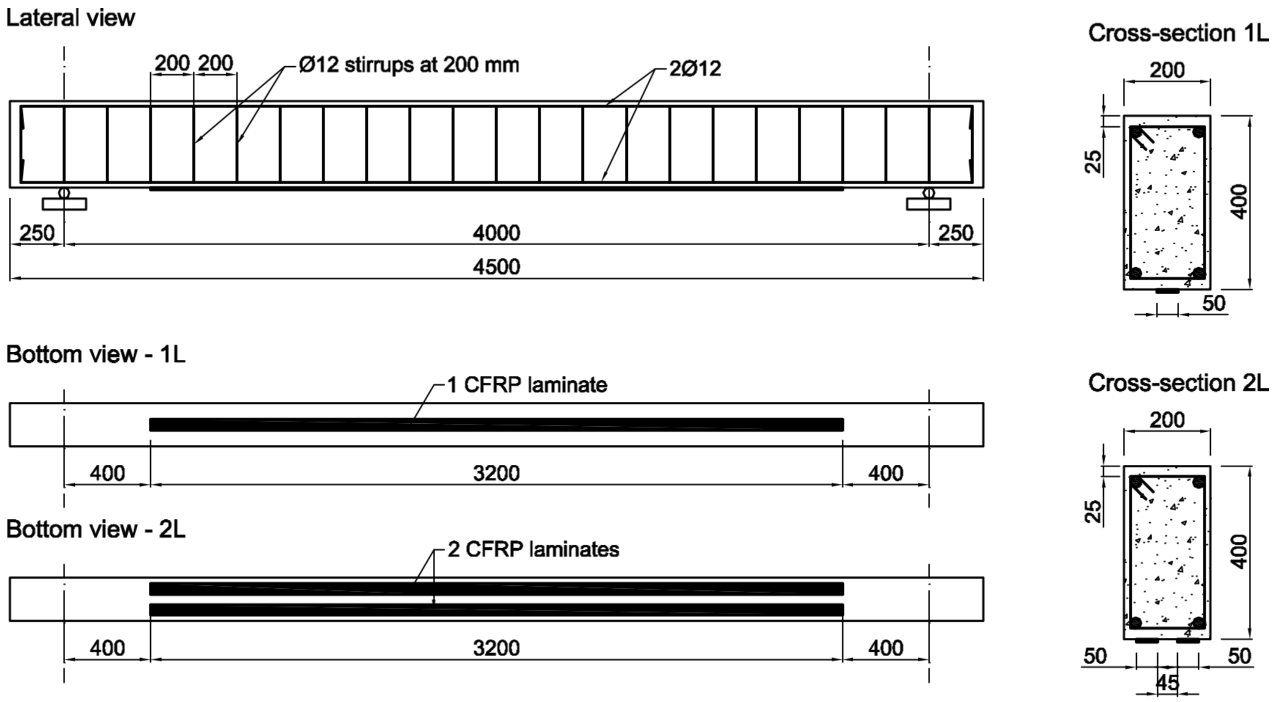

Figure 1. Details of test beams, reinforcement layout and strengthening schemes.

Laminates used in the experimental research had a low elastic modulus and were brought in semi-rigid formats. This type of carbon fiber strips presents a completely linear stress-strain curve up to failure, with no problems of premature rupture under maintained load and it was chosen due to its well defined material properties as opposed to those of a wet lay-up system. The CFRP strips had a fiber volume of 68%, a density of 1,6 g/cm^3, a modulus of elasticity of 158 GPa, an ultimate tensile strength of 2200 MPa and an elongation at break of 1,5 %.

2.2 Test setup and instrumentation

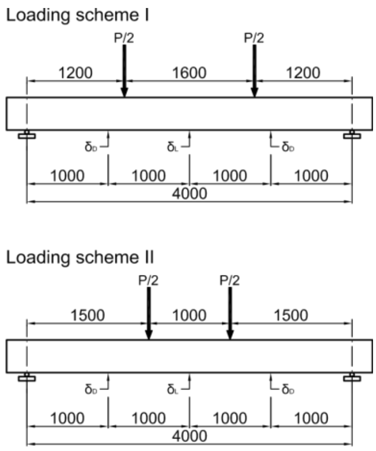

Figure 2. Loading scheme types.

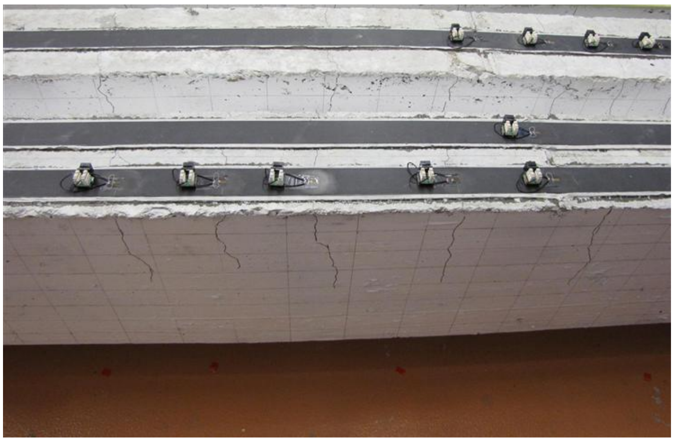

Figure 3. Positioning of the strain gauges above the flexural cracks.

Experiments took place one week after the installation of the composite system. Two loading schemes were used, the difference residing in the distance between the applied forces (Fig. 2). Deflection was measured at the mid-span section and at a one meter distance relative to the center. An overall description of the tested specimens, together with their corresponding equivalent reinforcement coefficient ρ_{eq}, is presented in Table 1.

Table 1: Description of the test beams

Test-beam	Loading scheme	Number of laminates	CFRP area (mm^2)	ρ_{eq} X 10^{-2}
B00-REF	I – 1,6 m	-	-	0,283
B01-I-1L	I – 1,6 m	1	70	0,352
B02-I-2L	I – 1,6 m	2	140	0,421
B03-II-1L	II – 1,0 m	1	70	0,352
B04-II-2L	II – 1,0 m	2	140	0,421

Electrical strain gauges were attached on one half of each beam in order to measure the strains in the CFRP strips. The gauges were fitted to match the flexural cracks developed in the preloading stage (Fig. 3). Additional strain gauges were positioned on the compressed top face of the concrete.

3. Test results and observations

3.1 Failure types and crack patterns

All beams experienced a brittle failure mechanism, characterized by the loss of composite action through plate debonding. This type of failure was due to high shear stresses occurring at the interface between the concrete and the CFRP plates. No failure took place in the epoxy adhesive layer. Plate detachment resulted typically in a layer of adhesive and cement paste still being attached to the FRP surface.

Failure modes fell broadly into two groups: those initiated by flexural cracks within the constant moment zone (Fig. 4) and those that occurred within the shear span of the beams (Fig. 5), initiated by shear cracks. For specimens B01-I-1L, B03-II-1L and B04-II-2L the debonding initiated in the pure bending region and then propagated towards one of the supports. The debonding plane occurred a few mm inside the concrete cover and in some places along the interface, near the adjacent adhesive layer. For B02-I-2L the debonding occurred earlier than for the other retrofitted beams, the main reason leading to this was the higher shear stress concentration, near the plates' ends. The debonding plane was observed inside the concrete cover along the steel reinforcement.

Figure 4. Mid-span debonding of FRP initiated by a flexural crack.

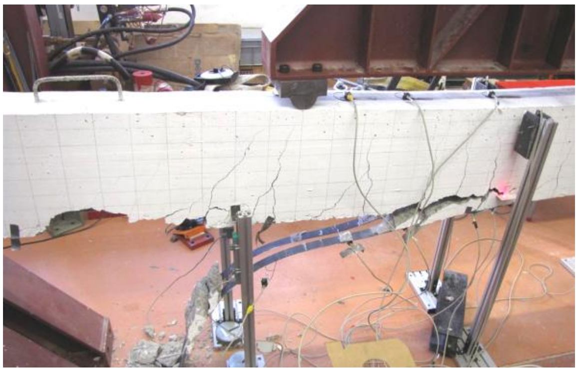

Figure 5. Delamination caused by excessive shear deformation.

The types of failure were found to be dependent on the amount of external FRP reinforcement and on the corresponding loading scheme. On one hand the two laminates attached to specimen B02-I-2L allowed it to reach a higher stiffness and higher moment capacity but on the other hand, compared to specimen B04-II-2L, the loading scheme produced a higher shear force which in the end led to a premature failure of the beam, forming a shear crack between the composites' ends and the loading point. Failure characteristics of the tested specimens are summarized in Table 2.

Table 2: Failure characteristics of the tested beams

Beam	**Mu (kNm)**	**Type of cracks**	**General failure type**	**Specific failure type**
B00-REF	41,4	F	Steel-yielding	-
B01-I-1L	66,5	F	Plate debonding	Intermediate crack interfacial debonding
B02-I-2L	73,4	F-S	Plate debonding	Concrete cover separation
B03-II-1L	66,9	F	Plate debonding	Intermediate crack interfacial debonding
B04-II-2L	91,2	F-S	Plate debonding	Intermediate crack interfacial debonding

The control beam had few flexural large-width cracks while the retrofitted beams had many flexural cracks with smaller widths. This indicates that the propagation of cracks was confined by the CFRP laminates. In addition, the cracks in B02-I-2L and B04-II-2L were fewer and had a smaller width than in the other retrofitted beams. Specimens strengthened with two CFRPs were characterized by the occurrence of shear (S) and flexural (F) cracks before debonding. In the meantime, specimens strengthened with a single CFRP strip were characterized by the occurrence of only flexural (F) cracks before debonding. The load capacity of the retrofitted beams was increased up to 120%.

Since all failures occurred in a brittle manner by plate debonding it is assumed that the full potential of the composite strengthening system was not used. Keeping the composite action of the strengthened beam is essential to the satisfactory performance of the plate-bonded system, so adequate anchorage of the CFRP plates at the ends and at other critical sections of the beams are essential prerequisites to maintain this composite action up to failure.

3.2 Strain distributions

The examination of the fracture surfaces of the poststrengthened beams raised the possibility that the debonding failure was caused by differential displacements in crack tips. The development of a crack in the concrete substrate might produce high strain concentration points in the FRP, inducing the tensile or shear failure of the reinforcement plate, or might initiate a local debonding, which then progresses alongside the beam.

After failure of the tested beams, observations were made concerning the impregnated patterns on the face of the CFRP strips that were in contact with the epoxy adhesive. As shown in Figure 6, for the beams where the debonding started in the middle, initiated by flexural cracks, there was a pattern that described the way the interfacial stresses were transferred during the loading stage.

Figure 6. Detail of the middle of the CFRP strips.

Figure 7. Detail of the ends of the CFRP strips.

However, the ends of the plate did not show any patterns, sign that they were pulled-off when failure occurred (Fig. 7). Figures 8-11 show the determined experimental strain profiles for the CFRP strip(s), from the high moment region to the plate's end, from zero to maximum force value. Graphics were computed for one half of the beam for symmetrical reasons. Similarity between the real and the measured strain profile is higher at lower loads while at levels closer to the maximum load, the experimental behavior becomes more irregular, probably due to the development of cracking, which the linear model simulates more roughly.

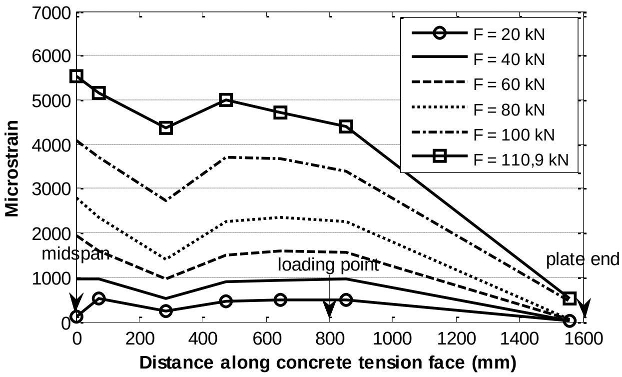

Figure 8. Experimental CFRP strain profile of beam B01-I-1L.

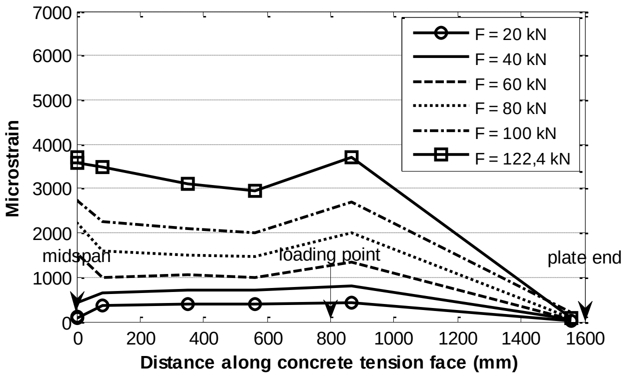

Figure 9. Experimental CFRP strain profile of beam B02-I-2L.

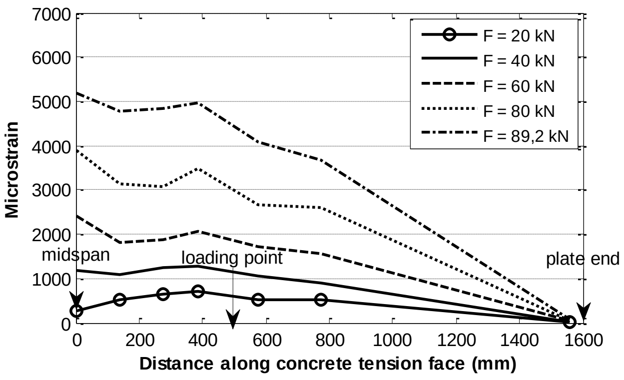

Figure 10. Experimental CFRP strain profile of beam B03-II-1L.

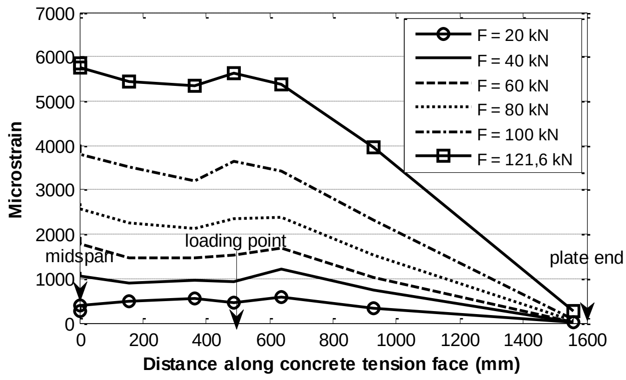

Figure 11. Experimental CFRP strain profile of beam B04-II-2L.

Regarding the general shape of the measured profiles, the CFRP strain behavior was similar for all the retrofitted beams except B02-I-2L, which suffered a different type of failure, by concrete cover separation, as described in the previous subsection. All beams experienced significantly higher strains when the applied load surpassed 80 kN. The strain profile of B01-I-1L indicated that the ultimate strain at 110,9 kN was just over 5500 με. The maximum value was recorded, as expected, at the middle span of the beam. Near the loading point the strain exhibited a small increase while at the end of the plate the value registered a minimum. The maximum strain value of 3800 με was registered for beam B02-I-2L at 100 mm to the right of the loading point. The value is really low considering the fact that only 27% of the CFRP’s ultimate capacity was used. This can be explained by the important shear deformations which occurred in that area, causing the premature peeling-off failure. For the remaining beams, B03-II-1L and B04-II-2L, the maximum measured strains at the middle span were approx. 5200 με and 5900 με, close to the registered values of beam B01-I-1L.

Table 3 presents for each beam the ultimate force and moment, the applied composite reinforcement area, the ultimate strain and stress measured and the corresponding FRP strain and FRP strength utilization ratio.

Table 3: Comparison of FRP strain and stress utilization ratios

Beam	**F_u (kN)**	**M_u (kNm)**	**A_{FRP} (mm^2)**	**$\varepsilon_{u,FRP}$ (μm)**	**FRP strain ratio (%)**	**$\sigma_{u,FRP}$ (MPa)**	**FRP strength ratio (%)**
B01-I-1L	110,9	66,5	70	5527	37	873	40
B02-I-2L	122,4	73,4	140	3800	25	600	27
B03-II-1L	89,2	66,9	70	5178	36	818	37
B04-II-2L	121,6	91,2	140	5858	39	926	42

The average strain value obtained during the tests was between 5000 με and 6000 με, sign that could indicate that the ultimate tensile strength developed in the CFRP plates was independent of the area of composite reinforcement and more reliant on the strength of the adherent concrete. Typical shear strength of concrete is high enough to transfer composite forces, however, as the beam bends, microcracks occur in the concrete, just above the epoxy adhesive, to compensate for the strains in the composite. The average FRP strength utilization ratio was only 37%. As a consequence, further improvements should be made in the design of the retrofitting system, by including anchorages at the beam’s ends in order to prevent premature failures by delamination.

3.3 Displacement profiles

An analysis of the measured deflections of the tested beams is illustrated in Fig. 12-15. The deflections along the length of the specimen are plotted at different force levels. The retrofitted beams developed lower displacements for higher force loads compared to the control beam.

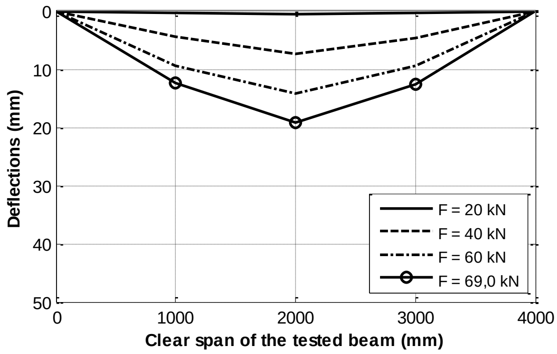

Figure 12. Displacement profile for beam B00-REF.

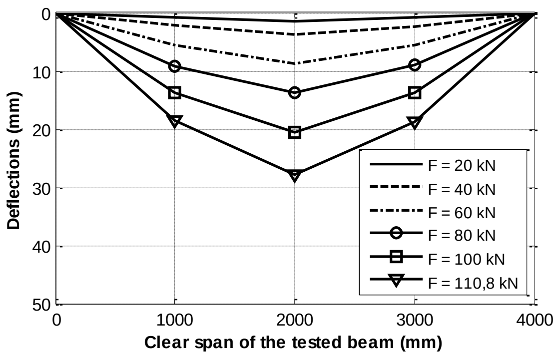

Figure 13. Displacement profile for beam B01-I-1L.

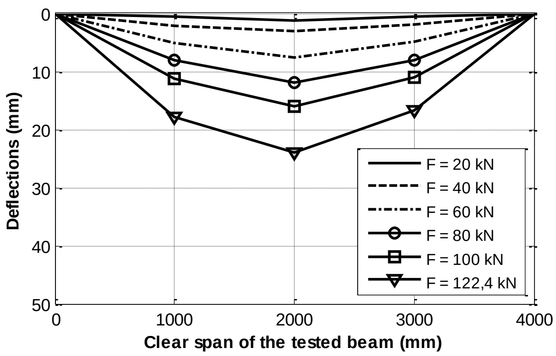

Figure 14. Displacement profile for beam B02-I-2L.

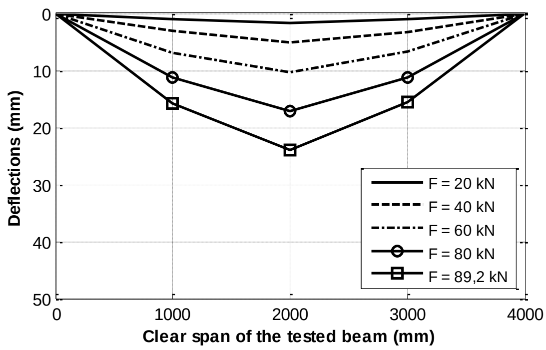

Figure 15. Displacement profile for beam B03-II-1L.

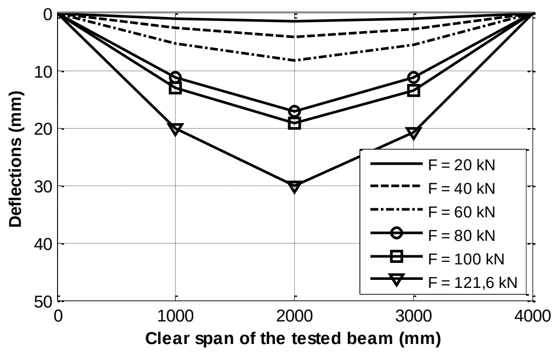

Figure 16. Displacement profile for beam B04-II-2L.

Maximum registered values were between 20 and 30 mm, higher for the double plated beams. Ultimate displacement values depended also on the failure mode of each beam.

4. Conclusions

The tests regarding the flexural performance of RC beams strengthened with composite materials showed that the externally bonded CFRP strips increased the ultimate capacity of the single-plated beams by a maximum of 61% and for the double-plated beams by a maximum of 120%, while crack widths and global deflections decreased. The ultimate load-carrying capacities of the retrofitted beams depended largely on the mechanical characteristics of the cover concrete so bonding a CFRP plate as external reinforcement without consideration of the end-anchorage stresses resulted in significant deficiency in deflection and rotational capability. Failure of the strengthened beams occurred in a brittle manner, with explosive debonding of the laminates. With such a failure mode, the concrete member was unable to make full use of the strength of the CFRP plates, which was clearly underused at a mere 27-42%. In order to delay the CFRP debonding, as well as to increase the efficiency of the strip, additional U-jacket strips or sheets located in the debonding initiation regions should be installed.

Acknowledgements

The author greatly acknowledges the support of CER LITEM-UPC and of the UPC Department of Strength of Materials and Structural Engineering.

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