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Research Article / Araştırma Makalesi

INFLUENCE OF CFRP ON THE STRENGTH OF RETROFITTED RC BEAMS WITHOUT STIRRUPS

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ABSTRACT

Experimental investigations were conducted to study the behavior of reinforced concrete (RC) and steel fiber reinforced concrete (SFRC) beams retrofitted and strengthened with carbon fiber reinforced polymer (CFRP). Four beams, each of which has a longitudinal reinforcement ratio of 1.34% and a shear span-to-effective depth ratio of 2.5, were tested under mid-span concentrated loads. The specimens consisted of a RC beam, a SFRC beam with 2.0% volume fraction of steel fibers and their companion beams that were loaded up to a certain damage level and then retrofitted with CFRP. The retrofitted beams were intentionally designed to be incompatible with the minimum requirements given by the code for FRP design. However, test results show that the retrofitting with CFRP increases the ductility of RC beams significantly even under such incompatibility.
Keywords: reinforced concrete; beam; carbon fiber reinforced polymer; strength; steel fiber.

ONARILAN ETRİYESİZ BETONARME KİRİŞLERİN DAYANIMINDA CFRP ETKİSİ

ÖZ

Bu çalışmada, hasar görmüş betonarme ve çelik lifli betonarme kirişlerin onarımı ve karbon lifli polimer (CFRP) ile güçlendirilmesinin kiriş davranışına etkisi incelenmiştir. Kesme açıklığının kiriş etkili derinliğine oranı 2.5 ve çekme donatısı oranı %1.34 olan dört kiriş açıklık ortasından tekil yüklenerek test edilmiştir. Test elemanları yalnız çekme donatılı, hacimsel çelik lif oranı %2 olan kirişler ve bu kirişlerin belirli bir hasar düzeyine kadar yüklenerek hasar gören ve daha sonra onarımı ve CFRP ile güçlendirilen kirişlerden oluşmaktadır. Onarımı ve güçlendirilmesi yapılan kirişler FRP ile ilgili yönetmeliklerdeki FRP genişliği ve boşluğu sınırlarının altında tasarlanmıştır. Fakat test sonuçları onarılan ve yönetmelik sınırlarının altında tasarlanan CFRP ile güçlendirilmesi yapılan kirişlerin düktilitesinde de önemli artışlar olduğunu göstermiştir.
Anahtar Sözcükler: Betonarme, kiriş, karbon lifli polimer, dayanım, çelik lif.

1. INTRODUCTION

The issue of upgrading the existing civil engineering structures has been of great importance for over a decade. The reasons of strengthening of structural members can be summarized as

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possible changes in the purpose of use after the construction, deficiencies in seismic performance, corrosion of steel, aging, poor workmanship etc. The aim of the strengthening is to improve load-carrying capacity, rigidity and ductility. There are various techniques for strengthening the existing structural members, one of which is to use fiber reinforced polymers (FRP). The advantages of FRP are high tensile strength, immunity to corrosion, low weight, easy application even in confined space, etc.

Previous experimental and analytical investigations show that using FRP increases the load-carrying capacity and rigidity. Chaallal et al. (1998) investigated the use of carbon FRP (CFRP) laminate strips applied in different angles to strengthen rectangular reinforced concrete (RC) beams in shear and observed an increase in the strength by 70% and improvement in the stiffness. In a similar study conducted by Triantafillou (1998), an increase in the shear strength ranging from 65% to 95% was observed and it was concluded that CFRP strips applied at 45° to the horizontal were more effective than the vertical strips because the fibers were almost perpendicular to the shear cracks. Khalifa et al. (1998) proposed two design approaches for determining the contribution of CFRP to shear strength. One of the approaches is based on the effective FRP stress following the research of Triantafillou (1998) and the other one is based on bond mechanism. In another study, Khalifa et al. (2000) investigated the shear performance of RC beams with T-section strengthened by various configurations of externally bonded CFRP sheets and concluded that externally bonded CFRP sheets are able to increase the shear capacity of RC beams significantly and the most effective configuration is the U-wrap with end anchorage. Lima and Barros (2007) studied the design models of various specifications for shear strengthening of RC beams with externally bonded FRP composites through a statistical analysis on the beams available in the literature and found that analytical formulations cannot predict the contribution of FRP composites to shear strength with enough accuracy. Onal (2009) tested RC beams with insufficient bending and shear strengths strengthened with CFRP sheets under four-point loading and observed an increase in the strength by 40% and a limited increase in the rigidity and energy consumption. Alzate et al. (2009) carried out experimental and theoretical researches on RC beams strengthened with FRP in order to understand interaction mechanisms between the external and internal reinforcements and the concrete, and concluded that the shear capacities of RC beams increase significantly as a result of the CFRP strengthening, especially for the configuration of completely wrapping sections. Menegotto et al. 2009) conducted an experimental work and developed an analytical model in order to predict the underlying mechanisms of the shear strengthening of concrete beams by FRP. Bukhari et al. (2010) reviewed existing design guidelines for strengthening RC beams in shear with CFRP sheets and performed experimental and analytical investigations, in which they concluded that the shear strength was considerably increased by the CFRP sheets and it is beneficial to orient the sheets at 45° to the axis of the beam. Belarbi et al. (2013) reviewed the existing guidelines/specifications for the design of concrete structures strengthened in shear using externally bonded FRP systems and identified the factors that need further investigation.

In this study, four beams without stirrups were tested to study the behavior of RC and SFRC beams retrofitted with CFRP. The specimens consisted of a RC beam and a SFRC beam together with their companion beams loaded up to a certain damage level and then retrofitted with CFRP.

2. EXPERIMENTAL PROGRAM

2.1. Test variables

Four beams without stirrups including a reference RC beam (A2.5R), an SFRC beam (A2.5F2.0) with 2.0% volume fraction of steel fibers (Ulusoy 2015) and their companion beams (DA2.5RC10/10 and DA2.5F2.0C10/10) loaded up to a certain damage level and then retrofitted and strengthened in shear by using CFRP strips perpendicular to their axes were tested under three-point loading to determine their ultimate load capacities. All beams were singly reinforced with two Ø16 bars (d_b = 16 mm bottom reinforcing bars were placed, resulting in a tensile reinforcement ratio (ρ) of 1.34%). Hooked-end steel fibers with a length (L_f) of 30 mm and a nominal diameter (D_f) of 0.55 mm, resulting in an aspect ratio (L_f/D_f) of 54.5, were used as the shear reinforcement for A2.5F2.0 and DA2.5F2.0C10/10 beams.

Specimen details and dimensions of all beams are shown in Fig. 1 and Table 1, where f_c is the concrete compressive cylinder strength, V_f is the volume fraction of steel fibers, ρ is the tensile reinforcement ratio, w_f is the width of CFRP strips and s_f is the spacing of CFRP strips. All beams are 150 mm wide (b_w), 230 mm deep (h), 200 mm effective depth (d), simply supported with a span length of 1000 mm between the supports and loaded at mid-span. The shear span-to-depth ratio (a/d) of each beam was kept constant at a value of 2.5 to govern shear behavior rather than a bending behavior.

The beam designation includes a combination of letters and numbers: A to indicate the series; D to indicate the damaged and retrofitted beams; R to indicate the reference beam; F to indicate the volume fraction of steel fibers; C to indicate the CFRP width and spacing (10/10). For example, a beam of series DA having a volume fraction of steel fibers equal to 2.0%, a CFRP width (w_f) and spacing (s_f) of 100 mm and 100 mm, respectively, is designated as DA2.5F2.0C10/10.

According to Turkish Earthquake Code (2007) and ACI 440 (2008), the FRP spacing (sf) should not exceed the sum of d/4 and the width of the strip (wf). The Italian CNR-DT200 (2004) guidelines indicate that $50mm \le w_f \le 250mm$ and $w_f \le s_f \le \min\left(0.5d, 3w_f, w_f + 200mm\right)$. In this study, the beams were intentionally designed to be incompatible with the minimum requirements given by these codes for FRP design.

Table 1. Properties of beams and CFRP strips

Beams	f_c (MPa)	V_f (%)	ρ (%)	w_f (mm)	s_f (mm)
A2.5R	39.00	0.0	1.34	-	-
A2.5F2.0	21.43	2.0		-	-
DA2.5RC10/10	39.00	0.0		100	100
DA2.5F2.0C10/10	21.43	2.0		100	100

To investigate the effect of V_f on shear behavior, two values of volume fractions (0 and 2%) were selected. According to the provision of ACI318 (2008), Section 5.6.6.2(a), steel fibers should be considered acceptable for shear strength when the dosage rate of deformed steel fibers is not less than 60 kg/m^3. This rate is equivalent to a mixture with V_f = 0.75%. Two of the specimens (A2.5F2.0 and DA2.5F2.0C10/10) satisfy the minimum requirement.

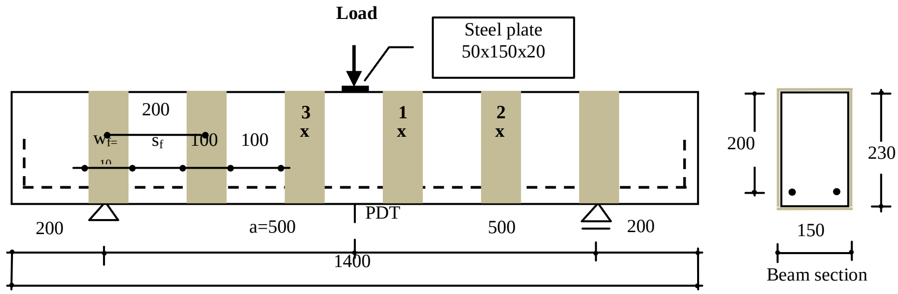


Figure 1. Locations of PDT, strain gauges(1, 2, 3) and section of the test beams (unit: mm)

Generally, three different strengthening schemes in shear are used. These are completely wrapping, three-sided (U-wrap) and two-sided. The scheme of completely wrapping was used in this study. The arrangement of the flexural reinforcement, the cross-sectional dimensions of beams, the locations of strain gauges and potentiometric displacement transducers (PDTs) at the mid-span of the retrofitted and strengthened test beams are shown in Fig. 1. Six PDTs were used for each test to measure net vertical displacement at various locations. Three strain gauges were attached to CFRP strips and oriented along the fiber direction to monitor the strains in the CFRP strips.

A series beams were designed in such a way that shear failure would occur between the support and loading point. On the other hand, retrofitted beams were designed in such a way that flexure failure would occur.

2.2. Materials

The concrete was made of Portland Cement (PC 42.5) and a super plasticizer with retarder meeting ASTM C 494 requirements for Type A admixture. The crushed stone aggregates are expanded clay aggregates with a maximum size of 12 mm and the crushed sand aggregates are natural river sands with a maximum size of 5 mm.

Unidirectional CFRP sheets were used. According to the manufacturer, the CFRP sheets have an elasticity modulus of 230 GPa, an ultimate tensile strength of 4900 MPa, a maximum elongation of 2.1% and a thickness of 0.166 mm. They were bonded on the concrete surface by using an epoxy based resin.

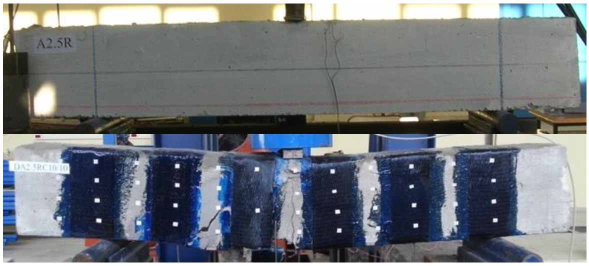
2.3. Retrofitting of beams

It is important to mention that the mechanical concrete surface preparation method (sand blasting, water blasting, or grinder) has a significant effect on the bond behavior of FRP. Before the application of FRP, the corners of the beams were rounded to a radius of 30 mm and surface preparations were made. Then, the concrete surface was prepared by using pressurized air blasting and then epoxy-based primer was used to fill the concrete pores and provide better bond properties. A first coat of epoxy-based resin was applied to adhere first layer of CFRP through the fiber alignment. The strips were then coated with a second layer of epoxy-based resin. The final stage of application was to adhere a second layer of CFRP strips. The beams were made ready for the experiment by keeping them approximately at +25°C temperature until the test day.

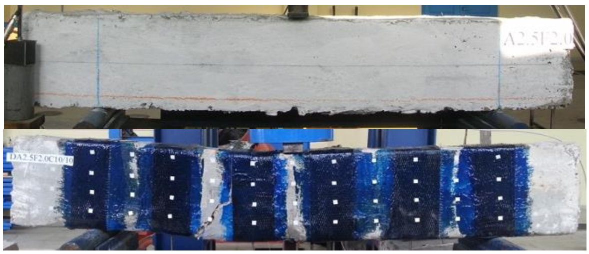
3. RESULTS AND DISCUSSION

3.1. Behavior of test beams

All beams retrofitted and strengthened with CFRP failed in flexure and the crack patterns are shown in Figure 2. During early stages of loading, fine vertical flexural cracks appeared around the mid-span of all beams, as expected. With the increase in load, new flexural cracks were formed away from the mid-span area. With further increase in load, those vertical flexural cracks appeared around the mid-span started to extend towards the loading point (Figure 2). So, the retrofitted beams reached their load-carrying capacities with flexural failures. No slipping failure of longitudinal reinforcements and CFRPs were observed in all beams.



A2.5R DA2.5RC10/10



A2.5F2.0 DA2.5F2.0C10/10

Figure 2. The cracks patterns of test beams at the end of the testing

Table 2. Flexural loads and deflections of beams theoretically and experimentally

Beams	$M_{flex.ACI}$ (kNm)	$P_{flex.ACI}$ (kN)	P_{co} (kN)	δ_{co} (mm)	δ_u (mm)	δ_u / δ_{co}
A2.5R	30.91	123.64	81	1.89	--	--
A2.5F2.0	28.55	114.20	100	5.09	--	--
DA2.5RC10/10	30.91	123.64	180.23	26.82	31.07	1.16
DA2.5F2.0C10/10	28.55	114.20	109.84	10.95	16.57	1.51

The nominal flexural load-carrying capacity $\left(P_{flex.,ACI}\right)$ calculated from the flexural moment capacity $\left(M_{flex.,ACI}\right)$ according to ACI318 (2014), the peak load of beam obtained experimentally P_{co}, the deflection at the peak load δ_{co} and the ultimate deflection δ_u of each beam are given in Table 2.

It is observed from Table 2 that the used shear strengthening technique enhanced the load-carrying capacity. The retrofitted beams exhibited a considerable strength enhancement compared to those of the beams A2.5R and A2.5F2.0.

3.2. Comparison of load–deflection relationships of beams

Load-deflection curves are given in Fig. 3. As can be seen from Fig. 3, the beam DA2.5RC10/10 reached a peak load of 180.23 kN whereas the reference beam reached a peak load of 81 kN. There is an 122% increase in the strength. The use of CFRP increased both the load-carrying capacity and ductility by preventing the development of shear cracks. The rigidity of DA2.5RC10/10 is smaller than that of A2.5RC since the beam DA2.5RC10/10 was damaged.

CFRP retrofitted DA2.5RC10/10 and DA2.5F2.0C10/10 beams exhibited a significantly enhanced behavior particularly in terms of ductility (Fig. 3). Peak loads of 180.23 and 109.84kN were reached at 5.4% and 2.2% drift ratio for DA2.5RC10/10 and DA2.5F2.0C10/10 beams, respectively DA2.5RC10/10 and DA2.5F2.0C10/10 beams failed after 6.2% and 3.3% drift ratio due to rupture of the concrete. DA2.5RC10/10 beam exhibited even a more pronounced enhancement in ductility.

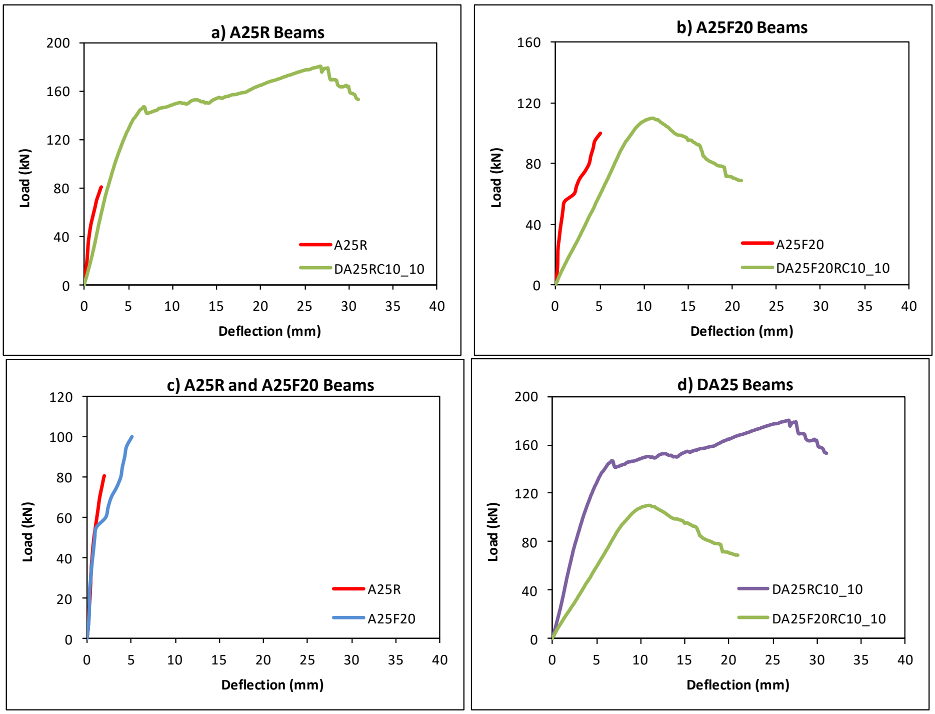


Figure 3. Load-deflection curves of beams

3.3. Strength of beams

The nominal shear strength of RC beam strengthened in shear with full wrapping of the section with CFRP sheets has two components: concrete and CFRP, which is given as follows

$$V_n = V_c + V_{CFRP} \tag{1}$$

in which V_c and V_{CFRP} are the contribution of concrete and CFRP to shear strength, respectively.

In a study conducted by Arslan et al. (2016), the ratios of the experimental values to the corresponding predictions of the equations proposed by Arslan (2014) and Sharma (1986) have a mean value of 0.83 and 1.24 with the lower coefficients of variation equal to 0.12 and 0.15, respectively. It is observed that the equation proposed by Sharma (1986) underestimates the ultimate shear strength of test specimens involved in the study of Arslan et al.'s (2016). In this study, the shear strength of concrete is calculated from the equation proposed by Sharma (1986) for predicting the ultimate shear strength of SFRC beams without stirrups. The equation, which is recommended by ACI 544 (1996), is

$$v_c = kf_{ct}\left(\frac{d}{a}\right)^{0.25} \text{ (MPa)}, \tag{2}$$

where f_{ct} is the concrete tensile strength, $k = 1$ if f_{ct} is obtained by direct tension test, $k = 2/3$ if f_{ct} is obtained by indirect tension test and $k = 4/9$ if f_{ct} is obtained by using modulus of rupture or f_{ct}=0.79$f_c^{0.5}$.

According to ACI 440.2R (2008), the shear strength provided by the FRP reinforcement can be determined by calculating the force resulting from the tensile stress in the FRP across the assumed crack. The shear contribution of the FRP shear reinforcement is then given by

$$V_{FRP} = \frac{A_{fv} f_{fe}(\sin\alpha + \cos\alpha)d_f}{s_f} \tag{3}$$

in which α is the angle of inclination of fibers, d_f and s_f are the depth and spacing of FRP strips, respectively. A_{fv} is the area of FRP reinforcement that can be calculated as $A_{fv} = 2t_f w_f$, t_f and w_f are the thickness and width of FRP strips, f_{fe} is the effective tensile stress in the FRP shear reinforcement at ultimate which is directly proportional to the level of strain that can be developed in the FRP shear reinforcement at ultimate as

$$f_{fe} = \varepsilon_{fe} E_f \tag{4}$$

in which E_f is the elastic modulus of FRP and ε_{fe} is the maximum strain that can be achieved in the FRP system at the ultimate load stage.

Table 3. Strengths of beams theoretically and experimentally

Beams	v_c (MPa) (Eq. 2)	v_{FRP} (MPa) (Eq. 3)	$v_n = v_c + v_{FRP}$ (MPa)	$v_{flex.,ACI}$	$v_{u,Exp.}$ (MPa)	Failure
A2.5R	1.74	---	1.74	2.06	1.35	Shear
A2.5F2.0	1.29	---	1.29	1.90	1.67	Shear
DA2.5RC10/10	1.74	3.05	4.80	2.06	3.00	Flexure
DA2.5F2.0C10/10	1.29	1.38	2.67	1.90	1.83	Flexure

The nominal shear strength can be calculated as a simple superposition of concrete contribution to the shear strength based on Sharma's (1986) equation and the shear strength provided by the CFRP reinforcement according to ACI 440.2R (2008). The nominal shear strength (vn) of DA2.5RC10/10 and DA2.5F2.0C10/10 are 2.33 and 1.41 times the shear strengths calculated from the flexural moment capacities according to ACI318 (2014). It can be stated that the contributions of CFRP to the shear strength at ultimate state are 1.65 MPa (vu,DA2.5RC10/10 - vu,A2.5RC) and 0.16 MPa (vu,DA2.5F2.0C10/10 - vu,A2.5F2.0) in case of the beams with volume fractions of steel fibers equal to 0% and 2.0%, respectively (Table 3). Since the damaged concrete among steel fibers could not be removed completely so that it could not be replaced with epoxy-based primer, it is observed that the contribution of CFRP strips to shear strength decreases with the increasing volume fraction of steel fibers.

4. CONCLUSIONS

Based on the results presented in this paper, the following conclusions can be drawn:

The test results showed that there is an 122% increase in the strength due to the CFRP retrofitting for DA2.5RC10/10. The CFRP strengthening of structural members increases the load-carrying capacity and ductility, even though the beam is damaged. The ductility is of great importance for all structural members in the earthquake region, so CFRP can be used for strengthening of both damaged and undamaged structural members.

From the test result for DA2.5F2.0C10/10, there is an 10% increase in the strength due to the CFRP retrofitting. Since the damaged concrete among steel fibers could not be removed completely so that it could not be replaced with epoxy-based primer, the contribution of CFRP strips to shear strength decreases with the increasing volume fraction of steel fibers.

The experiments show that there exists a significant amount of contribution of CFRP strips to shear strength. However, further experiments should be conducted with a wider range of amount of CFRP strips, shear span-to-depth ratio, concrete strength and various loading schemes in order to obtain more reliable assessments.

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