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Influence of CFRP on the shear strength of RC and SFRC beams

Riza Secer Orkun Keskin *, Guray Arslan, Kadir Sengun

Department of Civil Engineering, Yildiz Technical University, Istanbul, Turkey

HIGHLIGHTS

- Strengthening with CFRP changed the failure modes of beams.
- The load-carrying capacity of RC beam was increased by CFRP strengthening.
- The load-carrying capacities of SFRC beams was increased by CFRP strengthening.
- The CFRP strengthening improved the deflection capacity beyond cracking.

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ABSTRACT

The mechanical properties and the crack control characteristics of concrete are significantly improved by the addition of steel fibres. In certain cases, there may be still need for further improvements in the mechanical properties or cracking characteristics. There exist various methods for strengthening structural members, one of which is the use of fibre reinforced polymers (FRP). The focus of this study is on the influence of carbon FRP (CFRP) strengthening on the shear behaviour of reinforced concrete (RC) and steel fibre reinforced concrete (SFRC) beams without web reinforcement. For this purpose, three series – a series of RC beams and two series of SFRC beams – consisting of nine test specimens in total were tested under three-point loading. The behaviours of test specimens were examined in the context of strength, stiffness and ductility. It was found that the strength and ductility of both RC and SFRC beams can be improved by the CFRP strengthening while it does not have a significant effect on the stiffness.

1. Introduction

It is possible to improve the mechanical properties -especially beyond cracking- and the crack control characteristics of concrete significantly by the addition of steel fibres [1]. There has been numerous experimental studies conducted by various researchers [2–20] reporting that improvements in shear strength and ductility of reinforced concrete (RC) beams can be observed as a result of the enhanced post-cracking features. A number of researches [5,21,10,1,22,23] was conducted to exploit the benefits of steel fibres with the aim of replacing conventional shear reinforcement usually in the form of vertical stirrups with steel fibres. Also, numerical/analytical studies [24,6,25,26,8,27–36] have been carried out to develop models predicting the shear strength of steel fibre reinforced concrete (SFRC) beams. Despite the enhanced mechanical properties and cracking behaviour due to the use of steel fibres, there may be still need for further improvements in the mechanical properties or cracking characteristics because of various reasons such as the change in the loading conditions due to a change in the purpose of use of the structure, the need for an upgrade due to possible changes in the codes, the possible deteriorations of structural members in time, etc.

There exist various methods for strengthening structural members. The use of fibre reinforced polymers (FRP) has many advantages such as relatively high tensile strength and low weight of FRP, easy and rapid application even in confined spaces, etc. Experimental studies carried out by various researchers have shown the contribution of FRP to the strength, stiffness and ductility of RC structural members. Triantafillou [37] conducted a research consisting of developing an analytical model for design of concrete members strengthened with composites and testing of RC beams strengthened with carbon FRP (CFRP), in which increases of strength ranging from 65% to 95% were observed. Khalifa et al. [38] tested RC beams with T-section strengthened with various configurations of CFRP sheets and observed an increase in the shear strength within the range of 35% to 145%. Alzate et al. [39] tested RC beams with insufficient shear reinforcement and observed that CFRP sheets increased the shear strength

* Corresponding author.
E-mail addresses: okeskin@yildiz.edu.tr (R.S.O. Keskin), aguray@yildiz.edu.tr (G. Arslan), kkadirsengun@gmail.com (K. Sengun).

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significantly but did not increase the stiffness. Bukhari et al. [40] also observed significant increases in the shear strength but slight enhancements in the stiffness of the CFRP strengthened beams through their experimental work and concluded that it is beneficial to use CFRP sheets aligned at 45° to the axis of the beam so that they are approximately perpendicular to the diagonal cracks like Triantafillou [37] suggested. Any experimental study on strengthening SFRC beams with carbon FRP (CFRP) is not available in the literature to the authors' knowledge.

This study focuses on the influence of CFRP strengthening on the shear behaviour of RC and SFRC beams without web reinforcement. For this purpose, nine test specimens consisting of a series of RC beams and two series of SFRC beams were tested under three-point loading. The behaviours of test specimens were examined in the context of strength, stiffness and ductility.

2. Experimental program

2.1. Test specimens

Three series – a series of RC beams and two series of SFRC beams – consisting of nine test specimens in total were constructed. The specimen designation includes a combination of letters and numbers: "A" followed by the shear span-to-effective depth ratio to indicate all test specimens in this research; "D" to indicate that it is damaged prior to strengthening; "R" to indicate that it is a reference beam; "F" to present the volume fraction of steel fibres; "C" to present the width and spacing of CFRP strips. For example, a beam damaged prior to strengthening that has steel fibres with a volume fraction of 2.0% and strengthened with 10 cm wide CFRP strips with a spacing of 10 cm is designated as DA2.5F2.0C10/10.

The concrete mix proportions for all series of beams are given in Table 1. The concrete compressive strength (f_c) for each series is presented in Table 2. All beams were reinforced with two 16 mm diameter bars, resulting in a longitudinal reinforcement ratio (ρ) of 1.34%, without any web reinforcement. The yield and ultimate strengths of longitudinal bars are 420 MPa and 550 MPa, respectively. Hooked-end steel fibres with a length (L_f) of 30 mm and a nominal diameter (D_f) of 0.55 mm, resulting in an aspect ratio of 54.5, were used as the only shear reinforcement. Two series of SFRC beams differ by the volume fraction of steel fibres (V_f), which is 2.0% in one series and 3.0% in the other (Table 2). Before casting the specimens, concrete was poured into a container in which steel fibres were mixed into concrete matrix by using a paddle mixer in order to overcome the reduced workability due to the relatively high volume fractions of steel fibres and obtain a properly mixed concrete. The ultimate strength of steel fibres is 1156 MPa. CFRP sheets with an elasticity modulus of 230 GPa, a tensile strength of 4900 MPa, a maximum elongation of 2.1% and a thickness of 0.166 mm (as reported by the manufacturer) were used for strengthening the test specimens.

All beams are 150 mm × 230 mm × 1400 mm with an effective depth (d) of 200 mm and a cover of 22 mm. The beams except the reference ones were strengthened with CFRP strips wrapped around the beams on all four sides in two layers with a spacing (s_f) of 10 cm. The width of CFRP strips (w_f) is either 5 cm or 10 cm (Table 2). The corners of the beams were rounded with 30 mm radius and surface preparations were made before the CFRP application. Two of the beams were loaded up to a certain damage level before strengthening. Then the cracks were repaired by using an epoxy-based mortar. The geometry, the longitudinal reinforcement arrangement and the configuration of CFRP strips of one of the beams are depicted in Fig. 1.

2.2. Testing and instrumentation

The beams were tested under a static rate (30 µm/s) of concentrated loading at mid-span using a displacement-controlled loading machine (Fig. 2). A computer-aided data acquisition system was used for monitoring load, deflections and strains at various locations at pre-determined time intervals. The net deflections of the beams were recorded by using potentiometric displacement transducers. Electrical strain gauges were installed on three CFRP strips along the fibre direction in order to monitor the development of strains in the CFRP strips with progressive loading. The tests provided information on the overall behaviour of beams including development of cracks, crack patterns and failure modes.

Table 1
Mix proportions of concrete.

Material	Mixture proportions (kg/m^3)	
	A2.5R series A2.5F3.0 series	A2.5F2.0 series
0–5 mm crushed sand	1180	1150
5–12 mm crushed stone	721	310
12–22 mm crushed stone	–	470
Fly ash (40% of binder)	80	90
Cement CEMI 42.5R	240	220
Water/Binder	0.55	0.55
Superplasticizer	3.20	3.10

3. Experimental results and discussions

All beams strengthened with CFRP strips, even the ones damaged before strengthening, failed in flexure. The crack patterns of strengthened beams are shown in Figs. 3–8. 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. Neither the slipping failure of longitudinal reinforcement nor the debonding of CFRP strips was observed.

Theoretical and experimental load-carrying capacities of all beams together with the deflections measured at the maximum and ultimate loads are summarized in Table 3, where $M_{cr,flex}$ is the flexural cracking moment capacity, $P_{cr,flex}$ is the flexural cracking load calculated from $M_{cr,flex}$, $M_{flex,ACI}$ is the flexural moment capacity according to ACI 318 [41], $P_{flex,ACI}$ is the nominal flexural load calculated from $M_{flex,ACI}$, P_{co} is the maximum load, δ_{co} is the mid-span deflection measured under P_{co}, P_u is the ultimate load that is assumed to be equal to 80% of P_{co}, δ_u is the mid-span deflection measured under P_u and the dissipated energy is the area under the load-deflection curve. It is observed in Table 3 that the CFRP strengthening enhanced the load-carrying and ultimate deflection capacities of both RC and SFRC beams. The increase in the maximum load is significant even in the case of beams damaged before strengthening. The maximum loads carried by RC beams strengthened with CFRP are the same; however the post-cracking behaviours are different. The ultimate deflection capacity of the strengthened RC beam without any damage (A2.5RC10/10) is far better than that of the beam damaged before strengthening (DA2.5RC10/10). The improvement in the load-carrying capacity due to the CFRP strengthening is more pronounced in case of the SFRC beam having 2.0% volume fraction of steel fibres compared to the one having 3.0% volume fraction of steel fibres. It is observed through SFRC beams having 2.0% volume fraction of steel fibres that the enhancements in the load-carrying and ultimate deflection capacities increase with the amount of CFRP reinforcement. The SFRC beam damaged before strengthening (DA2.5F2.0C10/10) also exhibited an increased load-carrying capacity, but not as much as the others did.

According to ACI 318 [41], the governing equation defining the shear strength of RC members states that the shear capacity must exceed the shear demand as

$$\phi v_n \geqslant v_u, \tag{1}$$

where ϕ is the strength reduction factor, v_n is the nominal shear strength and v_u is the factored shear force at the section considered. The nominal shear strength of SFRC beams – without stirrups – strengthened with CFRP strips wrapped around the beams on all four sides can be written in the form of two components as

$$v_n = v_c + v_{FRP}, \tag{2}$$

where v_c is the contribution of SFRC to shear strength and v_{FRP} is the contribution of FRP to shear strength. The contribution of SFRC can be calculated from the equation given by Arslan [34] as

$$v_c = v_{oc} + v_d, \tag{3}$$