The Combined Use of Carbon Fiber on the Sides and Soffit of High-Strength RC Beams with Traditional Steel Bars and Steel Fiber Shear Reinforcement

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ABSTRACT

This study investigates the structural performance of high-strength reinforced concrete beams under shear forces using two combinations of shear reinforcement; the first combination option was provided as Stirrups (ST)-Carbon Fiber (CF), and the second option was provided by Steel Fiber (SF)-Carbon Fiber (CF). The steel fiber shear reinforcement was provided in two volume fractions, V_f=0.5%, and V_f=1.0%. Steel stirrups, on the other hand, come in two configurations, Φ8mm@300mm and Φ8mm@200mm, which are equivalent to the shear strength effects of 0.5% and 1.0% steel fiber content, respectively. A 45° inclined CF material has been externally applied on both sides of the tested beams in addition to the soffit part of the beams. A total of ten beams, including tow reference beams. The first reference beam was with no any form of shear reinforcement and the other beam was with CF at the soffit part of the beam only and without shear reinforcement. The results of four-point bending tests, including ultimate load capacity, failure mode, and deflection, were reported and analyzed. The results show that carbon fiber significantly enhances shear resistance regardless of whether the beam was reinforced with steel stirrups or steel fiber. However, the CF contribution is more pronounced by more than twice when high-strength beams are reinforced with steel fiber compared to steel stirrups. Furthermore, the result showed that the application of carbon fiber at the soffit part of the beam in comparison with the results obtained by *Hayder A kadhim & Ali A. Sultan* **(2023)** has a negligible effect on the shear strength, the mode of failure and load deflection behavior of the tested beams.

Keywords: carbon fiber sides and bottom, Steel fiber, stirrups, shear strength, high strength R.C. beams

1- Introduction

The shear behavior of reinforced structural concrete elements continues to be a substantial research area. There remains an ongoing necessity for adjustments and refinements to shear theories, particularly when applied to reinforced concrete components. Hence, various empirical design techniques can be employed to mitigate the potentially catastrophic consequences of these solicitation forces on reinforced concrete structures. For years, stirrups have proven effective in providing essential shear resistance *Yoo, T. Yuan, Hamrat and Jin, Liu* [1]–[4]. For example *Saeed* [5] investigated the impact of stirrup ratios on shear strength and crack control in high-strength reinforced concrete beams (Fć= 41.4 MPa). Nine specimens with dimensions of 553 x 254 x 76 mm (length, height, and width) were created, employing different steel stirrup ratios 1.47% and 2.6% with Ø=10mm bars. The results demonstrated that using steel stirrups at ratios of 1.47% and 2.6% enhanced shear strength by 35.5% and 42.2%, respectively. However, in closely spaced stirrups, there can be difficulties, leading to the formation of voids and a weak connection between the concrete and the reinforcement bars.

Recently, randomly oriented steel fibers has been implemented as an alternative approach to steel stirrups to enhance shear resistance which has been proven a viable solution for bolstering the shear strength of reinforced concrete (RC) beams *Committee, A C I*, *K. Kwak* [6][7]. However, the potential benefits of incorporating steel fibers for shear resistance haven not been fully investigated, primarily due to an incomplete understanding of their role in the shear behavior of beams *Kern*, *Yang, Lin, and Hwang* [8] [9] [10]. As an example of the previous work incorporating steel fiber, *TOMA* [11] assessed the influence of steel fibers on RC beam shear behavior. Nine beams sized (150 × 200 × 1200) mm underwent testing, with two steel fiber percentages (0.5% and 1.0%) added to the concrete mixes. Results showed that including steel fibers improved beam deformability and shear capacity. The shear capacity increased by (167% and 215%) for the 0.5% and 1.0% steel fiber volume fractions, respectively. Similarly, *Biolzi* [12] examined the steel fiber impact on shear-flexure response in RC beams in a study that included thirty-six beams sized 150 x 150 x 600 mm under four-point loading. The results showed that adding steel fibers significantly increased shear and flexural strength, improving ductility and stiffness. Furthermore, Mansur and *Hameed* [13][14] observed that the failure mode has been changed from shear to flexure, and the concrete's shear strength was improved as a result of employing steel fibers.

The most typical way for strengthening, rehabilitating, or repairing reinforced concrete (RC) elements is to employ external carbon fiber reinforced polymer (CFRP) sheets *Al-Rousan* [15]. CFRP may significantly increase the flexural and shear capability of degraded parts, hence extending their useful life. CFRP materials may be employed in a variety of configurations for the reinforcing of degraded concrete elements as well as the primary reinforcement for concrete in new structures. One of the primary benefits of employing CFRP material in structural engineering applications is that it may be attached to structural components in a variety of configurations due to its lightweight, and flexibility. This material can also provide desired structural features such as corrosion resistance, high stiffness-to-weight ratio, high tensile strength, and high fatigue resistance *Alagusundaramoorth, Al-Modhafer, and Zhang* [16] [17] [18]. Ibrahim [19], for example, conducted experiments to confirm the shear behavior of CFRP-strengthened RC beams. Six beams sized 2000 x 300 x 200 mm were cast and tested, with parameters involving strip orientation (vertical and inclined). Results showed that inclined CFRP strips provided higher shear strength compared to vertical strips at the same distances, enhancing yield and ultimate loads by 11% and 13%, respectively.

Significant research has been conducted on the combined effect of shear steel reinforcement with carbon fibers. *Weiwen, and Adhikary* [20][21] studied the interaction between steel stirrups and FRP sheets and their impact on shear capacity. It also examines the interplay between stirrups, concrete, and CFRP sheets. The experimental results revealed a negative relationship, as increasing stirrups leads to a reduction in CFRP shear contribution. Hence, *Bashir H. Osman* [22] proved that the side bonding of CFRP increased shear strength by 15%, U-shape by 18%, and full wrap by 11%. Notably, steel stirrups had a more significant influence on shear strengthening, shear cracking, and deflection, making them a preferable choice, also *Nadeem, A. Bukhari, and Carlo* [23] [24] [25]showed that reinforcing RC beams with inclined CFRP sheets from the sides effectively increase shear capacity. Moreover, *A. Khalifa and Al-Ghanim et* [26] [27] indicated that greater CFRP sheet area correlated with increased stiffness and shear capacity.

Concrete is a brittle material and due to its low tensile strength is a danger in the shear failure of R.C. beams that are without shear reinforcement. Historically, various types of fibers have been utilized to reinforce brittle materials. In recent decades, the combined effect of steel fibers with carbon fibers reinforced polymer has been studied, whereas, *Riza* [28] assessed the impact of CFRP strengthening on shear strength in beams internally reinforced with SFRC and stirrups. Nine beams, 150 mm wide, 230 mm high, and a total width of 1400 mm, were cast and tested with varying steel fiber parameters. Steel fibers with 0.55 mm diameter and 30 mm length, with aspect ratios of 54.5, were used at two-volume fraction ratios (2% and 3%). Except for the control beam, the beams were reinforced with CFRP strips (50 mm or 100 mm width) spaced 100 mm apart on all four sides and two CFRP layers. The results indicated that applying CFRP strips altered the failure mode of RC and SFRC beams from shear to flexural failure. Additionally, the load-carrying capacity enhancement in SFRC beams due to CFRP decreased as the steel fiber volume fraction increased, especially with a 3.0% steel fiber volume fraction. However, ductility and deflection capacity increased.

This brief review highlights the limited experimental work exploring the interaction between externally bonded carbon fiber (CF) on the sides and soffit of beams with steel fiber or stirrups in RC sections. It remains unexplored whether such CF application positively affects the ultimate shear capacity of RC elements. To investigate this, ten beams were cast with dimensions (120 mm width, 200 mm height, and 1200 mm length) and subjected to four-point loading. Steel fibers with a diameter of 0.5 mm, a length of 30 mm, and an aspect ratio of 60 were used in two series of volume fraction 0.5 and 1% and two series of stirrups with ST300 and ST200 in addition to CFRP sheet from sides (CF) and from bottom (BCF).

2 - Experimental Work

The test program involved the use of reinforced concrete beams measuring 120mm in width, 200mm in depth, and 1200mm in length. A total of ten beams were cast for testing, comprising both control beams and beams reinforced with steel fiber or stirrups made of carbon fiber-reinforced concrete. The steel fiber reinforced beams had different fiber volume fractions 0.0, 0.5 and 1.0%, and the stirrups had varying spacing 200 and 300 mm. All beams were externally strengthened with CFRP sheets on the sides or bottom or together. The steel fibers used were of hook-end type with an aspect ratio of 60 (length 30mm, diameter 0.5mm), and they had a tensile strength of 1300 MPa. Each beam was reinforced with two 16mm diameter reinforcing bars placed with a clear cover of 20mm, and 8mm closed shear stirrups were included at spacings of 200mm and 300mm, except for the control beam which had no stirrups. The mechanical properties of the steel employed in this study are listed in Table 1. The purpose of the stirrups was to prevent shear failure on one side of the beam and allow for a closer examination of shear crack patterns and shear resistance mechanisms on the part without shear reinforcement. In Table 2, the mixing proportions for high-strength concrete are presented for both the control concrete mix and the steel fiber concrete mix.

The CFRP sheets used had a modulus of elasticity of 220 MPa and a tensile strength of 3500 MPa. CFRP was bonded to the concrete surface using epoxy resin, and the beams were strengthened by placing CFRP sheets on the sides with 100mm spacing from center to center of the sheets and a width of 50mm. Additionally, CFRP sheets were applied to the soffit part of the beam with a length of 1000mm and a width of 100mm. No effort was made to independently verify these characteristics. The application of CFRP sheets was accomplished using the "Sikadur-330" bonding agent following manufacturer-recommended surface preparation procedures. All beams were tested with the same shear span to depth ratio. The testing was conducted using a machine with a capacity of 2000kN, and the net deflection of the beam's center was measured using a digital dial gauge with a capacity of 50mm and an accuracy of 0.01mm.

Table 1: Mechanical characteristics of steel bars

Diameter (mm)	Average Yield Stress (MPa)	Min. Limit of Yield Stress (MPa)	Average Ultimate Stress (MPa)	Min. Limit of Ultimate Stress (MPa)	Average Elongation (%)	Min. Limit for Elongation (%)
8	525	420	645	620	14.4	9
16	665	420	735	620	12.6	9

Table 2: Concrete Mix ratios of 1M3

Type of Mix	Cement (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Water (Liter/ m^3)	Super Plasticizer (%)	SF Ratio (%)
NC	470	1150	740	175	6 Liters	0
SFRC	470	1150	740	175	6 Liters	0.5%, 1%

2-1 Test specimen preparation

The compressive strength of three different concrete mixes containing 0%, 0.5%, and 1% steel fiber respectively was experimentally determined. This was achieved by subjecting three cubes measuring 150 x 150 x 150 mm from each mix to testing at the 28-day. The testing procedure was done according to the guidelines outlined in BS 1881-116 and employed a digital compression machine with a 2000 kN capacity. The average value of the compressive strength was determined based on the results obtained from these three cubes.

Fig.1 schematically illustrates the configuration of the beams subjected to testing within this research. In the upper depiction, a longitudinal view along with a section within the central span of the beams is displayed. These beams have been reinforced for shear through the incorporation of steel stirrups and steel fiber. Notably, certain beams have also been externally fortified with CFRP material inclined at a specific angle. The decision to adopt an inclined CFRP application, as opposed to vertical alignment, stems from the intention to attain optimal shear resistance, a finding corroborated by *Chaallal and Nollet* [43].

Conversely, the lower portion of the diagram depicts the longitudinal view and a section within the middle span of the beams reinforced for shear exclusively with steel fiber. Additionally, the figure outlines the arrangement of CFRP for beams externally strengthened from lateral sides and beneath, or a combination of both, utilizing CFRP. Each vertical surface of the beams earmarked for CFRP treatment has been enhanced using four CFRP sheets. These sheets, measuring 240 mm in length and 50 mm in width, are positioned at each shear span with a 50 mm separation between them. Furthermore, a CFRP sheet measuring 100 mm in width and 1000 mm in length is employed from the underside. Importantly, the reference beams, lacking CFRP reinforcement, have been designed following the guidelines of ACI-318 and ACI 544.4R-2018. The design intention for these reference beams is to ensure shear failure rather than flexural failure. This meticulous design approach facilitates a precise evaluation of the impact of CFRP reinforcement on the ultimate failure mode of the fortified specimens.

It is also noteworthy that a single 10 mm diameter steel bar has been used in all beams to secure the vertical stirrups (if any) in their designated positions during the concrete pouring process.

Table 3 provides comprehensive details regarding the tested beams, including their corresponding specimen identification symbols. To illustrate, the identifier " BCF-CF0-SF0-ST0 " denotes a control beam devoid of any shear-resistant elements. In contrast, "BCF-CF-SF0-ST200" designates a beam sample featuring Ø8@200mm steel stirrups, devoid of steel fiber content, and augmented with a 45-degree inclined CFRP layer. Another example, "BCF-CF0-0.5SF-ST0" corresponds to a beam sample incorporating a 0.5% steel fiber ratio, devoid of steel stirrups, and enhanced with a 45-degree inclined CFRP layer.

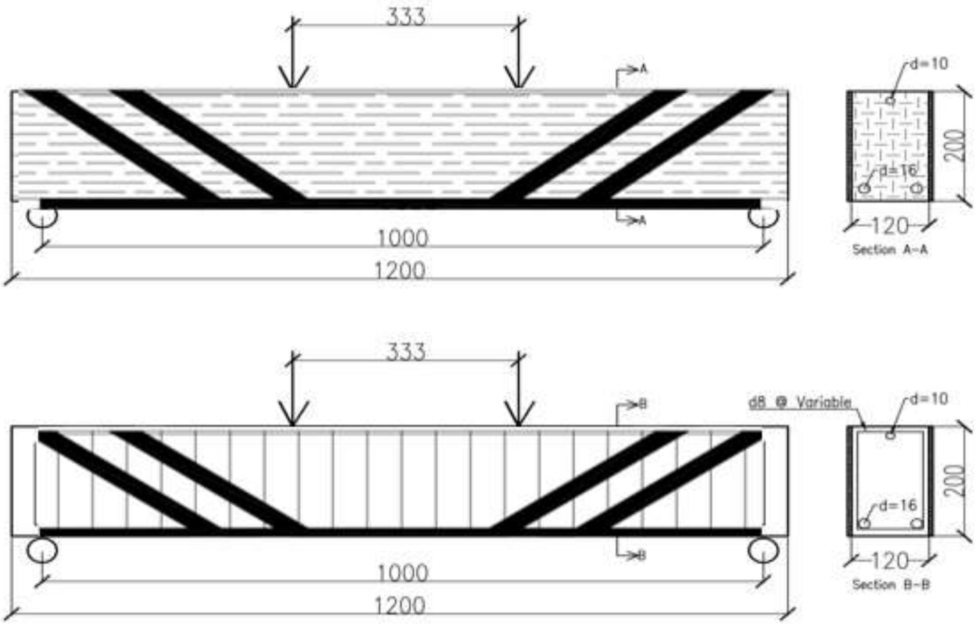


Figure 1. Specimens cross-sections

Table 3: Details of the Tested Beams

Items	Specimens	CFRP	Stirrups	SF
1	ST0-SF0-CF0	0.0	0.0	0.0
2	BCF-CF0-SF0-ST0	Bottom	0.0	0.0
3	BCF-CF0-SF0-ST300	Bottom	Ø8 @300mm	0.0
4	BCF-CF0-SF0-ST200	Bottom	Ø8 @200mm	0.0
5	BCF-CF-SF0-ST300	45°+ Bottom	Ø8 @300mm	0.0
6	BCF-CF-SF0-ST200	45°+ Bottom	Ø8 @200mm	0.0
7	BCF-CF0-0.5SF-ST0	Bottom	0.0	0.5%
8	BCF-CF0-1.0SF-ST0	Bottom	0.0	1.0 %
9	BCF-CF-0.5SF-ST0	45°+ Bottom	0.0	0.5%
10	BCF-CF-1.0SF-ST0	45°+ Bottom	0.0	1.0 %

All beams were subjected to testing until failure using the "Fourth-Point load" configuration. The load was incrementally raised from zero to reach the maximum load-bearing capacity, with intervals of 2.0 kN/sec. Detailed measurements of deflection at the midpoint of the span were meticulously recorded, and close observation was maintained over the initiation and progression of cracks. The failure mode of each tested beam was also comprehensively investigated. Figure 2 illustrates a test beam during the testing process.

Figure 2. A test beam with inclined CFRP during testing.

3. Test Results and Discussion

3.1 Ultimate load-carrying capacity

The load capacity, mid-span deflection at the point of failure, and the failure modes of the tested beam specimens are listed in Table 4. Additionally, Table 5 presents both the shear capacity in comparison with the control beam and the constituent components contributing to the shear capacity increase for each beam.

Table 4: Summary of beam test results

No.		Specimen	Pu (kN)	Mid-Span Deflection (mm)	Mode of failure
1	R.B	ST0-SF0-CF0	98.7	5.94	Shear failure
2	CB	BCF-CF0-SF0-ST0	106.4	5.21	Shear failure
3	G1	BCF-CF0-SF0-ST300	150.1	6.89	Shear failure
4		BCF-CF0-SF0-ST200	165.7	7.89	Shear failure
5	G2	BCF-CF-SF0-ST300	182.0	7.31	CFRP Debonding
6		BCF-CF-SF0-ST200	218.4	8.25	CFRP Debonding
7	G3	BCF-CF0-0.5SF-ST0	150.9	6.94	Shear failure
8		BCF-CF0-1.0SF-ST0	173.7	8.23	Shear failure
9	G4	BCF-CF-0.5SF-ST0	223.3	8.2	CFRP Debonding
10		BCF-CF-1.0SF-ST0	253.4	9.49	Flexural failure

Table 5: Shear strength contribution of each strengthening material

No.	Specimen	V_u (kN)	Increase (kN)	V_c (kN)	V_s (kN)	V_{SF} (kN)	V_{CF} (kN)	$V_{CF(Bottom)}$ (kN)
1	ST0-SF0-CF0	49.35	0.0	49.35	0.0	0.0	0.0	0.0

2	BCF-CF0-SF0-ST0	53.2	3.85	49.35	0.0	0.0	0.0	3.85
3	BCF-CF0-SF0-ST300	75.05	25.70	49.35	21.85	0.0	0.0	3.85
4	BCF-CF0-SF0-ST200	82.85	33.50	49.35	29.65	0.0	0.0	3.85
5	BCF-CF-SF0-ST300	91.00	41.65	49.35	21.85	0.0	15.95	3.85
6	BCF-CF-SF0-ST200	107.02	59.85	49.35	29.65	0.0	24.35	3.85
7	BCF-CF0-0.5SF-ST0	75.48	26.13	49.35	0.0	22.28	0.0	3.85
8	BCF-CF0-1.0SF-ST0	86.85	37.50	49.35	0.0	33.65	0.0	3.85
9	BCF-CF-0.5SF-ST0	111.65	62.30	49.35	0.0	22.28	36.17	3.85
10	BCF-CF-1.0SF-ST0	126.70	83.85	49.35	0.0	33.65	39.85	3.85

Tables 4 and 5 demonstrate that the control beam, named "BCF-CF0-SF0-ST0" experienced shear failure at 53.2 kN. The result of concrete shear strength was obtained from R.B (ST0-SF0-CF0) without CF is 49.35 kN which shows the failure mode in Fig 9.a . Furthermore, the contribution of CFRP from the soffit part of the beam has been dependent on the increase of shear strength on CB (BCF-CF0-SF0-ST0) by reduced it from the shear strength of R.B (ST0-SF0-CF0). This value significantly exceeds the theoretically calculated shear limit using ACI 318-2019, highlighting the conservative nature of the ACI code in addressing shear-type failures in RC elements, as previously mentioned. In contrast, beams "BCF-CF0-SF0-ST300" and "BCF-CF0-SF0-ST200" (Group 1) failed under shear loads of 75.05 kN and 82.85 kN, respectively. This shows an increase in load-carrying capacity, with improvements of (41.1 and 57.7)%, respectively, when compared to the control beam.

Similarly, in Group 3, the beams labeled "BCF-CF0-0.5SF-ST0" and "BCF-CF0-1.0SF-ST0" exhibited maximum shear failures at 75.48 kN and 86.85 kN, respectively. These results show a similar percentage increase in load-carrying capacity compared to the "BCF-CF0-SF0-ST300" and "BCF-CF0-SF0-ST200" beams when compared to the control beam. Up to this point, the primary objective, as discussed earlier, has been achieved, confirming nearly identical results for both shear-strengthening materials, stirrups, and steel fibers. Figure 3 illustrates the enhanced load-carrying capacity of beam samples featuring stirrups and steel fibers in comparison to the control beam.

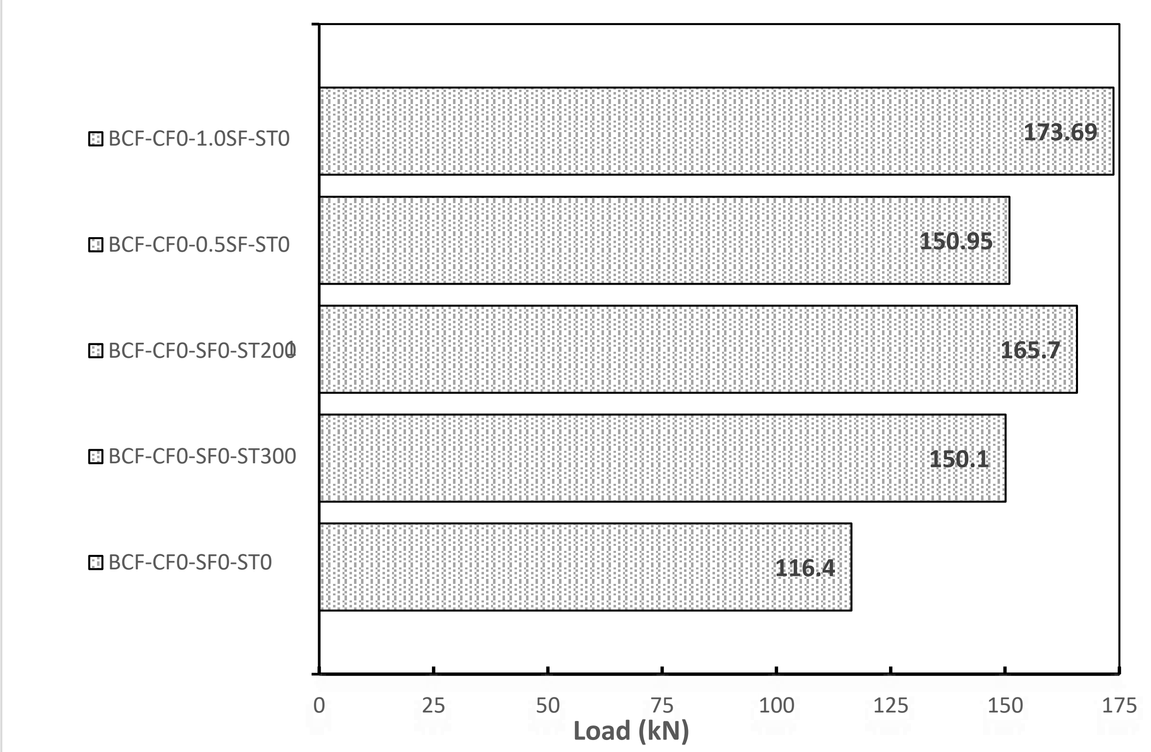


Figure 3 The load-carrying capacity of beam samples with steel stirrups or steel fiber with an additional CFRP Strengthening from the bottom only

In contrast, Figure 4 shows the load-carrying capacity of beam specimens strengthened with CFRP, along with either steel stirrups or steel fiber (G2 & G4). This figure shows the impact of combining stirrups or steel fiber with externally bonded CFRP sheets on the shear capacity of the beams.

The load-carrying capacity of "BCF-CF-SF0-ST300" and "BCF-CF-SF0-ST200" beams, when compared to the control beam, exhibited remarkable increases of 71.05% and 101.16%, respectively. Similarly, there was a substantial enhancement in the shear capacity of "BCF-CF-0.5SF-ST0" and "BCF-CF-1.0SF-ST0" beams in comparison to the control beam. Specifically, the percent increase in the shear capacity of these beams was 109.87% and 138.15%, respectively**.**

Comparing the results between G2 and G1, as well as those from G4 and G3, strongly highlights the superior impact of CFRP reinforcement when applied to beams initially strengthened against shear with steel fiber. For instance, beam #9 in the G4 group exhibited a remarkable 147 kN increase in shear capacity, whereas the improvement in shear strength for beam #5 in G2 was limited to 112 kN. These results are from previous research conducted by. Amin, [29]

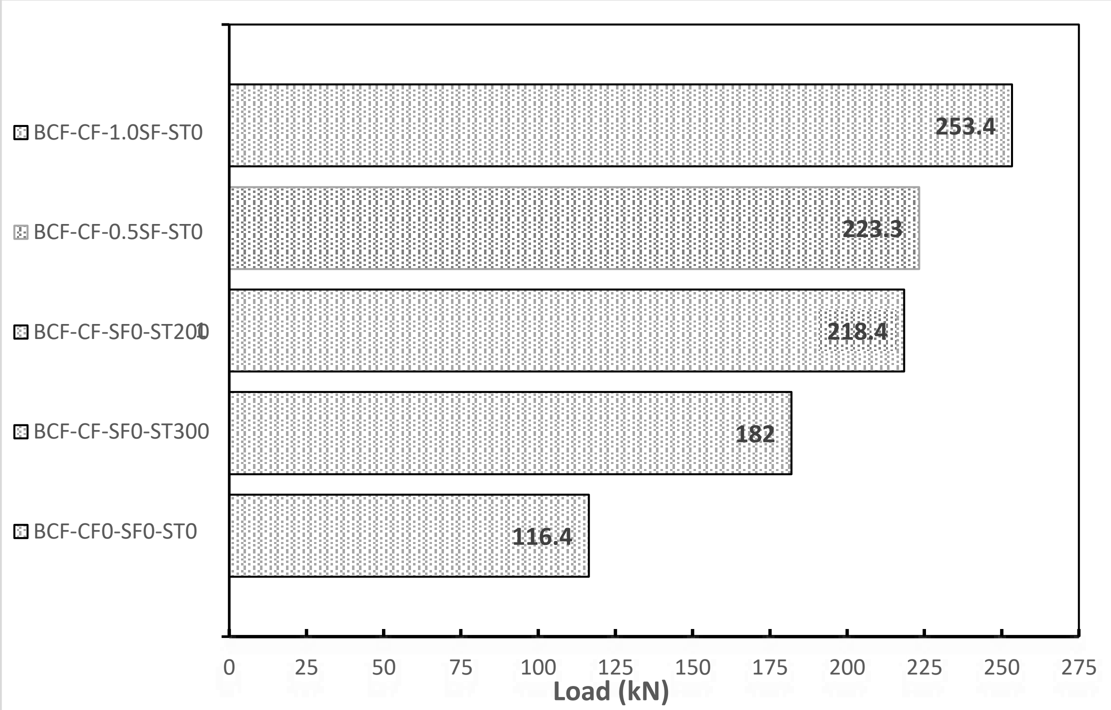


Figure 4. The load-carrying capacity of beam samples with ST or SF with an additional CFRP Strengthening from the sides and bottom.

3.2 Load-deflection relationship

The load-deflection characteristics of all the tested beams are shown in Figures 5 to 8. From these figures, it is proven that beams reinforced with steel stirrups (G1) and those reinforced with steel fibers (G3) exhibit nearly identical load-deflection behavior, both offering more` ductility compared to the control beam.

For instance, in the case of G1 specimens with 10 mm diameter steel stirrups placed at 300 mm and 200 mm intervals, the maximum deflections were 32.24% and 51.44%, respectively. Similarly, specimens from the G3 group, featuring steel fiber volume fractions of 0.5% and 1.0%, showed an increase in maximum deflection at failure by 33.2% and 57.96%, respectively, when compared to the control beam.

The enhancement in both load-carrying capacity and deflection at failure indicates that both steel stirrups and steel fibers have significantly improved the overall performance of the tested beams against shear forces.

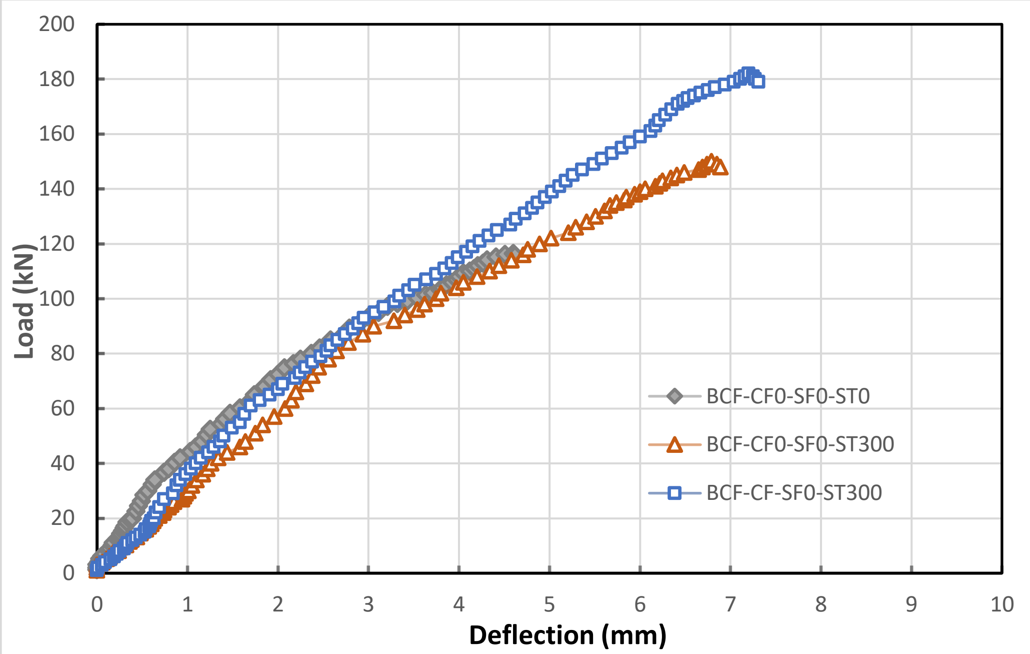


Figure 5. Load-midspan deflection curves for the CB ST300 with and without CFRP strengthening and with an additional BCF.

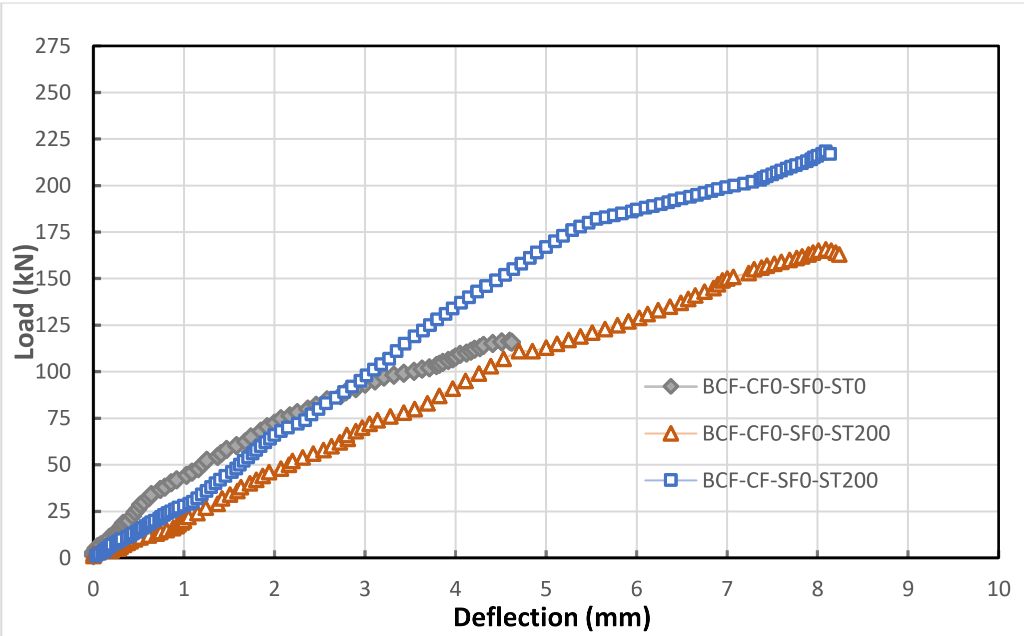


Figure 6. Load-midspan deflection curves for the CB ST200 with and without CFRP strengthening and with an additional BCF.

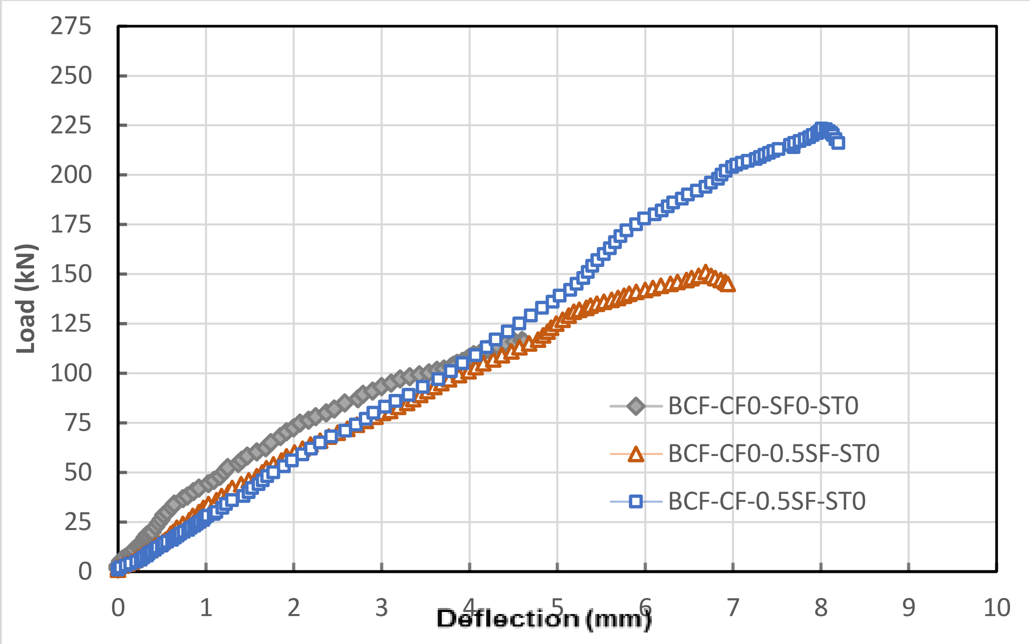


Figure 7. Load-deflection curves for the CB and with beam 0.5SF with and without CFRP strengthening and with an additional BCF.

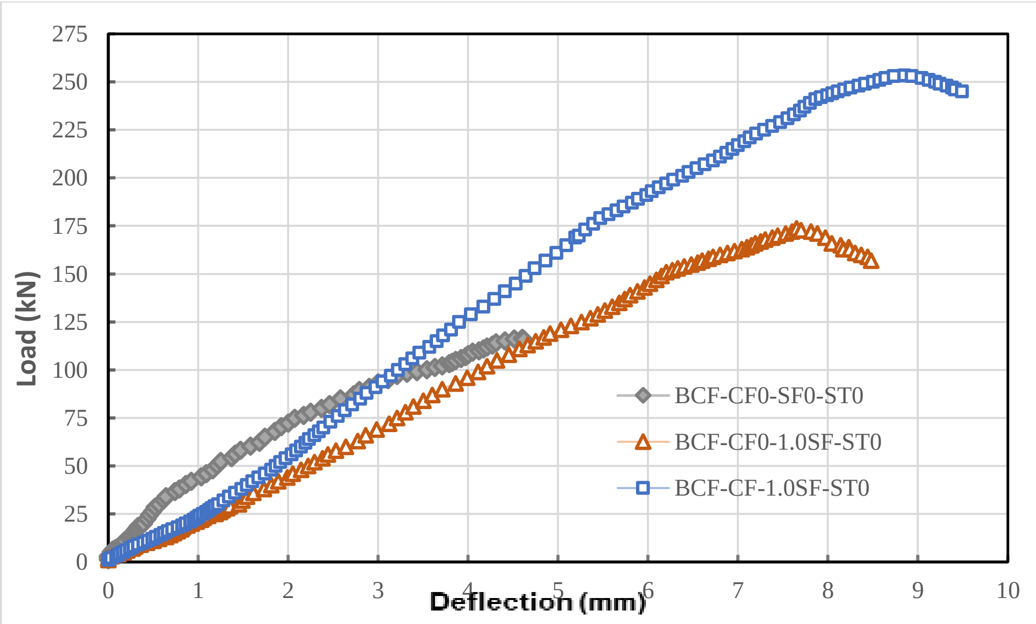


Figure 8. Load-deflection curves for the CB and beams 1.0SF with and without CFRP strengthening and with an additional BCF.

The incorporation of steel stirrups, ST300 and ST200, in combination with carbon fibers (CF) resulted in a notable increase in load-deflection for (G2) specimens, with enhancements of 40.38% and 58.46%, respectively, when compared to the control beam. This suggests that both combinations contributed significantly and equally to the improved performance.

On the other hand, the maximum deflection contribution from CF was observed in (G4) beams, BCF-CF-0.5SF-ST0 and BCF-CF-1.0SF-ST0, with increases of 57.39% and 82.15%, respectively. These strengthened beams exhibited higher load-carrying capacity and displacement than other specimens without reinforcement.

When considering the interaction between CF and steel fibers (SF) at a 1.0% volume fraction, it was found to contribute more to displacement compared to the interaction between ST200 and CF. Similarly, at a 0.5% volume fraction, the interaction between CF and SF in beam BCF-CF-0.5SF-ST0 contributed more to deflection than the interaction between CF and ST300 in beam ST300-SF0-CF-BCF. This indicates that CFRP's contribution to deflection increases as the internal strength (SFRC or stirrups) is augmented, a phenomenon supported by Mofidi et [30].

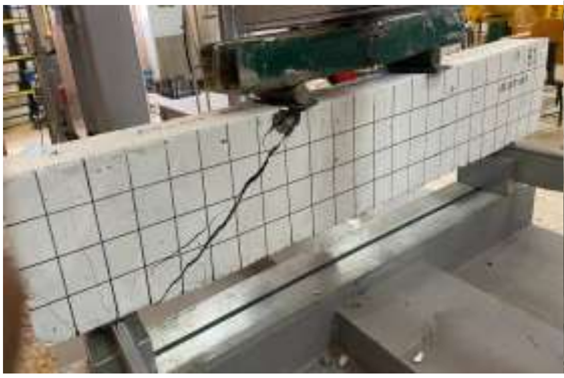
3.3 Failure mode and crack pattern

The test results illustrated that three modes of failure have been identified in the tested specimens which are shear failure, CFRP Debonding, and flexural failure, as explained in Table 4. The presence of steel fibers has a significant impact on crack patterns. Steel stirrups with a ratio (spacing =200 mm and 300 mm) spacing have the same influence on the failure mode. The crack pattern for RC beams with SFRC or steel stirrups had a distinct difference in width and number, and all the crack patterns shown in Figure 9 for the beam are dependent on calculating the concrete shear strength. In the reference beam ST0-SF0-CF0 as shown in Fig 9. a failure mode is a shear failure with a single crack. Also, for the control beam BCF-CF0-SF0-ST0, Figure 9. b shows the creation of a single large shear crack between the point load and the support within the regions of constant shear at failure. Furthermore, the beam BCF-CF0-SF0-ST300 failed due to two diagonal cracks that combined Since the beam had just a minimum amount of steel stirrups, it was unable to resist more stress after the induction of inclined cracks, and the failure mechanism for it is illustrated in Figure 9. c. On the other hand, BCF-CF0-SF0-ST200 failed due to diagonal cracks even after the beams were strengthened with the maximum amount of shear reinforcement which allowed the beam to resist additional stress during the loading stage, the failure mode is shown in Figure 9. d.

When the volume fraction of steel fibers in the beams increased from 0.5% to 1%, the predominant failure mode remained a shear failure, characterized by a variety of cracks in these beams, as illustrated in Figures 9. e to 9. f. This observation highlights the beneficial impact of fibers, as they induce the formation of multiple cracks before ultimate failure.

Moreover, the data suggests that the influence of steel stirrups and steel fibers with minimal values in this study resulted in the same failure mechanism. Conversely, when both steel fibers and stirrups were at their maximum values, the outcome was a comparable shear failure.

These figures serve to illustrate that the fibers effectively mitigate crack formation and carry residual stresses beyond the point of cracking. In this manner, the fibers effectively act as sutures, bridging the gaps created by the cracks.



a (ST0-SF0-CF0)

b (BCF-CF0-SF0-ST0)

c (BCF-CF0-SF0-ST300) d (BCF-CF0-SF0-ST200)

e(BCF-CF0-0.5SF-ST0) f (BCF-CF0-1.0SF-ST0)

Fig. 9 Failure modes of the test beams as control beam and beams strengthened internally by SFRC or stirrups and without CFRP sheet.

Figure 10 provides an insightful overview of the failure mechanisms and crack patterns witnessed in CFRP sheet-strengthened beams. Figures 10. a and 10. b display the mode of failure where beams BCF-CF-SF0-ST300 and BCF-CF-SF0-ST200 experienced failure due to the debonding of CFRP sheets. Furthermore, as shown in Figure 10. c, the beam BCF-CF-0.5SF-ST0 exhibited shear failure due to the debonding of CFRP. In contrast, Figure 10.d shows the failure mode of beam BCF-CF-1.0SF-ST0 which is a flexural failure.

A calculated deduction from the results reveals that the inclusion of 1.0% steel fiber led to a transition in the failure mode from CFRP debonding to flexural failure at the mid-span, corroborating results reported by *Song and Hwang* [10]. Conversely, beams reinforced with the maximum stirrup value succumbed to failure due to CFRP debonding.

Moreover, the results highlight that engaging with a modest quantity of steel fibers or stirrups yielded consistent failure behavior, specifically CFRP debonding failure.

Furthermore, the interaction between CFRP and the maximum volume of steel fiber engenders a distinct failure mode and crack pattern compared to the interaction involving CFRP and steel stirrups. In contrast to the failure mode attributed to the interaction between steel stirrups and CFRP, which retains CFRP debonding as the primary failure mode, the presence of steel fiber exerts a more substantial influence in the interaction, prompting a transition from CFRP debonding failure to flexural failure.

a (BCF-CF-SF0-ST300) b (BCF-CF-SF0-ST200)

c (BCF-CF-0.5SF-ST0) d (BCF-CF-1.0SF-ST0)

Fig. 10 Failure modes of CB and beams of ST or SF with CFRP addition to BCF

4. Conclusion:

- By increasing the volume percentage of steel fibers from 0.5% to 1.0%, the ultimate load increased from 49% to 92.7%, and the deflection at failure increased from 20% to 42%. Furthermore, the improvements by increasing the stirrups amount on both ultimate load and deflection were the same as beams strengthened by SFRC (0.5% and 1%).
- The failure mechanism and crack pattern of RC beams reinforced with a volume percentage of 0.5 to 1.0% steel fiber were shear failures with increasing crack numbers and decreasing crack width, similarly, the failure mode for beams with stirrups ST300 and ST200 failed with shear failure while with a single crack.
- In general, the test results indicated that strengthening the EBR with 45˚ CFRP sheets and at the soffit part of the beam significantly enhanced the load-carrying capacity and deflection of the tested beams.
- The interaction between steel fiber with volume ratios of 0.5 and 1.0% and CFRP from the soffit and sides increased the ultimate load by 109.87% and 138.15%, similarly, the shear strength for the beams strengthened internally with ST300 and ST200 was improved by 71.05% and 101.16%, respectively.
- The interaction between CFRP from sides and the soffits of beams with SF or ST led to improvement in the deflection at failure which increased from (40.38 and 58.46)%, % respectively, for ST300 and ST200, by increasing the steel stirrups amount. Furthermore, beams with steel fiber (0.5 and 1.0)% produced improvement in load deflection by 57.39% and 82.15%, respectively.
- The results of the testing identified three modes of failure, with shear failure being a mode for all beams except (ST300-SF0-CF-BCF, ST200-SF0-CF-BCF, and ST0-0.5SF-CF-BCF, which failed via CFRP-Debonding, and ST0-1.0SF-CF-BCF, which failed due to flexural failure).
- The interaction between 1.0% vol steel fiber and CFRP with two cases produced the maximum contribution value in shear capacity and deflection.
- The contribution of strengthening by CFRP sheet from the soffit part of beams (BCF) in comparison with the results obtained by *Hayder A kadhim* **(**volume 5 at Dec 2023**)** has a slight effect on the shear strength and load deflection of the beam and without effect on the mode of failure has a slight effect on its may side without effect on mode of failure, negative effect on load deflection of beams and the contribution on shear strength has very limited. In comparison with results of beams without bottom CFRP strengthen.

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