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Interaction of stirrups – steel fiber – carbon fiber in resisting of shear forces in high strength RC beams

Interacción de estribos – fibra de acero – fibra de carbono en la resistencia de fuerzas de corte en vigas RC de alta Resistencia

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ABSTRACT

This research is dedicated to investigating the structural performance of high-strength strengthened concrete beams in resisting shear forces when stirrups (ST)-carbon fiber (CF) and steel fiber (SF) materials are used as shear reinforcement. Shear reinforcement has been provided in either of the two forms. The first form consisted of steel fibers of two volume fractions: Vf=0.5% and Vf=1.0%. The second form consisted of ST of two configurations: Φ8mm@300mm and Φ8mm@200mm, which experimentally have equivalent shear effects to the SF of 0.5 and 1.0% fiber content, respectively. With both forms, a 45º inclined CF material has been externally applied. In addition to the reference beam of no form of shear reinforcement, a total of nine beams were tested for failure under the “four-point bending” test, and the results obtained were reported and discussed in terms of the maximum load capacity, failure mode, and deflection. The results obtained indicated the great contribution of CF in providing extra resistance to the applied shear forces regardless of whether a beam had been reinforced in terms of ST or SF. However, the contribution of CF is more pronounced (more than double) when the high-strength beams were reinforced utilizing SF as compared to the ST.

Keywords: Steel fiber; stirrups; carbon fiber- shear strength- R.C., beams.

RESUMEN

Esta investigación está dedicada a investigar el desempeño estructural de vigas de concreto reforzado de alta resistencia para resistir fuerzas de corte cuando se utilizan materiales de estribos (ST)-fibra de carbono (CF) y fibra de acero (SF) como refuerzo de corte. Se ha proporcionado refuerzo de cortante en cualquiera de las dos formas. La primera forma estaba formada por fibras de acero de dos fracciones en volumen: Vf=0,5% y Vf=1,0%. La segunda forma consistió en ST de dos configuraciones: Φ8mm@300mm y Φ8mm@200mm, que experimentalmente tienen efectos de corte equivalentes al SF de 0,5 y 1,0% de contenido de fibra, respectivamente. En ambas formas se ha aplicado externamente un material CF inclinado 45º. Además de la viga de referencia sin ningún tipo de refuerzo de corte, se ensayó la falla de un total de nueve vigas bajo la prueba de “flexión en cuatro puntos”, y los resultados obtenidos se informaron y discutieron en términos de capacidad de carga máxima, modo de falla. y deflexión. Los resultados obtenidos indicaron la gran contribución del CF al proporcionar una resistencia extra a los esfuerzos cortantes aplicados independientemente de si una viga había sido reforzada en términos de ST o SF. Sin embargo, la contribución de CF es más pronunciada (más del doble) cuando las vigas de alta resistencia se reforzaron utilizando SF en comparación con las vigas ST.

Palabras claves: Fibra de acero; estribos; fibra de carbono- resistencia al corte- R.C., vigas.

1. INTRODUCCIÓN

The failure of shear for reinforced concrete elements such as beams is a serious issue as it happens suddenly and can lead to catastrophic results, and therefore, this primary concern needs to be mightily avoided. Steel bars known as "stirrups, or web reinforcement" have been successfully used for years to provide the necessary shear resistance(Frosch, 2000; Lee & Hwang, 2010; Russo & Puleri, 1997; Zararis, 2003). In recent years, however, some alternatives such as steel and synthetic fibers as well as carbon fibers and steel fiber have been used for the same purpose as will be discussed in the next paragraphs.

Steel fiber has been recognized among the best alternatives for conventional steel reinforcement in reinforced concrete members. It can be used as a replacement to the steel bars or as an additive in conjunction with steel reinforcement to enhance the flexural, shear, torsional, and ductility characteristics of reinforced concrete elements. Among the other types of fibers, steel fiber is fast becoming a key material in reinforced concrete components. Therefore, recently, there has been a growing interest in investigating the importance of implementing this material in many scientific articles. Considerable researchers have been conducted in the combination of conventional shear steel reinforcement and steel fibers, (Araújo et al., 2014; Kwak et al., 2002; D.-Y. Yoo et al., 2017) showed that using a 0.75% ratio of steel fiber volume and minimum stirrups have improved their shear strength and ductility. (Saeed & Sarhat, 1999) found that combining stirrups and steel fibers (1.47% stirrups with 0.4% steel fiber) increased the ultimate shear strength by 92.8%. In contrast, combining 0.8% steel fiber with 2.6% stirrups decreased efficacy, possibly due to difficulties in achieving thorough mixing. (Arslan et al., 2019), reported the interaction of a volume ratio of 2% steel fiber with steel stirrups spaced at 150, 200, and 300 mm led to some kind of changes in the failure mode from shear to flexural. However, failure mode still occurred as shear when using steel fibers with a ratio of less than 2%. (Gomes et al., 2018) also reported the use of a steel fiber ratio of 1% has led to changes in the failure mode from shear to flexure, whereas the failure mode remained as shear if the steel fiber ratio was less than 1.2%.

Concrete is a fragile 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, a significant amount of research (ACI, 1996), (Arslan, 2008, 2014; Committee, 1996; Dinh et al., 2011) has stressed the use of steel fibers to develop the mechanical properties of concrete in those characteristics with the use of steel fibers. and use it to replace the stirrups in the shear strength of beams. (D. Y. Yoo & Yang, 2018) showed that increasing the effective depth from 181 to 887 mm reduced the shear resistance of the SFRC-HSC by 129%. (Yuan et al., 2020) performed a test for 10 R.C. beams with different SFRC volume ratios (0.0%, 0.3%, 0.6%, 0.9%, and 1.2%), hence, the results illustrated increasing fiber volume has increased the value of the first load crack, also, at the ultimate steel fiber volume percentage of 1.2%, the maximum load was greater by 24%. (Hameed & Al-Sherrawi, 2018; Mansur et al., 1986; Torres & Lantsoght, 2019) reported the mode of failure has changed from shear to flexure and the shear strength of concrete has enhanced due to using the steel fibers.

A common method of reinforcing concrete structures like buildings and bridges is by using steel bars. However, in cases where there are problems with flexure or shear weaknesses, external steel plates or stirrups have been effectively employed for strengthening and repairing purposes. In recent years, bonding fiber-reinforced polymer (CFRP) fabrics, plates, or sheets to RC beams has become a common and effective method for strengthening. Many researchers (Alagusundaramoorthy et al., 2003; Hou et al., 2022; Siddika et al., 2019) have demonstrated that using CFRP for reinforcement offers several advantages over other methods, primarily due to its high strength, lightweight, and durability.

(W. Li et al., 2018), (SIDDIQUI, 2009) have proved, that the increase in stirrups amount in cross-section has caused a decrease in the role of CFRP sheet on shear strength (negative relationship). (Bousselham & Chaallal, 2006; Mofidi & Chaallal, 2011; Osman et al., 2018) demonstrated that CFRP with a single layer had a larger strain than CFRP with several layers; also, the strain was greater for slender beams than for deep beams. (Bukhari et al., 2010), (Pellegrino & Modena, 2002) reported the strengthening by CFRP with 45˚ had given fewer cracks and propagation than 90˚ as well as increased the shear capacity. (W. Li & Leung, 2016), (Jayaprakash et al., 2008) illustrated the mode of failure for entire tested beams was the CFRP de-bonding among the CFRP sheet and the concrete surface.

Externally bonded (EB) fiber-reinforced polymer (FRP) has become an attractive alternative to traditional reinforcement methods owing to its low stiffness-to-weight and strength-to-weight ratios, and its low susceptibility to corrosion. Recently, using this technique in real applications has increased, and it has become a well-established solution in the market for strengthening beams without stirrups. (A. Li et al., 2001)(Al-Ghanem et al., 2017),(Al-Ghanem et al., 2017; Khalifa et al., 1999) showed that the increasing CFRP sheet area led to a rise in stiffness and shear capacity. (Adhikary & Mutsuyoshi, 2004) (Zhang & Hsu, 2005) illustrated the failure mode which is a CFRP de-ponding from the surface of the concrete. Furthermore, the strengthened method was reported by (M Abdel Hafez, 2007), (S. B. Singh, 2013) the strengthening by CFRP sheet is 45˚ best method of external bonding in comparison with 90˚. Also, (Ibrahim et al., 2017; Murad, 2018) illustrated the R.C. beams strengthened by CFRP sheet with full warps from three sides with directions (0˚, 45˚and 90˚) produced increasing load-carrying capacity, where the highest contribution value belongs to the strengthen by 45˚.

The incorporation of steel fibers can lead to a significant enhancement in the mechanical properties and crack control features of concrete. However, in some instances, additional improvement in mechanical properties or crack resistance may still be necessary. Various techniques, incorporating the usage of fiber-reinforced polymers (FRP), exist for strengthening structural components. This study investigates the effect of carbon FRP (CFRP) strengthening on the shear behavior of reinforced concrete (RC) and steel fiber reinforced concrete (SFRC) beams without web reinforcement. (Keskin et al., 2017) showed the interaction between CF to the beam containing steel fibers changed failure from shear to bending. On the other side, the load-carrying capacity of R.C. beams has increased by using the volume fraction of SFRC. In contrast, the improvement of shear strength by CFRP strips with a volume proportion of steel fiber of 3% (more than 2%) is very limited. where the ductility and deflection capacity increased due to the use of CFRP.

From this brief review, it can be stated that there has been little experimental work investigating the interaction between externally bonded carbon fiber and steel fiber RC sections, and whether such implementation of CF has a positive impact on the final shear capacity of RC elements. Nine beams with cross section (120 mm in width, 200 mm in height) and length of 1200 mm were cast and tested under 4-point loading where hooked-end steel fiber with a diameter (0.5 mm), length (30 mm) and (0.6) in aspect ratio were used with two series of volume fraction (0.5% and 1%).

2. MATERIAL AND METHODS

To accurately investigate the role of externally bonded carbon fiber in providing extra resistance to the shear forces when steel bars or steel fibers had been originally used to resist such forces, nine high-strength concrete beams of 46.8 MPa were made and tested to failure. The empirical program has been split into two major tasks.

The first task involved the determination of the exact stirrups configurations (i.e., bar size and spacing) that can provide equivalent shear resistance to the steel fiber contents of 0.5 and 1.0%. This task was necessary so that when applying CF to both kinds of RC sections, one can clearly and easily determine the role of such an additional strengthening material in developing the shear capacity with both kinds of RC sections (i.e., with reinforcing bars and fibers).

Steel fiber contents had been chosen as 0.5% and 1.0% for practical considerations and to be in agreement with the contents recommended by many researchers. Once this task has been achieved successfully, the second task, as has been mentioned previously, involves the application of carbon fiber to both kinds of beams originally strengthened against shear utilizing steel bars or steel fibers. In addition to these nine beam specimens, a reference beam of no form of shear reinforcement has been made to serve as a control beam for comparison. The details of mixture proportions of concrete, test specimens, materials used, and test setup as carried out in this research will be discussed in the next sections.

2.1. Mixture Proportions and Materials

The mixing rates of high-strength concrete for control concrete mix and steel fiber concrete mix are illustrated in Table 1, where Portland cement type II and locally available aggregates were used in the current study. Steel bars of 16 mm and 8 mm in diameter have been employed as flexural and shear reinforcements, respectively. The cement, steel bars, and both types of aggregates had been tested according to the relevant ASTM standards before use. Table 2 illustrates the mechanical features of the steel used in this research. The coarse aggregate was chosen with an ultimate size of 19mm. In addition, a commercially available multi-superplasticizer (SP-42) was implemented in both mixes to enhance the workability of concrete and to reduce the water content to get the intended high-strength concrete.

Hooked-end steel fibers at 0.5% and 1.0% volume fractions were employed in the SFRC mix. Table 3 describes the characteristics of these steel fibers.

The Carbon Fiber (CF) used, on the other hand, has the characteristics listed in Table 4 that are provided by the manufacturer and no attempts have been made to check these characteristics. The CFRP sheets have been installed using the “Sikadur-330” bonding agent after surface preparation as recommended by the manufacturer.

Table 1. The Mix Concrete of Proportions for Normal and Steel Fiber Concrete.

Type of Mix	Cement (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Water (Liter/ m^3)	Superplasticizer (%)	SF Ratio (%)
NC	470	1100	700	170	6 Liters	0
SFRC	470	1100	700	170	6 Liters	0.5%, 1%

Table 2. Mechanical Properties of the Steel Reinforcement Employed.

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 (%)
16	654	420	765	620	12.4	9
8	510	420	630	620	14.3	9

Table 1. Properties of the Hooked Steel Fiber Used.

Properties	Specification
Length $\boldsymbol{Lf}$ (mm)	30
Diameter $\boldsymbol{Df}$ (mm)	0.5
Tensile strength (MPa)	1300
Aspet ratio ($\boldsymbol{Lf/df}$)	60

Table 2. Characteristics of CFRP Sheets Used.

Properties	Specification
Tensile strength (MPa)	3500
Modulus of Elasticity (GPa)	220
Thickness (mm)	0.167

2.2. Preparation of Specimens and Mechanical Test

The strength of compression of every single one of three different mixes of 0, 0.5, and 1% steel fiber was determined by testing three cubes of 150*150*150 mm for each mix at the age of 28 days. The test was done according to BS 1881-116 and using a digital compression machine with a capacity of (2000 kN). The compressive strength was detected by employing the average value of three cubes. The cubic compressive strengths were 58, 66, and 72 MPa for the mixes of 0, 0.5, and 1% steel fiber, respectively. These cubic compressive strength values have been transformed into the equivalent cylindrical compressive strength using the conversion factor of 0.738 recommended by (Zhu et al., 2019) before use in the design phase of the tested beams.

2.3. Test setup of beams and properties

The specifics of the beams under testing as part of this study are illustrated schematically in Fig.1. The upper figure illustrates the longitudinal view and a section in the middle span of the beams reinforced for shear using steel stirrups. The figure also shows the degree-inclined CFRP material that has been externally applied on some of the tested beams. The application of inclined CFRP, rather than a vertical alignment has been decided to achieve the maximum shear resistance as has been reported by (Chaallal et al., 1998). The lower part of the figure, on the other hand, shows the longitudinal view and a section in the middle span of the beams reinforced for shear using steel fiber. The figure also shows the CFRP configuration for the beams that have been externally strengthened by using CFRP. Each vertical face of the CFRP-designated beams has been strengthened by four CFRP sheets (two sheets at each shear span) of 240 mm in length and 50 mm in width with a spacing between both sheets of 50mm. It should be observed that the reference beams (i.e., without CFRP strengthening) have been designed according to ACI-318 and ACI 544.4R-2018 to be unsuccessful in shear rather than in flexure to carefully specify the impact of CFRP reinforcing the final mode of failure of the strengthened specimens. It should be noted also that a single steel bar of 10 mm in diameter has been used in all beams to hook up the vertical stirrups in place during the pouring process.

Details of the tested beams with the specimen identification symbols are provided in Table 5. For example, “ST0-SF0-CF0” refers to the reference beam where no form of shear-resisting material has been used; “ST200-SF0-CF” refers to the beam sample of steel stirrups of Ø8@200mm, no steel fiber content and a 45^{o} inclined CFRP layer used in the sample and “ST0-0.5SF-CF0” refers to the beam sample of steel fiber ratio 0.5%, no steel stirrups and a 45^{o} inclined CFRP layer used.

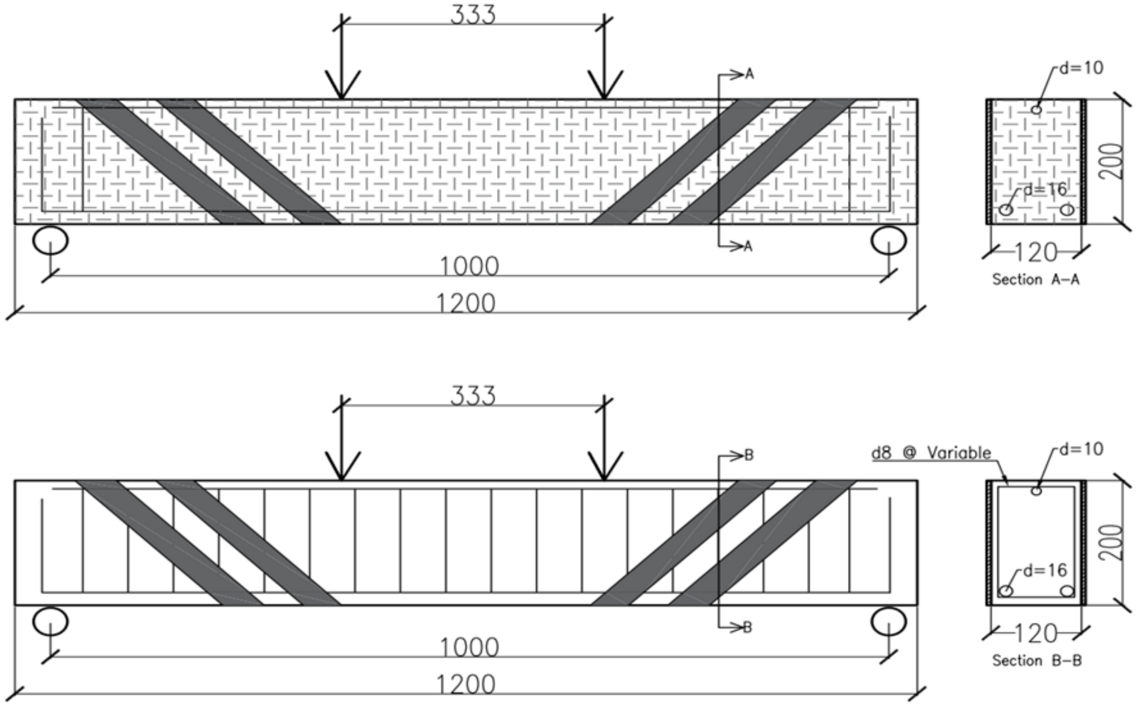


Figure 1. Schematic representation of the tested beams

Table 3. Data of the Tested Beams

Items	Group	Specimens	Stirrups	SF	CFRP	H (mm)	B (mm)	d (mm)
1	Control	ST0-SF0-CF0	0	0	No	200	120	172
2	G1	ST300-SF0-CF0	Ø8 @300mm	0	No			164
3		ST200-SF0-CF0	Ø8@200mm	0	No			164
4	G2	ST300-SF0-CF	Ø8@300mm	0	Yes			164
5		ST200-SF0-CF	Ø8@200mm	0	Yes			164
6	G3	ST0-0.5SF-CF0	0	0.5%	No			172
7		ST0-1.0SF-CF0	0	1.0%	No			172
8	G4	ST0-0.5SF-CF	0	0.5%	Yes			172
9		ST0-1.0SF-CF	0	1.0%	Yes			172

All beams have been tested until failure under the “Fourth-Point Bending” scheme. The load has been increased from zero to maximum carrying capacity with an interval of 2.0 kN/sec. The deflection at the span center has been recorded thoroughly and the crack initiation and propagation have been monitored carefully. The mode of failure has been investigated for each tested beam as well. Figure 2. shows a test beam during testing.

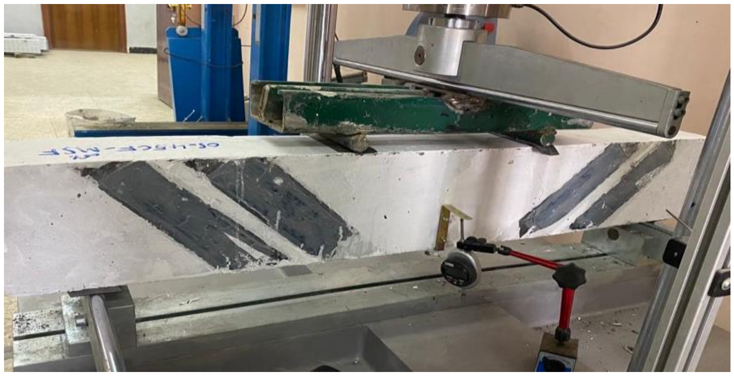


Figure 2. A test beam with inclined CFRP during testing

3. RESULTS AND DISCUSSION

3.1. Ultimate load-carrying capacity

Table 6 displays the load-carrying capacity, the middle of the span deviation at failure, and failure modes of the investigated beam samples. In contrast, the shear capability increase of each beam in contrast to the controlling beam and the shear capacity components are listed in Table 7.

Table 4. Summary of beam test results

No.	Specimen	Pu (kN)	Mid-Span Deflection (mm)	Failure mode
1	ST0-SF0-CF0	98.70	5.94	Shear failure
2	ST300-SF0-CF0	146.90	7.14	Shear failure
3	ST200-SF0-CF0	187.49	8.09	Shear failure
4	ST300-SF0-CF	179.44	8.42	CFRP Debonding
5	ST200-SF0-CF	225.00	8.52	CFRP Debonding
6	ST0-0.5SF-CF0	147.17	7.14	Shear failure
7	ST0-1.0SF-CF0	190.21	8.44	Shear failure
8	ST0-0.5SF-CF	218.13	9.67	CFRP Debonding
9	ST0-1.0SF-CF	266.80	10.43	Flexural failure

Table 5. Shear strength contribution of each strengthening material.

No.	Specimen	Vu (kN)	Increase (kN)	Vc (kN)	Vs (kN)	VSF (kN)	VCF (kN)
1	ST0-SF0-CF0	49.35	---	49.35	0	0	0
2	ST300-SF0-CF0	73.45	24.1	49.35	24.1	0	0
3	ST200-SF0-CF0	93.74	44.39	49.35	44.39	0	0
4	ST300-SF0-CF	89.72	40.37	49.35	24.1	0	16.27
5	ST200-SF0-CF	112.5	63.15	49.35	44.39	0	18.76
6	ST0-0.5SF-CF0	73.58	24.23	49.35	0	24.23	0
7	ST0-1.0SF-CF0	95.10	45.75	49.35	0	45.75	0
8	ST0-0.5SF-CF	109.06	59.71	49.35	0	24.23	35.48
9	ST0-1.0SF-CF	133.40	84.05	49.35	0	45.75	38.30

Tables 6 and 7 illustrate that the controlling beam "ST0-SF0-CF0" failed at a shear load of 49.35 kN. It can be noted that this value is much larger than the theoretical shear value calculated via ACI 318-2019, which indicates the conservative of the ACI code when dealing with the shear-type failure of RC elements as stated earlier. On the other hand, the beams “ST300-SF0-CF0” and “ST200-SF0-CF0” (Group 1) failed at a shearing load of 73.45 and 93.74 kN, which indicates an increasing load-carrying capability of 48.8 and 89.9%, respectively, as compared to the controlling beam.

Similarly, the beams of Group 3, “ST0-0.5SF-CF0” and “ST0-1.0SF-CF0” failed at a maximum shear load of 73.58 and 95.10 kN, respectively, approximately similar percent increase to the “ST300-SF0-CF0” and “ST200-SF0-CF0” beams compared to the beam of controlling. Until this point, the first task, as was discussed earlier, has been achieved and the results of both shear strengthening materials of stirrups and steel fiber have been confirmed to be nearly identical. The increasing carrying capacity, as indicated by beam samples with stirrups and steel fibers in comparison to the control beam is shown in Figure 3.

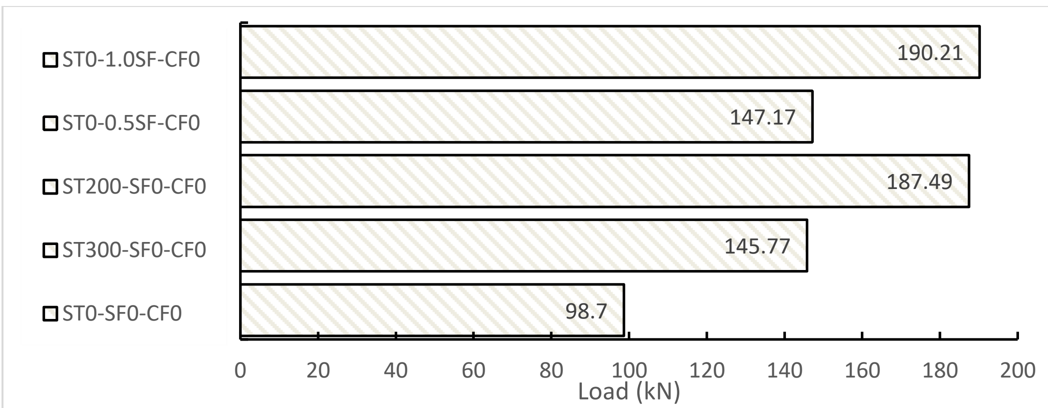


Figure 3. The load capacity of beam samples with steel stirrups or steel fiber without an additional CFRP Strengthening.

Figure 4. in contrast, shows the load capacity of beam samples reinforced by CFRP in addition to either steel stirrups or steel fiber (G2 & G4). This figure clearly illustrates the impacts of combining stirrups or steel fiber with the outwardly bonded CFRP sheet on the shear capability beams. The rise in the load capacity of “ST300-SF0-CF” and “ST200-SF0-CF” beams in comparison to the beam of controlling was 81.8 and 127.9%, respectively. Similarly, a considerable rise in the shear capability of beams “ST0-0.5SF-CF” and “ST0-1.0SF-CF” in comparison to the controlling beam has been noticed; the rate increase in the shear capacity of beams “ST0-0.5SF-CF” and “ST0-1.0SF-CF” was 120.9 and 170.3%, respectively.
Comparing the results obtained from G2 and G1, and the results of beams in G4 and G3, clearly emphasized the superiority of CFRP contribution when applied to the beams originally strengthened against shear by steel fiber. For example, beam #9 in the G4 group showed a 133.40 kN rise in the capacity of shear, while the increase in the shear strength of beam #5 in G2 was limited to 112.50 kN, such results agree with the previously published work done by (Amin & Foster, 2016; BT.-T. Bui, W. S. A. Nana, B. Doucet-Ferru, A. Bennani, H. Lequay, 2020; Pellegrino & Modena, 2002).

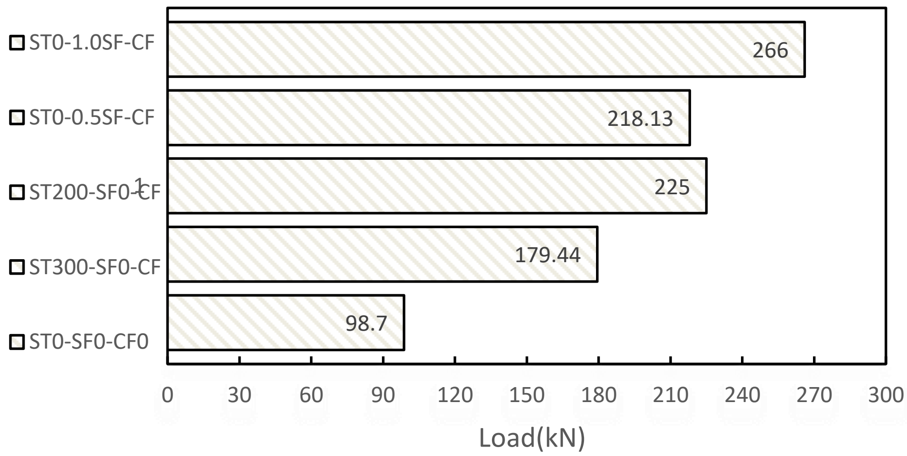


Figure 4. The load-carrying capability of beam samples with steel stirrups or steel fiber with an additional CFRP Strengthening.

3.2. Load-deflection relationship

Figures 5 to 8 illustrate the load-deflection associations of entire tested beams. These graphs show the behavior of beams that have been strengthened with steel stirrups (G1) or with steel fiber (G3) showed almost identical load-deflection relationships, and both groups provided greater ductility than the control beam. For example, the highest deflection of G1 steel stirrup specimens was observed. of 10 mm diameter distributed at 300 and 200 mm were 20.2 and 36.2%, respectively. Similarly, specimens of the G3 group with 0.5 and 1.0% volume fractions of steel fibers have caused an increase in the maximum deflection at failure by 20.2 and 42.1 %, correspondingly, in comparison to the control beam. Increasing both the load-carrying capacity and the deflection at failure is evidence that both steel stirrups and steel fibers have improved the overall performance of tested beams against shear forces.

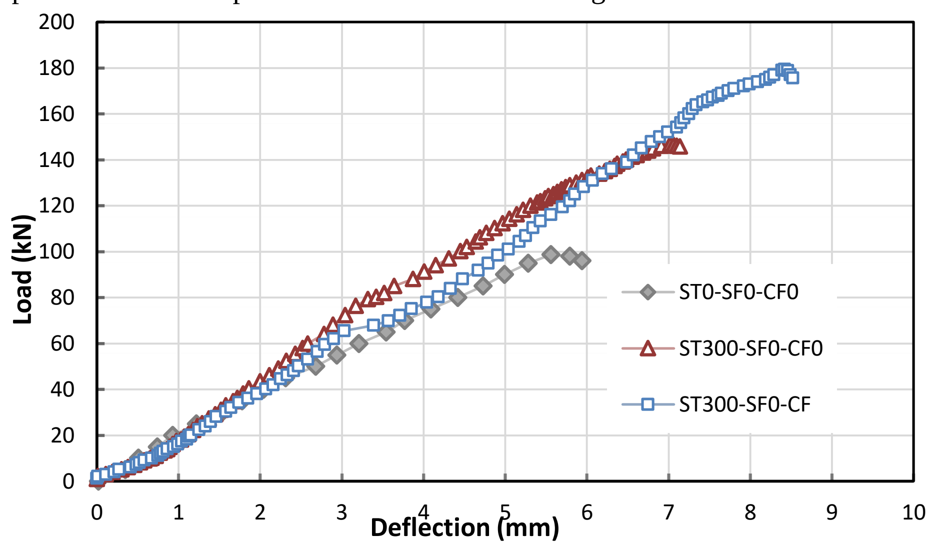


Figure 5. Load-midspan deflection curves for the beam of control and the beams originally strengthened by Φ10@300mm steel stirrups with and without CFRP strengthening.

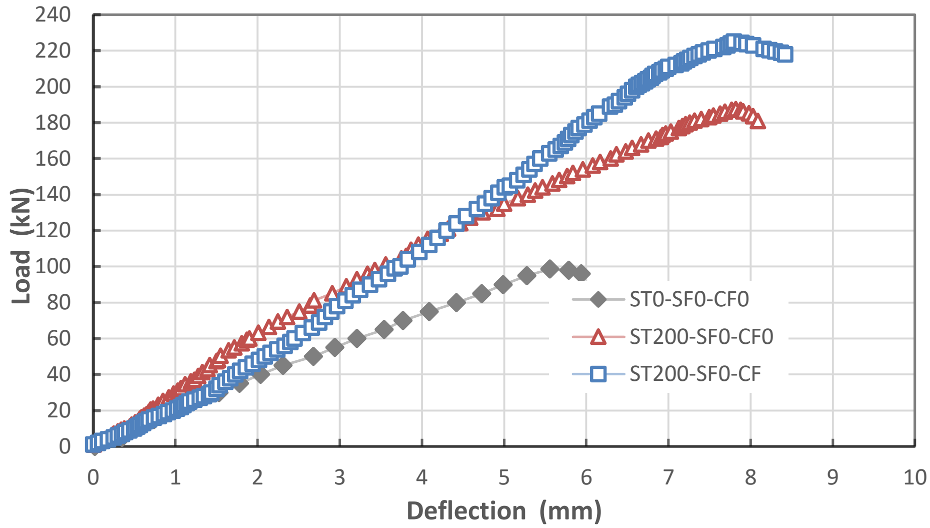


Figure 6. The curves of load-midspan deflection for the beam of controlling and the beams originally strengthened by Φ10@200mm steel stirrups with and without CFRP strengthening.

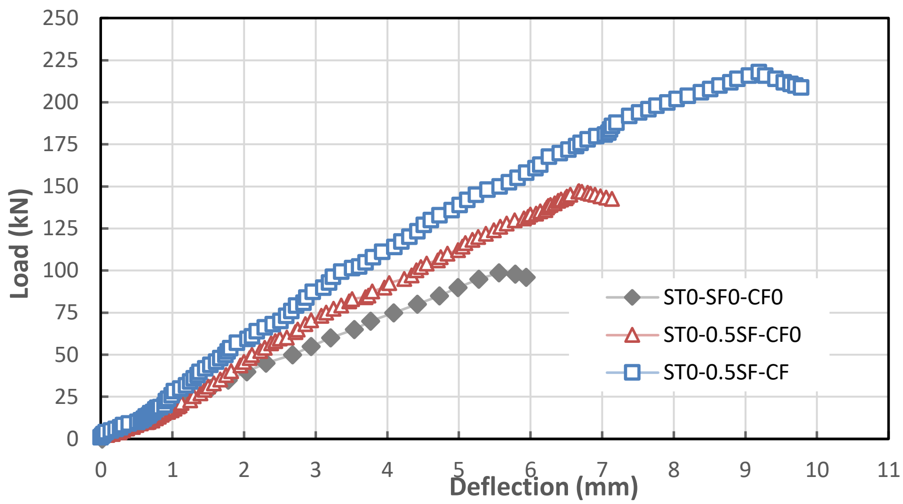


Figure 7. Load-midspan deflection curvatures for the beam of control and the beams originally strengthened by 0.5% steel fiber with and without CFRP strengthening.

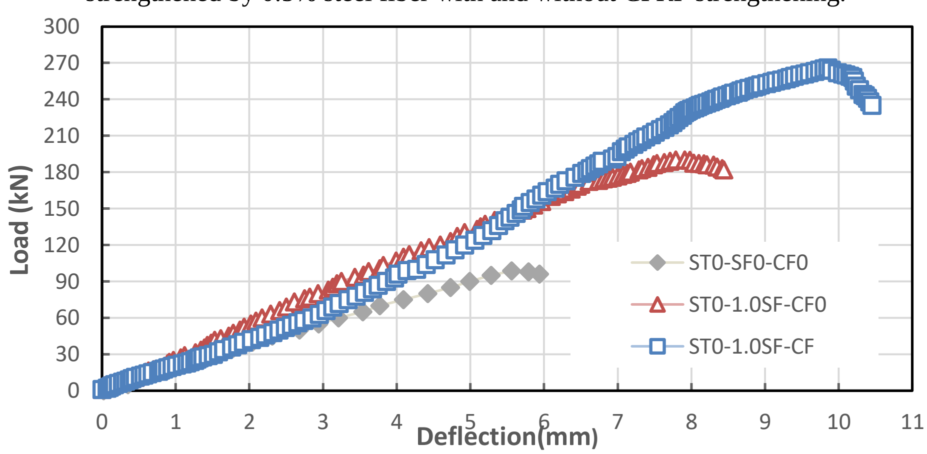


Figure 8. Load-midspan deflection curves for the beam of control and the beams originally strengthened by 1.0% steel fiber with and without CFRP strengthening.

The increase in load-deflection of (G2) specimens due to the interaction of steel stirrups ST300 and ST200 with CF are 41.7% and 43.4%, respectively, in contrast to the controlling beam, which may be said to represent identical contributions.

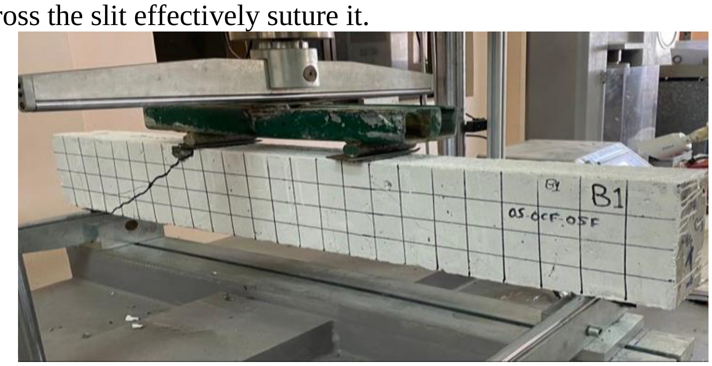
The max contribution of CF in deflection was produced by (G4) beams ST0-0.5SF-CF and ST0-1.0SF-CF by 62.8 and 75.6 % respectively, it is obvious that the reinforced beams were able to support more loads and displacements than the other examples.

The interaction between CF and SF with (1%) is more contributive in displacement if compared with the interaction among steel stirrups (ST200) and CF. In the same way, the interaction between the CF and SF with (0.5%) of beam ST0-0.5SF-CF was contributing to deflection more than the contribution of interaction between CF and steel stirrups (ST300) of beam ST300-SF0-CF. Hence, the contribution of CFRP in deflection has increased with increasing the internal strength (SFRC or stirrups) as proven *by* (Dinh, 2009).

3.3. The modes of failure and crack pattern

The findings illustrated that three failure types have been recognized in the specimens under testing, namely, shear failure, CFRP Debonding, and flexural failure, as explained in Table 6. The existence of steel fibers had 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 are shown in Figure 9. In the control beam, Figure 9. shows the creation of one great shear crack among the point load and the support within the areas of persistent shear at failure. Furthermore, the beam (ST300-SF0-CF0) failed owing to dual diagonal cracks that combined for 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. b. On the other hand, ST200-SF0-CF0 had failure owing 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. c.

Due to an increase in the volume fraction of steel fibers in beams from 0.5% to 1%, the failure mode remained a failure of shear with various cracks in such beams, as illustrated in Figures 9.d to 9. e, which demonstrates the encouraging effect of fibers by making various cracks before failure. Furthermore, according to the data, the influence of steel stirrups and steel fiber with minimum values in this study produced the same failure mechanism. In addition, the influence of steel fibers and stirrups with maximum values for both resulted in a similar failure which is a shear failure. In contrast, these figures can demonstrate that the fibers efficiently suppress cracking and transmit residual stresses beyond cracking. In this way, the fibers across the slit effectively suture it.



a- ST0-SF0-CF0

(b) - ST300-SF0-CF0 (c)- ST200-SF0-CF0

(d)- ST0-0.5SF-CF0 (e)- ST0-1.0SF-CF0

Fig. 9 The types of failure for the test beams as control beams and beams reinforced internally by SFRC or stirrups and without CFRP sheet.

Figure 10 illustrates the failure mechanisms and crack patterning for beams strengthened by CFRP sheets. Figures 10. a and 10. b demonstrate that beams ST300-SF0-CF and ST200-SF0-CF failed owing to the debonding of the CFRP sheets. Furthermore, as illustrated in Figure 10 c, the beam ST0-0.5SF-CF failed in shear owing to CFRP debonding. In contrast, as shown in Figure 10.d, beam ST0-1.0SF-CF failed in flexural failure.

As calculated from the results the existence of 1% steel fiber made changes in failure type from CFRP debonding to flexural failure at mid-span as reported by (Yin & Wu, 2003),(B. Singh & Jain, 2014). The beam that was reinforced by stirrups with maximum value, on the other hand, failed due to CFRP debonding. Moreover, the results showed that interacting with a minimum amount of steel fibers or stirrups produced identical failure behavior, which is CFRP debonding failure.

The interaction of the CFRP with a maximum amount of steel fiber in a failure mode and crack patterns differs from that of the CFRP and steel stirrups. When compared to mode failure due to interaction between steel stirrups and CFRP, which still has CFRP debonding as mode failure, steel fiber has a greater influence in interaction related to the change in the mode of failure from CFRP debonding to flexural failure.

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

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

Fig. 10 Failure modes of the test beams as strengthened internally by SFRC or stirrups and with CFRP sheet.

4. CONCLUSIONS

- Adding steel fibers at 0.5% and 1% volume fractions increased the strength of compression of HSC by 13.6% and 22%, respectively. It should be noted that the cubic with the maximum compressive strength among all studied specimens were those with a steel fiber volume ratio of 1%.
- As the volume percentage of steel fibers is raised from 0.5% to 1%, the ultimate load increased from 49% to 92.7%, and the failure deflection rose 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 that have been volume-reinforced percentage of 0.5 to 1% steel fiber were shear failures with increasing crack numbers and decreasing crack width.
- In general, the findings of the test illustrated that strengthening the EBR with 45˚ CFRP sheets considerably enhanced the load capacity and deflection of the investigated beams.
- The interaction between steel fiber with ratios of 0.5 and 1% and CFRP increased the maximum load by 120.9 and 170.3% and increased the deflection by 62.8% and 75.6.3% respectively.
- The ultimate load and the deflection at failure increased by 48.8% to 89.9% and 20% to 36 %respectively, by increasing the steel stirrups amount.
- The interaction of steel stirrups ST300 and ST200 with CFRP improved shear capacity by 81% and 127%, respectively, and increased deflection by 41.74 and 43.4 %, in comparison with the reference beam.
- The results of the testing identified three modes of failure, with shear failure being a mode for all beams except (ST300-SF0-CF, ST200-SF0-CF, and ST0-0.5SF-CF, which failed via CFRP-Debonding, and ST0-1.0SF-CF, which failed due to flexural failure).
- The interaction between 1%vol steel fiber and CFRP produced the maximum contribution value in shear capacity and deflection.

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