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SHEAR BEHAVIOR OF SELF-COMPACTING CONCRETE BEAMS REINFORCED WITH B500WR AND STRENGTHENED WITH CFRP

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ABSTRACT

Fiber Reinforced Polymer (FRP) has become increasingly attractive due to its advantageous low weight, high stiffness and strength-to-weight ratio, corrosion resistance, lower maintenance costs, and faster installation time. Experimental and numerical studies researches show that using (FRP) materials to strengthen reinforced concrete (RC) beams in shear is an effective method. The purpose of this paper is to study the effect of strengthening self-compacting concrete beams using carbon fiber-reinforced polymer (CFRP) fabrics with different wrapping schemes in shear. Five rectangular beams of a rectangular cross section of 100×250 mm and a length of 1650 mm were cast and tested under four-point bending. One beam was used as a control beam without external strengthening, while the other four beams were strengthened in shear using U-Wrapped CFRP with different widths and densities. The used CFRP led to an increase in the load-carrying capacity, failure load, displacement ductility ratio, and displacement ductility index, but energy ductility was decreased. The investigation results are presented in terms of ultimate load, deflection, tensile and compressive strains, and cracking pattern.

KEYWORDS: Self-Compacting, Concrete Beams, Shear, CFRP, strengthened.

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سلوك القص للكمرات الخرسانيه ذاتيه الدمك ومسلحة بحديد B500WR ومدعمه بالياف الكربون

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الملخص:

أصبح أستخدام البوليمرات المدعمه بالألياف منتشرا بشكل متزايد نظرًا للمميزات العديده التي منها الوزن المنخفض وصلابته العالية ونسبة القوة إلى الوزن ، ومقاومة التآكل ، وانخفاض تكاليف الصيانة ، والسرعه في التنفيذ مما يوفر الوقت.وقد أظهرت الدراسات المعمليه والتحليليه أن استخدام الياف الكربون في لتقوية الكمرات الخرسانية المسلحة في القص هو طريقة فعالة.ولذلك فإن الغرض من هذا البحث هو دراسة تأثير تقوية الكمرات الخرسانية ذاتية الدمك باستخدام ألواح البوليمر المقوى بألياف الكربون مع طرق مختلفه لتدعيم الكمرات واختبارها في القص. تم صب خمس كمرات مستطيلة ذات ابعاد ١٠٠ × ٢٥٠ مم وطول ١٦٥٠ مم واختبارها في الانحناء عند أربع نقاط وقد كانت الكمرة المرجعيه بدون تدعيم. بينما تم تقوية الكمرات الأربعة الأخرى في القص باستخدام الياف الكربون (شكل U) بعده طرق وكثافات مختلفه. تم عرض نتائج الاختبارات من حيث الحمل النهائي ، والانحراف ، والشد ، والانضغاط ، ونمط التكسير.

الكلمات المفتاحيه : خرسانه ذاتية الدمك, كمرات خرسانيه, القص, تدعيم باستخدام الياف الكربون

1. INTRODUCTION

The need to retrofit existing reinforced concrete structures has increased over the decades. Strengthening and rehabilitation of structures are major issues worldwide. In most situations, strengthening is required when there is an increase in the applied load, and human errors in the initial construction. Strengthening using FRP laminates is increased due to the development of structurally effective adhesives [1].
In general, the three ways in which the FRP laminates can be bonded to RC beams to strengthen them in shear include side bonded, where the laminates are bonded to the vertical sides of the beam (U-wrapped), where the laminates are bonded to the sides of the beam as well as the tension face in a U-shaped manner and completely wrapped, where the laminates are bonded around the beam.
Earlier research has demonstrated that the addition of carbon fiber-reinforced polymer (CFRP) laminate to reinforced concrete beams can increase stiffness and maximum load of the beams. [2:15]**.** Studies proved that completely wrapped beams perform the best in terms of enhancing the shear capacity and ductility of RC beams. This is due to the higher attained effective strain along the fiber's vertical direction than that with side-bonded and U-wrap strengthening schemes. However, practically it cannot be implemented in many cases, where the beams are connected to the slabs. Hence, the U-wrapped scheme is the most commonly used method to strengthen RC beams in shear. In general, most of the studies concluded that FRP is an effective method for strengthening RC beams. However, many factors affect the enhancement in shear capacity. These factors have been reported in many experimental investigations [16: 25]. The efficiency of FRP system to strengthen shear deficient RC beams depends on all those parameters reported in the literature. These factors include beam geometry, strengthening material, strengthening scheme, shear span to depth ratio (a/d), concrete compressive strength, flexural reinforcement ratio, loading type, and layout method (wet or dry).

Bencardino, F., [26] investigated the strength and ductility of reinforced concrete beams externally reinforced with carbon fiber fabric in flexure and shear using externally epoxy-bonded bidirectional carbon fiber fabric. The composite reinforcement led to an increase in load-carrying capacity at flexural beams. While significant reductions in deflection, curvature, and, structural ductility were also observed.

Abd El-Latif, H. et al., [27] studied the flexure and shear behavior of reinforced concrete beams strengthened using innovative local composite fabric. This composite consisted of locally woven fabric and local resin. They concluded that the failure load of the strengthened specimens in shear showed an increase in the overall load capacity up to 59 %, and the mode of failure was changed from shear failure to flexure failure.
Kishore et al., [28] investigated the effect of external wrapping using (CFRP) laminates on the load carrying capacity of reinforced concrete beams. The main variables considered were the internal reinforcement ratio and position of the strengthening. They concluded that beams strengthened by CFRP laminates are structurally efficient and were upgraded to more load-carrying capacity. The deficient beams showed more softening due to crack propagation, whereas the beams, when strengthened by the laminates lost partial ductility.

Mhanna H., et al., [29] investigated the effect of strengthening shear deficient RC beams with externally bonded carbon fiber-reinforced polymer (CFRP) sheets with different wrapping configurations. Two shear strengthening wrapping schemes of CFRP sheets were investigated; U-Wrapped and completely wrapped. The experimental test concluded that an ideal way to increase the shear capacity and ductility of RC beams is to completely wrap the beams using CFRP sheets.
Nawaz et al., [30] carried out an experimental study to quantify the contribution of CFRP flexural reinforcement to the shear strength of RC beams. Three groups of three beams each were built without shear reinforcement. Each group had a different steel flexural reinforcement. One beam in each group was unstrengthened, while two beams were strengthened with CFRP plates on their soffit. The beams were tested under four-point loading and all failed in shear. They concluded that the shear capacity of RC beams strengthened with CFRP sheets as flexural reinforcement increased by about 10-70% over the control un-strengthened specimen and by about 13-138% for those strengthened with CFRP plates as flexural reinforcement.

Saqan E., et al.,[31] investigate the effectiveness of externally bonded CFRP flexural reinforcement to improve the shear strength of beams and quantify their contributions. A pilot test was conducted which included three beam specimens. All beams were reinforced with 2ϕ12 steel bars (approximately 1% reinforcement ratio) and were cast without transverse reinforcement in their shear span. Two beams were strengthened with one and two layers of CFRP plates as external flexural reinforcement while the third beam was left as the control specimen. The beams were tested under four-point loading. Load and mid-span deflection readings were recorded until failure. All specimens failed in shear as a result of a diagonal-tension crack. The strengthened specimens with one and two layers of CFRP plates showed an increase in their shear capacity of 55% and 76%, respectively, over the control specimen. It was concluded that CFRP plates, when externally bonded to the soffit of simply supported beams, enhance both flexural and shear capacity of such beams. As a result, a comprehensive testing program is now underway. Specimens will be tested by varying the steel reinforcement ratio, the CFRP reinforcement ratio, and CFRP plates vs. sheets, in an effort to quantify the contribution of flexural CFRP reinforcement in shear strengthening of RC beams.

Nawaz, W., [32] investigates the contribution of longitudinal CFRP reinforcement on the shear strength of shear deficient RC beams. To achieve this objective, nineteen beams were cast without transverse reinforcement in the shear span and tested under four-point bending. The specimens were divided into three groups with different longitudinal steel reinforcement ratios. Each group has one control un-strengthened beam and five beams strengthened at their soffit with CFRP plates or sheets. An equivalent longitudinal reinforcement ratio was computed based on the modular ratio of the CFRP and steel reinforcement and ranged from 0.14 to 2.29%. The load and mid-span displacement values and strain gauge readings at different discrete locations along the beam's shear and mid-spans were recorded until failure. The specimens failed in shear as a result of a diagonal-tension crack as expected. The strengthened specimens showed a significant increase in the load-carrying shear capacity over the control specimens. The increase in the concrete shear capacity for beams strengthened with sheets and plates ranged from 10 to 70% and 30 to 151%, respectively, over the control specimens. It was concluded that CFRP composite plates and sheets, when externally bonded to the soffit of simply supported beams, will enhance both the flexural and shear capacity of such beams. In addition, the concrete shear capacity of the tested specimens was predicted using the ACI 318-08 and CSA 2004 simplified and detailed shear design provisions. The results indicated that CSA 2004 shear design provisions, which are based on the modified compression field theory, yielded the closest agreement with the obtained experimental data.

Barrigo et al., [33] indicated that Full U-wrapping with FRP sheets perform better than partial U-wrapping and RC beams strengthened in shear with carbon FRP (CFRP) sheets exhibited the high-strength and stiffness compared with the glass FRP (GFRP) and FRCM (fiber reinforced cementitious matrix) systems. Moreover, the use of anchors had only a small impact on the behavior of full-depth strengthened beams, while they were effective in preventing the debonding of FRP sheets in their partial depths.

Hawileh et al. [34] investigate the effect on the shear strengthening of RC beams by externally bonding CFRP sheets to the beam's sub-surface. The increase in the shear strength of RC beams was in the range of 10–70% compared to the control beams.
Chen et al [35], studied the failure of FRP wrapping types (full wrapping, side, and U-strips) in an FRP strengthened RC beams and how it affects the shear behavior of the beam was examined by considering the shear crack opening and tried to be determined by the analytical study. They found that in the shear strengthening of FRP, the first crack load occurs at a higher shear load than the control beams

In this study, an experimental program was planned and executed to investigate the effect of strengthening self-compacting concrete beams using carbon fiber-reinforced polymer (CFRP) fabrics with different U-wrapping CFRP with different widths and densities in shear. Five rectangular RC beams were constructed and tested to evaluate load carrying capacity, failure load, displacement ductility ratio, and displacement ductility index. The results are presented in terms of ultimate load, deflection, tensile and compressive strains, and cracking pattern.

2. EXPERIMENTAL PROGRAM

2.1 **Materials**

Self-Compacting Concrete (SCC) of grade 40 was used to cast the specimens. Table 1 shows the concrete mix proportion used. The cement used in the mixes was CEMI-52.5

N conforming to the European Norms EN 197-1[36] and produced by Misr Beni Suef Company, Egypt. The fine aggregate was natural siliceous sand that conforms to the requirements of EN12620 [37]. The maximum aggregate size of the used coarse aggregate was 19 mm. High-range Water-reducing, Type F admixtures with dark brown color and density of 1.225 kg/L were used conforming with ASTM C494. Five percent by weight of the cement was replaced by silica fume. The w/c ratio was 0.38. Slump flow diameter as well as, the flow time for SCC mixture reaching diameter of 500 mm, T50, were measured. Six standard cubes with a side length of 150 mm were prepared and cured under standard conditions. The average measured Slump flow diameter was 700 mm. and the average measured T50 was 3.9 sec. The average measured compressive strength of the concrete was 41.0 MPa. Fig. 1 shows the slump flow diameter for the SCC mixture, and Fig. 2 shows the specimens during concrete pouring.

CFRP used had a tensile strength of 3900 N/mm^2 for dry fabric, with a Tensile E-Modulus of 230000 N/mm^2 and elongation at break of 1.5%. for the laminate (CFRP+epoxy), the ultimate tensile load is 480 kN/m width.

Table 1: Concrete Mix Proportion for Specimen

Cement	Silica fume	Coarse Agg.	Sand	Water	Type F(ISOFLEX 351)
475 kg	25 kg	824 kg	824 kg	190 lit.	13 kg.

Fig.1: The Slump Flow Diameter for SCC mixture

Fig. 2: The Specimens Before Concrete Pouring.

2.2 Tested Specimens

Five reinforced concrete (RC) beams were designed and cast using self-compacting concrete (SCC). **Fig. 3** shows the beam dimensions, reinforcement details, and cross-section details of the beam specimens. Two B500DWR 16 mm diameter steel bars were used to satisfy the Egyptian code requirements for under-reinforced sections. The secondary reinforcement was two bars, eight mm in diameter each, mild steel. Eight mm diameter mild steel closed stirrups at 200 mm intervals were used in the shear zone.

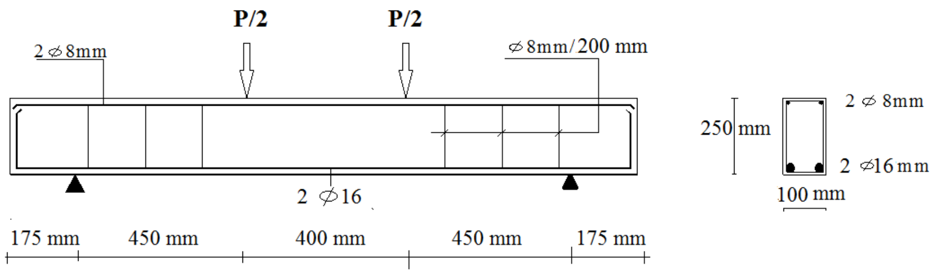

Fig .3: The Beam Dimensions and Reinforcement Details of the Beam Specimens

2.3 Strengthening Procedure

The strengthening procedure of the tested beams included surface preparation by grinding, application of a priming adhesive layer, and bonding of the CFRP fabrics with tensile force 3900 N/mm^2. Before bonding, special consideration was given to the surface preparation. As shown in Fig. 4, uniform mechanical grinding was employed to remove the outer weak surface of the concrete until the aggregates were exposed. Afterwhich, the surface of the beams was cleaned with compressed air to remove any loose particles. The epoxy resins were mixed as per the manufacturer's instructions until the mixture had a uniform color. CFRP fabrics were cut exactly according to the specified dimensions and placed over the beam specimens as shown in Fig. 5.

Fig . 4: Surface preparation by grinding

Fig .5: PlacingCFRP over the beam.

2.4 Details of the Strengthened Beams

The control Beam (SR) was left un-strengthened, while the other four beams were strengthened in shear using U-Wrapped CFRP with different width and density to investigate different CFRP fabric strengthening schemes. Table 2 and Fig. 6 show the details of the strengthened beams and CFRP wrapping schemes.

Table2: Details of the Strengthened Beams

Beam code	CFRP details		
	Noumber/ side	Width mm.	weight of square meter gm.
S1	6	50	300
S2	3	100	300
S3	3	100	500
S4	1	450	300

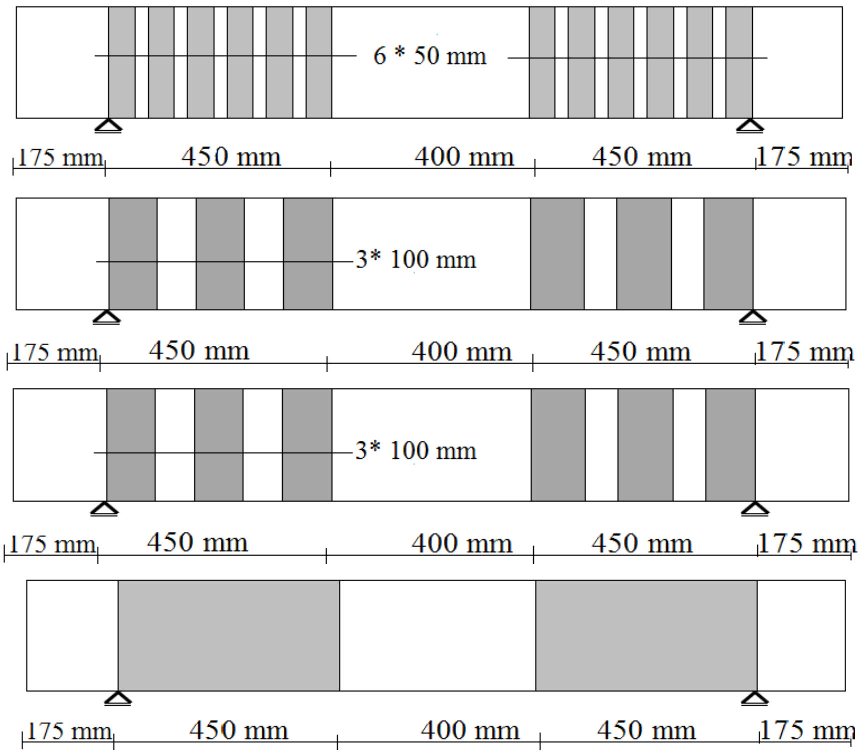

Fig. 6: CFRP wrapping schemes

The beams were loaded as shown in Fig. 7 and tested in four-point bending to failure. The clear span of the beams was 1300 mm and the two loading points were 400 mm apart located symmetrically about the beam's mid-span location. The shear span of the tested beams was 450 mm.

The beams were loaded monotonically using a digitally controlled Shimadzu Universal Testing Machine (UTM) that has a capacity of 500 kN. To measure tensile and compression strains, electrical strain gages were fixed on the main and secondary reinforced steel bars. Linear variable displacement transducers LVDT were used to measure deflections at the mid-span of the tested beams. The data from Electrical strain gages and the "LVDTs" were recorded using a data logger.

Fig.7: Test Setup

3. RESULTS AND DISCUSSION

3.1. Yield and Failure Load

Table 3 summarizes the yield and failure load experienced by the tested beams. The yield load for strengthened beams S1, S2, S3, and S4 ranged from 89% to 106% of that of the control beam. The failure loads for strengthened beams are more than that of the control beam. Beam S2 exhibited the maximum load-carrying capacity which is about 130 % of the control beam capacity.

Table 3: Comparison Between Yield and Maximum Load for Tested Beams

Beam code	yield load		maximum load	
	kN	Ratio to Control	kN	Ratio to Control
SR	180.72	100%	193.27	100%
S1	160.64	89%	222.13	115%
S2	171.93	95%	251	130%
S3	183.23	101%	235.94	122%
S4	192.01	106%	220.88	114%

3.2 Deflection

Table 4 shows the mid-span deflection of tested beams at the yield and failure loads. At the yield load, all the strengthened beams experienced deflection smaller than that of the control beam. The deflection of strengthened beams S1, S2, S3, and S4 ranged from 73% to 92% as that of the control beam. At the failure load, the deflection of strengthened beams ranged from 179% to 222% as that of the control beam.

Table 4: Comparison between deflections for tested beams

Beam code	Deflection at yield load		Maximum deflection	
	mm.	Ratio to Control.	mm.	Ratio to Control.
SR	4.5	100%	6.629	100%
S1	6.8	151%	12.13	183%
S2	8.25	183%	14.719	222%
S3	3.9	86.7%	11.889	179%
S4	5.2	115.6%	13.72	207%

Fig. 8 illustrates the load-deflection relationship, between the control beam, SR, and the four strengthened beams S1, S2, S3, and S4. As shown, the deflections of strengthened beams S3 and S4 are smaller than those of the control beam up to its failure load. On the other hand, the deflections of strengthened beams S1 and S2 are more than those of the control beam for all stages of loading.

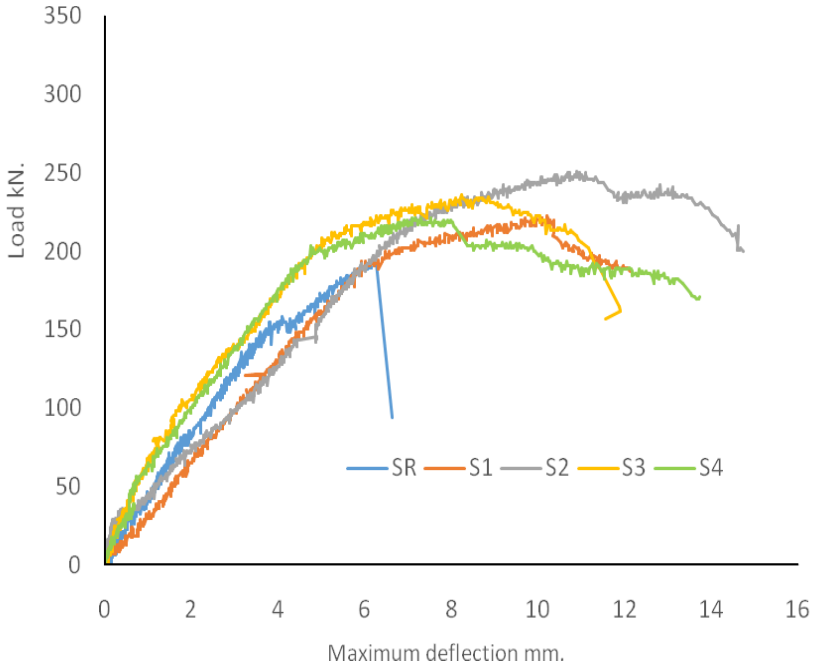

Fig.8: The Relation between Load and Maximum Deflection for Tested Beams

3.3 Tensile Strain Diagonal Tensile Strain and Compressive Strain

Table 5 shows tensile and strain, diagonal tensile strain, and compressive strain. Fig. 9 illustrates load and maximum tensile strain for the control beam, SR, and the four strengthened beams S1, S2, S3, and S4, while, The tensile strain of strengthened beams S1, S2, S3, and S4 ranged from 489% to 609% of that of control beam.

Fig. 10 illustrates load and diagonal tensile strain for the control beam, SR, and the four strengthened beams S1, S2, S3, and S4, while, The tensile strain of strengthened beams S1, S2, S3, and S4 ranged from 54% to 173% of that of control beam.

On the other hand, Fig. 11 illustrates load and maximum compressive strain for strengthened beams. The compressive strain of strengthened beams S1, S2, S3, and S4 ranged from 231% to 2331% of that of the Control beam.

Table 5: Tensile Strain Diagonal Tensile Strain and Compressive Strain for Tested Beams

Beam code	Tensile strain		Diagonal tensile strain		Compressive strain	
	mm/mm	Ratio to Control.	mm/mm	Ratio to Control.	mm/mm	Ratio to Control.
SR	0.0029	100%	0.0046	101%	0.0013	100%
S1	0.0142	489%	0.0079	173%	0.0101	776%
S2	0.0168	580%	0.0045	97%	0.0237	1823%
S3	0.0167	575%	0.0034	73%	0.0030	231%
S4	0.0177	610%	0.0025	54%	0.0303	2331%

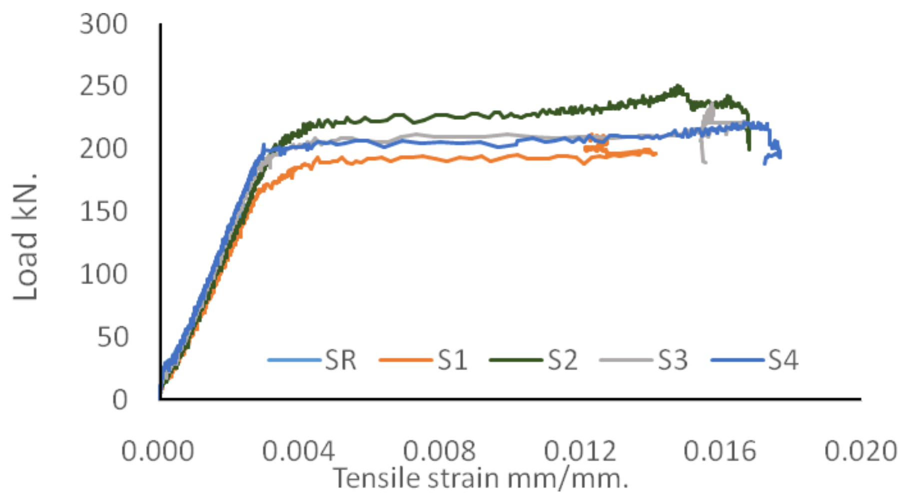

Fig. 9: The Relation between Load and Maximum Tensile Strain for Tested Beams

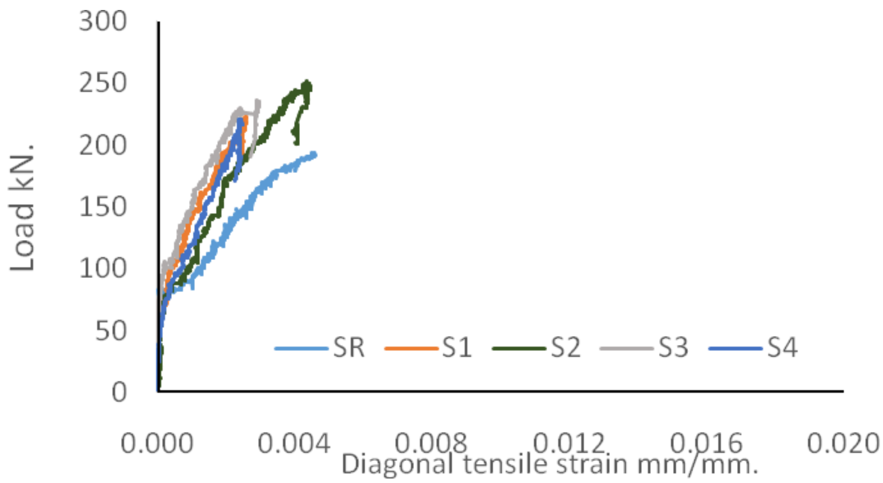

Fig. 10: The Relation Between Load and Maximum Diagonal Tensile Strain for Tested Beams

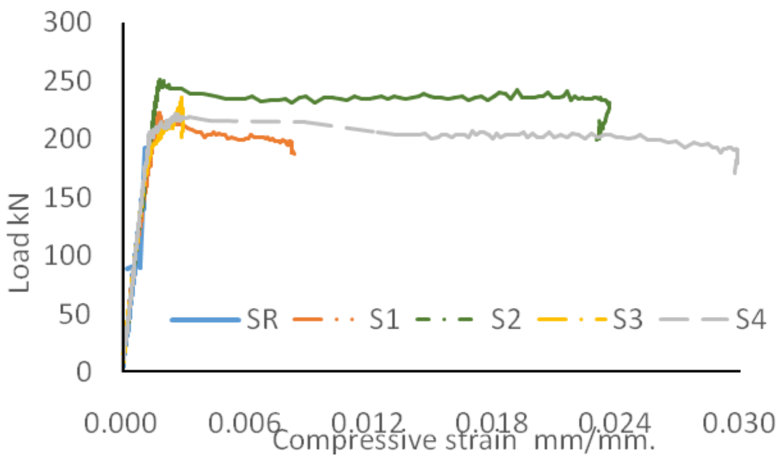

Fig. 11: The Relation between Load and Maximum Compressive Strain for Tested Beams

3.4 Cracking Patterns and Failure Mode

Fig.12 shows the cracking patterns of all tested beams. By revising this Figure it was observed that the crack pattern of the control beam SR was a shear failure. For strengthened beams (S1, S2, S3) failure was flexure failure. The strengthened beam S4 failed in compression; this means that the suggested system was competent since there was no shear crack and the mode of failure was changed from shear failure to flexure failure.

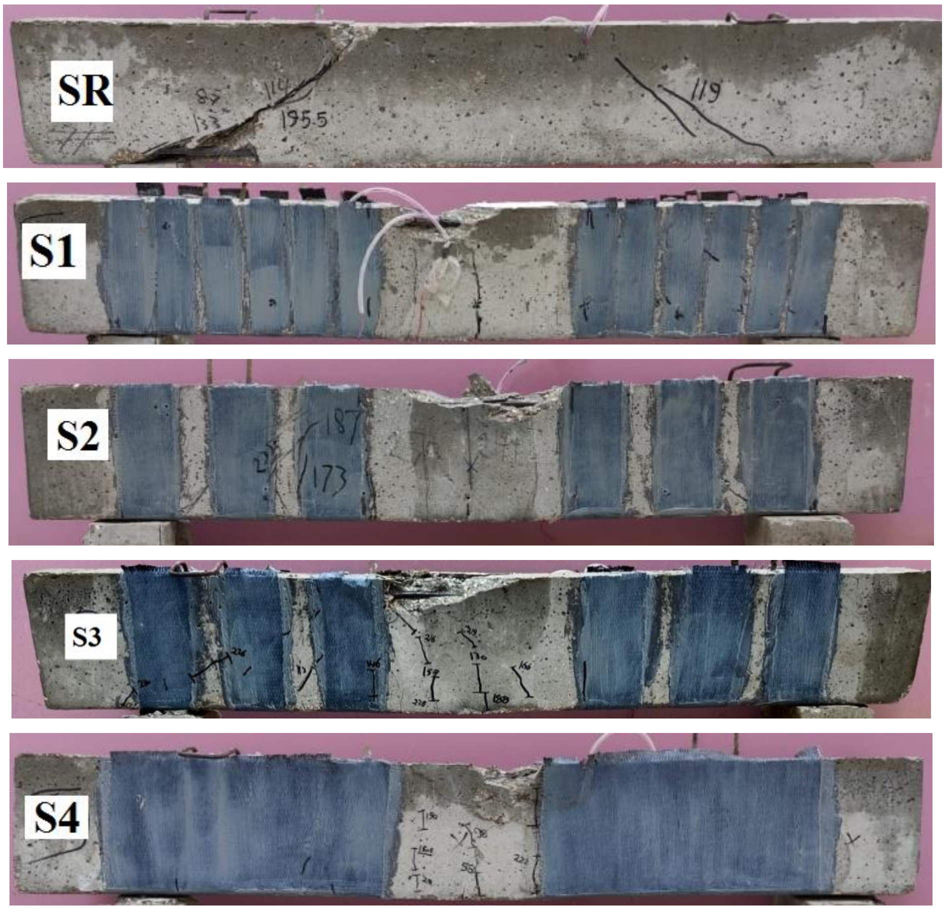

Fig. 12: Cracking Patterns and Modes of Failure at Ultimate Load for Tested Beams

3.5 Structural Ductility

A displacement ductility ratio was selected as an index by Azizinamini et al., [38]. This index is defined as the ratio of the maximum mid-span displacement over the first yield displacement of beams (equation (1)). The first yield displacement, y, corresponds to the intersection of the tangents to the load-displacement curve at the origin and maximum displacement, max (Fig. 13a).

Displacement ductility ratio$\mu_\Delta = \Delta_u / \Delta_y$ (1)

Cohn and Bartlett [39] proposed a relatively more appropriate definition for a displacement ductility index. Based on their definition, the displacement ductility index can be estimated as the ratio of the displacement corresponding to 85% of the maximum load on the post-peak portion of the curve to the displacement corresponding to the first yield displacement of a beam (equation (2) and **Fig. 13b**).

Displacement ductility index $\mu_{\Delta} = \Delta_{0.85Pmaximum} / \Delta_y$ (2)

On the other hand, energy ductility can be estimated as the ratio of the area under the load-deflection diagram at ultimate load to the area under the load-deflection diagram up to yielding of tension steel (elastic energy) equation (3)

Energyductility, $\mu_E = E_u / E_y$ (3)

Where
Δ_u = mid-span deflection at ultimate load;
$\Delta_{0.85Pmaximum}$ = displacement corresponding to 85% of the maximum load on the post-peak portion of the curve
Δy = mid-span deflection at tension-steel yielding;
Eu = area under the load-deflection diagram at ultimate load; and
E_y = area under the load-deflection diagram up to yielding of tension steel (elastic energy)

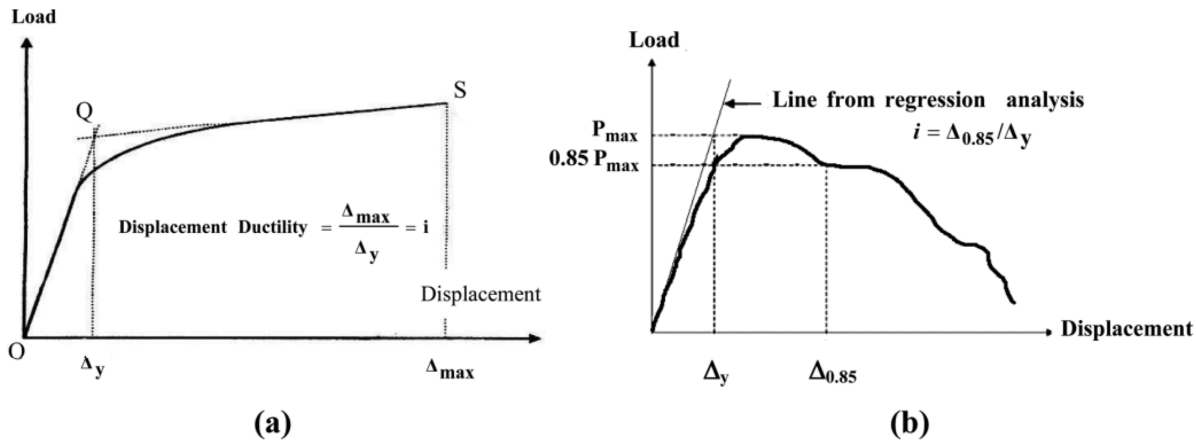

Fig.13: Definition of Displacement-Ductility Ratio

3.6 Ductility Indices for Tested Beams

Table 6 shows the Displacement ductility ratio, Displacement ductility index, and Energy ductility, whereas **Table 7** shows Ductility ratios for tested beams.

Table 6: Ductility indices for tested beams

Beam	SR	S1	S2	S3	S4
Failure load (kN)	193	222	251	236	221
Δ_u	6.629	12.13	14.719	11.889	13.72
Δ_y	4.5	6.8	8.25	3.9	5.2
Displacement ductility ratio	1.47	1.78	1.78	3.05	2.64
$\Delta_{u\ 0.85}$	6.35	11.8	14.3	11.2	11.8
Δ_y	4.5	6.8	8.25	3.9	5.2
Displacement ductility index	1.41	1.74	1.73	2.87	2.27
Energy ductility	0.45	0.31	0.29	0.29	0.22

Table 7: Ductility Ratios

Beam	SR	S1	S2	S3	S4
Failure load (kN)	1	1.15	1.30	1.22	1.15
Displacement ductility ratio	1	1.21	1.21	2.07	1.80
Displacement ductility index	1	1.23	1.23	2.04	1.61
Energy ductility	1	0.69	0.64	0.64	0.49

Referring to Tables 6 and 7, it could be concluded that:-
1 –The displacement ductility ratio for strengthened beams ranged from 121% to 207% to that of the control beam.
2 –The displacement ductility index for strengthened beams ranged from 123% to 204 % to that of the control beam.
3 –The energy ductility for strengthened beams ranged from 49 % to 69 % to that of the control beam.

CONCLUSIONS

This experimental study aims to study the effect of using B500WR in reinforcing self-compacting concrete beams strengthened with CFRP and subjected to shear. Based on the experimental results presented in this paper, the following can be concluded:
1) The use of CFRP fabrics in strengthening self-compacting concrete beams reinforced with B500DWR rebars increases load-carrying capacity, and changes the mode of failure of the beams.
2) The yield load for strengthened self-compacting concrete beams S1, S2, S3, and S4 ranged from 89 % to 106 % as that of the control beam.
3) The failure loads for strengthened beams ranged from 115% to 130% as that of the control beam.
4) The use of CFRP fabrics in strengthening self-compacting concrete beams in shear, led to an increase in the load-carrying capacity, failure, loads displacement ductility ratio, and displacement ductility index but energy ductility was decreased.

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