

Flexural Behavior of Self-Compacting RC Continuous Beams Strengthened by CFRP Sheets

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Abstract:

This search presented an experimental study of the flexural behavior of self-compacting reinforced concrete continuous beams externally strengthened by carbon fiber reinforced polymer (CFRP) Sheets. The practical study contained eight self-compacting reinforced concrete continuous beams (with two span), each span had (1500) mm length and (150x250) mm cross sectional dimensions. Seven of these beams strengthened externally by CFRP sheets with and without external anchorage. The experimental variables included location of CFRP sheets and anchor type and location.

The results, shows that the beams strengthened externally by CFRP sheets provided improvement in ultimate loads reached (60.71%). The usage of CFRP in the anchorage zone indicated an effective method in comparison to increasing the CFRP sheets lengths or extending them up to the support or under the loading points. Test results also showed that side strengthening provided an effective tool for increasing the load at the cracking stage and also the load capacity and reducing flexural crack widths.

Keywords: Self-compacting, Continuous, Beams, Strengthened, CFRP Sheets

الخلاصة

قدم هذا البحث دراسة عملية لتقصي سلوك انحناء العتبات الخرسانية المسلحة المستمرة ذاتية الرص المدعمة خارجيا بشرائح الياف الكربون البوليمرية. الدراسة العملية اشتملت على ثمانية عتبات خرسانية ذاتية الرص مسلحة مستمرة مكونة من فضائين كل فضاء بطول 1500 ملمتر بابعاد (150*250). تم تقوية سبعة من هذه العتبات الخرسانية المسلحة خارجيا باستخدام شرائح الياف الكربون البوليمرية مع استعمال او بدون استعمال الارساء الخارجي. المتغيرات الرئيسية تضمنت موقع شرائح الياف الكربون البوليمرية ونوع الارساء في النهايات. اظهرت النتائج العملية بان الاعتاب المقواة خارجيا بشرائح الياف الكربون البوليمرية ابدت زيادات ملحوظة في الاحمال القصوى. بلغت الزيادة في الحمال الاقصى الى (60.71%) بالمقارنة مع العتبة المرجعية غير المقواة بشرائح الياف الكربون البوليمرية. ان الارساء بالياف الكربون البوليمرية فعال جدا اكثر من جعل شريحة الياف الكربون البوليمرية تمتد تحت المساند او الحمل المركز (في زيادة الحمل النهائي وتقليل هطول الاعتاب). وان التقوية في الجوانب طريقة فعالة جدا في زيادة احمال التشقق الاولى وصلت الى (125%) بالمقارنة مع العتبة المرجعية غير المقواة بشرائح الياف الكربون البوليمرية.

كلمات مفتاحية: العتبات، ذاتية الرص، المستمرة المدعمة خارجيا بشرائح الياف الكربون البوليمرية

1. Introduction

For several years, the problem of the durability of concrete structures has been a major problem posed to engineers. The creation of durable concrete structures requires adequate compaction by vibrating. Over vibration can easily cause segregation. In conventional concrete it is difficult to ensure uniform material quality and good density in heavily reinforced locations. If steel is not properly surrounded by concrete it leads to durability problems. One solution for the achievement of durable concrete structures is the employment of self-compacting concrete (Okamura *et al.*, 2003).

Although many RC beams cast in-situ are continuous construction, there has been very limited research into the behavior of such beams with external reinforcement. In addition, most design guidelines were developed for simply supported beams with external FRP laminates. Ductility is even more important for statically indeterminate structures, such as continuous beams, as it allows for moment redistribution through the

rotations of plastic hinges. Moment redistribution permits the utilization of the full capacity of more segments of the beam. Using carbon fiber reinforced polymer (CFRP) laminates has proved to be an effective means of upgrading and strengthening reinforced concrete (RC) beams. However, premature failures such as peeling failure and laminate separation can significantly limit the capacity enhancement and prevent the full ultimate flexural capacity of the retrofitted beams from being attained. Laminate peeling or separation may occur due to the high longitudinal shear and transverse normal stresses at the laminates end resulting from the abrupt curtailment of the laminates (Ashour *et.al.*, 2004).

2. Experimental Program

The main objective of this study is to investigate the actual effect of CFRP in enhancing the flexural behavior of SCC continuous beams subjected to concentrated loads.

1 Tested Beams Details

Eight self-compacting RC continuous beams with roller supports at the ends and a hinge support in the middle consist of two span with length 1500 mm for each span and rectangular cross sectional dimensions of 250 mm overall depth and 150 mm width. The flexural reinforcement of the beams consisted of 2Ø12 mm bars at the top and 2Ø12 mm bars at the bottom and Ø10mm diameter closed stirrups spaced at 50mm along the beam length and the steel bar had a 90° hook of length (120mm) according to (ACI 318M-08) at each ends to provide sufficient anchorage. Concrete cover of 25 mm was adopted. A critical part of the design was ensuring the beams failed due to flexure and not shear. To accomplish this, the specimens were heavily reinforced for shear. Figure (1) shows specimen dimensions, reinforcement details, support locations, and location of loading points. The first concrete beam specimen (B1) was kept without strengthening as a control beam for comparison and the other seven beams are strengthening with externally bonded CFRP sheets.

Concrete beam specimen (B2) was strengthened with CFRP sheet having 1700 mm length, 50 mm width and 0.131 mm thickness installed on side face at the center of the middle support of negative moment zones as shown in Figure (2).

Concrete beam specimen (B3) was strengthened with CFRP sheet having 1700 mm length, 100 mm width and 0.131 mm thickness installed on top face at the center of the middle support and extended under point load from both ends.

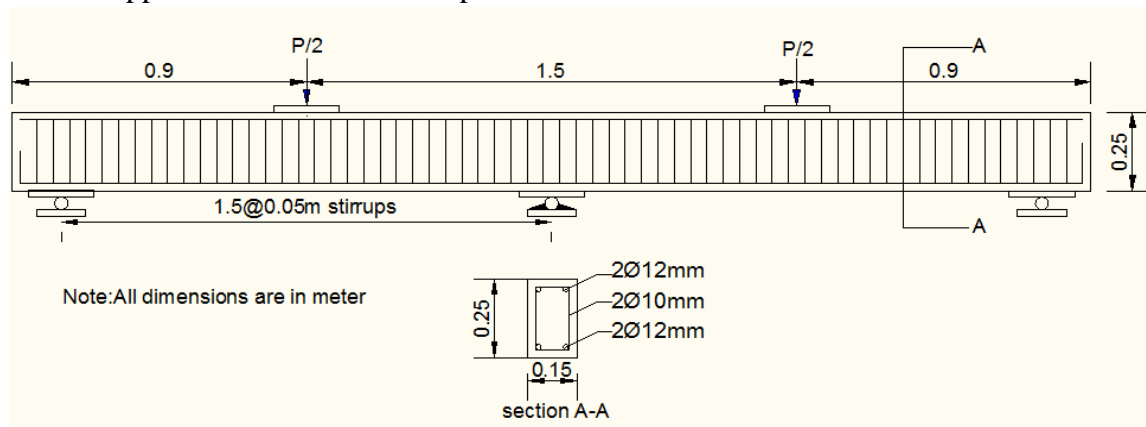


Figure (1) Reinforcement details of tested beams

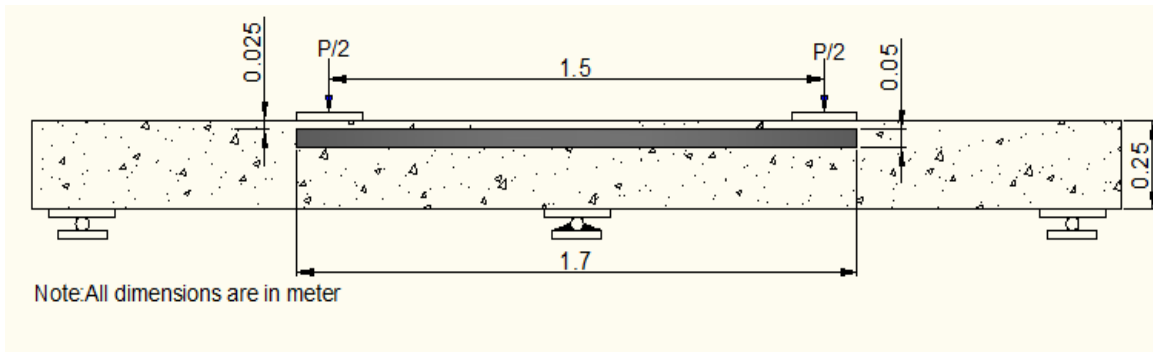


Figure (2) Specification and details of CFRP locations of beam B2

Concrete beam specimen (B4) was strengthened with CFRP sheet having 1200 mm length, 100 mm width and 0.131 mm thickness installed on top face at the center of the middle support shown in Figure (3), in each end of longitudinal CFRP sheet CFRP anchor installed. The CFRP anchors (which used in this search) in each end has 250mm length of the anchor with 100 mm of the anchor inserted into a 10 mm diameter-hole drilled into concrete and the rest of the anchor was spread out in a fan shape on the CFRP sheet, 100 mm width and 0.131 mm thickness as shown in Figure (4).

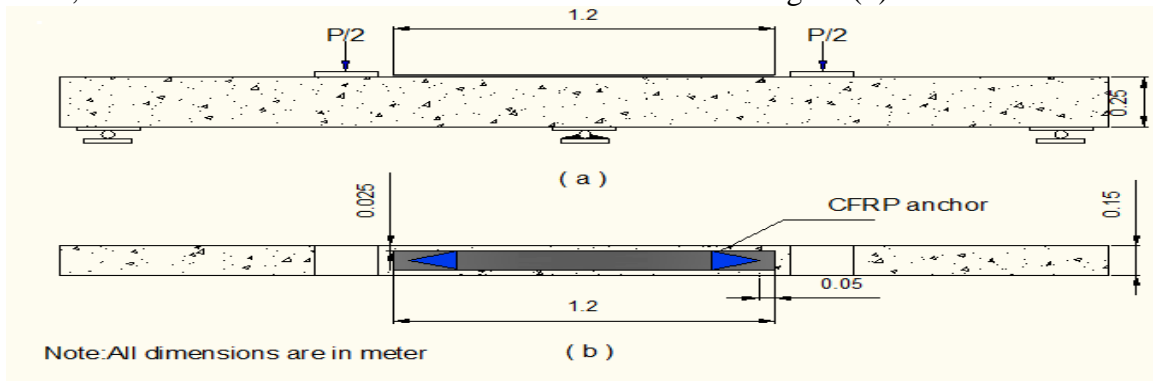


Figure (3) Specification and details of CFRP locations of beam B4
(a) Front side view (b) Top side view

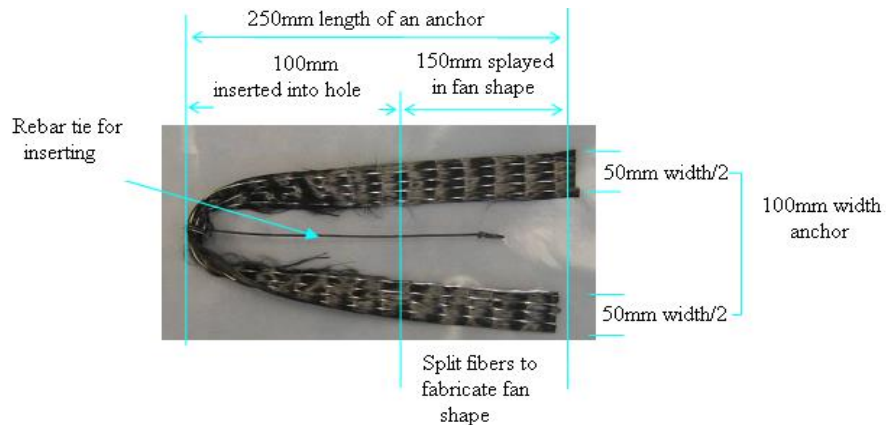


Figure (4) Specification and details of CFRP anchors

Concrete beam specimen (B5) was strengthened with CFRP sheet having 3200 mm length, 100 mm width and 0.131 mm thickness installed on bottom face at the positive moment zones included both spans and extended under three supports.

Concrete beam specimen (B6) was strengthened with CFRP sheet having 1200 mm length, 100 mm width and 0.131 mm thickness installed on bottom face at the positive moment zones for each span, with CFRP sheet anchor installed at each ends as shown in Figure (5).

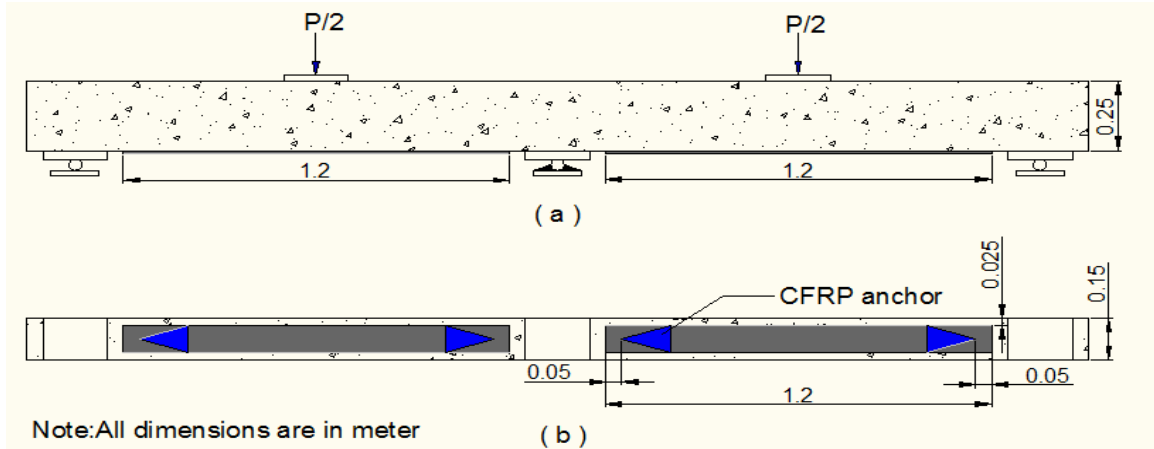


Figure (5) Specification and details of CFRP locations of beam B6
(a) Front side view (b) Bottom side view

Concrete beam specimen (B7) was strengthened with CFRP sheet having 1700 mm length, 50mm width and 0.131 mm thickness installed on side face at the center of the middle support of negative moment zones and having 3200 mm length, 50 mm width and 0.131 mm thickness installed on bottom face at the positive moment zones included both spans as shown in Figure (6).

Concrete beam specimen (B8) was strengthened with CFRP sheet having 1700 mm length, 100 mm width and 0.131 mm thickness installed on side face at the center of the middle support of negative moment zones extended under point load from both ends and having 3200 mm length, 100 mm width and 0.131 mm thickness installed on bottom face at the positive moment zones included both spans and extended under three supports as shown in Figure (7).

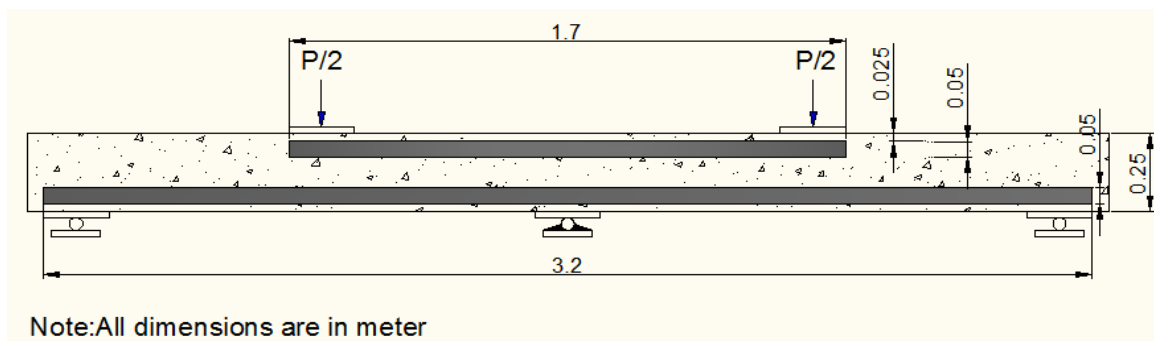


Figure (6) Specification and details of CFRP locations of beam B7

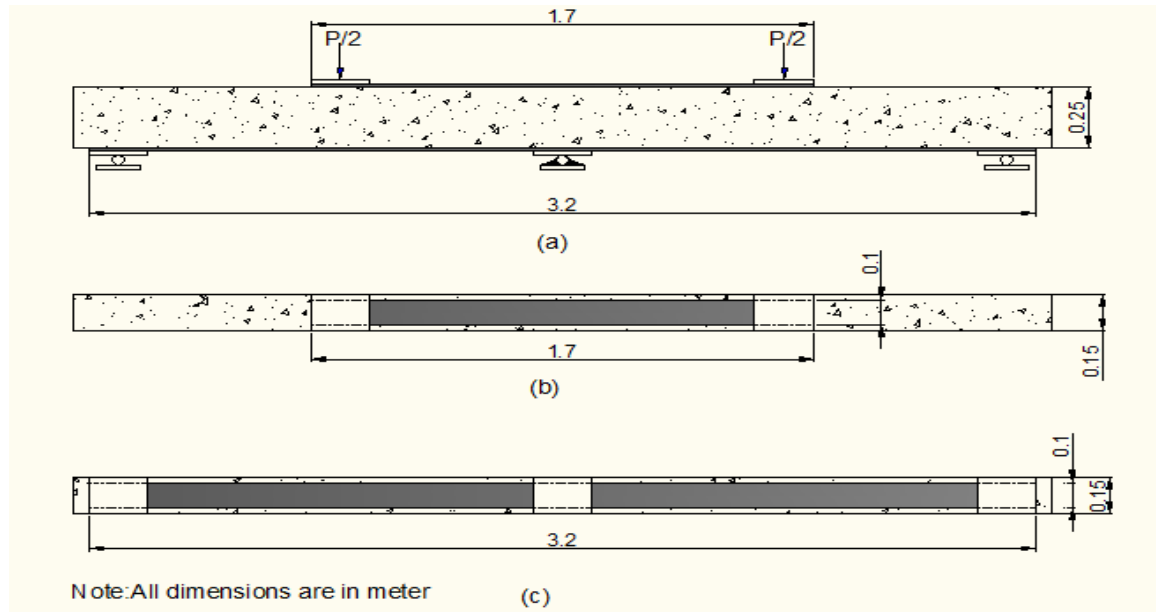


Figure (7) Specification and details of CFRP locations of beam B8

(a) Front side view (b) Top side view (c) Bottom side view

Table (1) describes carefully the locations of longitudinal CFRP sheet and type of anchorage.

Table (1) Description of the tested beams specimens

Beam Symbol	CFRP Locations	Type of Anchorage
B1	Nil	Nil
B2	At both side face of beam of negative zone	Nil
B3	At top face of beam of negative zone	Extend CFRP sheet under point load
B4	At top face of beam of negative zone	CFRP anchor
B5	At bottom face of beam of positive zones	Extend CFRP sheet under supports
B6	At bottom face of beam of positive zones	CFRP anchor
B7	At both side face of beam of negative zone and both side face of beam of positive zones	Nil
B8	At top face of beam of negative zone and bottom face of beam of positive zones	Extend CFRP sheet under Supports & point load

II Steel Reinforcing Bars

For all beams two type sizes of Ukrainian steel reinforcing deformed bar were used, bars size of (\varnothing 10 mm, \varnothing 12 mm) organize used. Table (2) gives the properties of steel reinforcement according to (ASTM A370-05).

Table (2) Material Properties for Steel Reinforcement

Properties for Grade400	Diameter(10mm)	Diameter(12mm)
Cross-sectional area, mm²	78.54	113.09
Diameter measured ,mm	10.398	11.649
Yield stress, MPa	577	552
Ultimate strength, MPa	695	673
Total elongation,%	13	16.3

III Carbon Fiber Reinforced Polymer (CFRP)

Carbon fiber fabric laminate of type SikaWrap Hex-230C has been used to externally strengthen the reinforced concrete beams, as shown in Figure (8). CFRP fibers when loaded in tension, do not exhibit any plastic behavior before rupture. The tensile behavior of CFRP fibers is characterized as a linearly elastic stress-strain relationship up to failure, which is sudden and can be catastrophic. The mechanical properties of CFRP laminate are given in Table (3) according to manufacturing specifications of Sika Company (Sika , 2005).

Table (3) Technical Properties of CFRP Sheet (Sika 2005)

Properties	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Elongation at break (%)	Width (mm)	Density (g/cm ³)	Thickness (mm)
Sika Wrap® Hex230C	4300	238	1.8	600	1.76	0.131

IV Bonding Materials

The building and construction industries represent some of the largest users of adhesive materials, many applications were non-structural in the sense that the bonded assemblies were not used to transmit or sustain significant stresses (e.g. crack injection and sealing, skid-resistant layers, bonding new concrete to old). Sikadur®-330 was used in this work for the bonding of CFRP sheet, as shown Figure (8). The technical properties of bonding materials are given in Table (4) according to manufacturing specifications of Sika Company (Sika , 2005).

Table (4) Technical Properties of Bonding Materials (Sika 2005)

Properties	Sikadur®-330
Tensile strengths , MPa	30 MPa
Bond Strengths	Concrete fracture on sandblasted substrate: >1 day
E-modulus, Mpa	4500
Elongation at break , %	0.9%
Open time , minute	30 minutes at +35°C
Full cure , days	7 days at +10°C
Mixing ratio	Part A :part B = 4 : 1 by weight



Figure (8) CFRP sheet and epoxy

V Trial Mix of Self-Compacting Concrete

Many trials were carried out on mixes by increasing the dosage of the admixture gradually, adjusting the w/cm ratio to ensure the self-compatibility. Table (5) indicates the mix proportion of SCC mix.

Table (5) Mix Proportions

Parameter	Concrete mixes		
	Mix A	Mix B	
Water/ powder (cement+limestone) ratio	0.319	Same	
Water/ cement ratio	0.37	Same	
Water (L\m3)	187.159	Same	
Cement (Kg\m3)	500	Same	
Limestone (Kg\m3)	86	Same	
Fine aggregate (Kg\m3)	807	Same	
Coarse aggregate (Kg\m3)	879	Same	
Glenium 51(L\m3)	9.522	/	
Glenium 54 (L\m3)	/	9.522	
Compressive Strength MPa	7 days	39	45
	28 days	64	70.537

VI Fresh Concrete Tests

In fresh state SCC is required to have three characteristics; filling ability, passing ability and segregation resistance. Therefore several test methods are implemented in this study in order to ensure that SCC mixes meet these requirements. Figure (9) shows the details of self-compacting concrete experimental program.

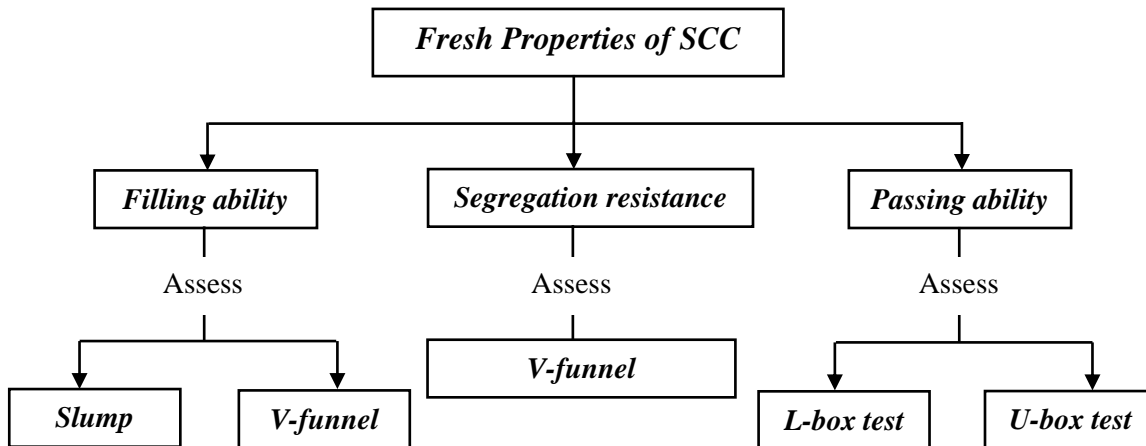


Figure (9) Details of self-compacting concrete fresh experimental program

3. Effect of Glenium G51 and Glenium G54 on SCC Properties

The workability tests were made on fresh concrete immediately after mixing including slump flow, V-funnel and L-box. These tests were carried out to ensure that the mixes satisfy the requirements of SCC, as shown in Table (6). Mix (group A) was on the higher limit of EFNARC specifications, mix of group A could be described as hard mix. Mix (group B) was on lower limit of EFNARC specifications, and mix (group B) could be described as soft mix.

Results indicated that the concrete mix has one variable type of Super Plasticizer that have important effect on SCC properties entirely, with reminding every others constant, to make the type of Super Plasticizer the only and mainly action on result changes. The mixes of two groups controlled to be among (EFNARC) specifications to satisfy self-compacting concrete.

Table (6) Results of fresh properties of SCC mixes

Mix Designation		Group A: with G51	Group B : with G54	EFNARC specifications
Slump flow	D (mm)	675	795	(650-800) ±50
	T _{50cm} (sec:part sec)	4:40	3	(2-5) sec
V-funnel	T _v (sec:part sec)	10:36	6:25	(6-12) sec
L-box	BR %	0.86	0.95	0.8<BR<1

Compressive Strength

The compressive strength is one of the most important properties of hardened concrete, and in general, is the characteristic material value for the classification of concrete in national and international codes. For this reason, it is of interest to investigate whether the changes in the type of filler using in SCC and types of concrete affect the compressive strengths. Table (7) shows cubes results, it noticed that compressive strength of group B at 7 days higher than group A by (15.38%), and at 28 days by (9.75%), and at test time by (8.98%).

Table (7) Cubes test results

Cubes (150×150×150)mm		Compressive Strength	
		Mix group A (G51)	Mix group B (G54)
Trial mix	7days	39	45
	28days	64	70.24
Average of all specimens	At test time	69	75.2

4. Concrete Samples

The actual mean compressive strength results were obtained from the average of at least three (150x150x150) mm cube and the average of at least three cylinders (150x300) mm samples were tested in uniaxial compression with each beam specimens using testing machine. Three cylinders (100x200) mm were tested for indirect tension by applying line load along the 200 mm long side to obtain the splitting tensile strength, which is a measure of the tensile strength of concrete (ASTM C496). One cylinders (150x300) mm samples were used to determine Static Modulus of Elasticity for each specimen (ASTM C469). The result of these test are given in Table (8).

Table (8) Concrete material properties of tested beams

Beam Symbol	Compressive strength (f_{cu}) MPa	Compressive Strength ($f'c$) MPa	Tensile Strength (f_{ct}) MPa	Modulus of elasticity MPa
B1	69.5	63.4	9.1	37233
B2	70.1	64.83	9.24	37693
B3	70.4	64	9.44	37427
B4	69.9	63.748	9.05	37346
B5	69.55	63	9.5	37104
B6	71.1	64.85	9.61	37699
B7	70.1	63.95	9	37410
B8	70.3	64	9.1	37426

5. Results of Tested Beams

1 Load Deflection Curves

The load versus vertical mid-span deflection curves for the tested beams specimens are shown in Figure (10).

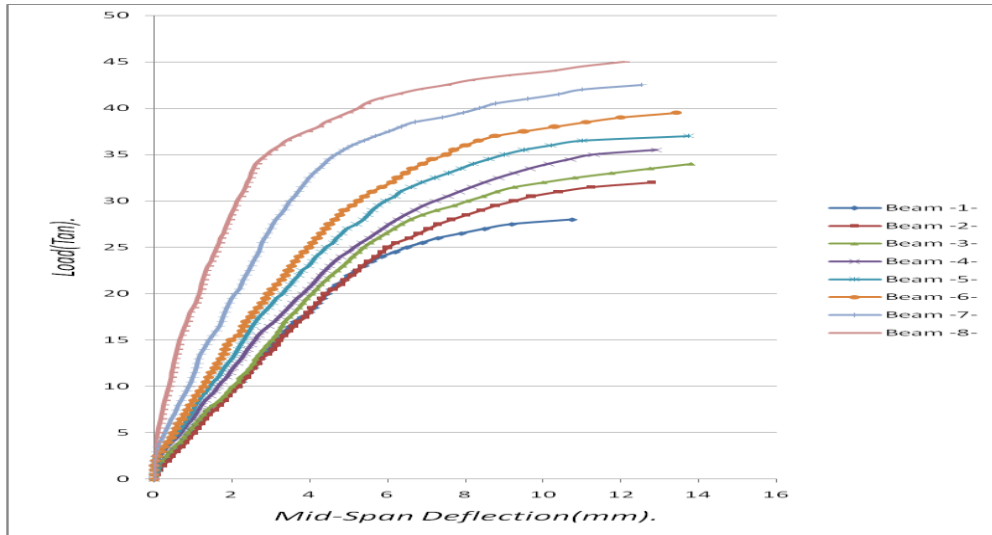


Figure (10) Load – mid span deflection curve for tested beams

II Cracking and Ultimate Loads

Table (9) provides experimental results of all tested beams specimens, which includes percentage increasing in the cracking load, ultimate loads and ultimate deflection for the strengthened beams with respect to unstrengthened beam (control beam).

Table (9) Experimental results of tested beams specimens

Beam Symbol	Cracking load (kN)	% of increase in cracking load (%)	Ultimate load (kN)	% of increase in ultimate load (%)	Ultimate deflection (mm)	% of increase in ultimate deflection (%)
B1	80	-	280	-	10.75	-
B2	100	25	320	14.285	12.75	18.6
B3	90	12.5	340	21.428	13.8	28.37
B4	95	18.75	355	26.785	12.9	20
B5	100	25	370	32.143	13.74	27.81
B6	120	50	395	41.071	13.42	24.93
B7	180	125	425	51.785	12.5	16.28
B8	150	87.5	450	60.714	12.08	12.37

6. Conclusions

1. At the same cost and mix proportions, the two mixes in the present study shows that the SCC with super plasticizer (Glenium 54) has much better fresh and mechanical properties than SCC with super plasticizer (Glenium 51), the increase in compressive strength is (9.75)% at age 28 days.

2. Using CFRP sheets to strengthen the self-compacting reinforced concrete continuous beams is very effective in increasing the initial cracking load and the ultimate load. The increases were up to (125)% and (60.714)%, respectively.
3. In all beams strengthened with external CFRP sheets, the crack pattern for flexural mode of failure was similar. The failure cracks appear in the tension face and they initiated from the tension side and move to the other sides of beams. The crack width continues to increase up to the beam failure.
4. The external anchorages (CFRP fan anchors) are very effective in increasing ultimate load capacities and the interaction between the CFRP and the concrete section and improving the structural behavior of the strengthened beams (increasing stiffness of the beam). The CFRP anchors better than increasing the CFRP sheets length and extended under point load from both ends for negative moment region or extended under three supports for positive moment region, because the CFRP anchors spread in the same direction of main longitudinal CFRP sheet in spite of the quantity of CFRP anchors is less (increased 26.785% and 41.07 in ultimate loads)
5. The rupture of CFRP sheets mode of failure was the dominate mode for all the self-compacting RC continuous beams strengthened with CFRP fan anchorage.
6. For the same quantity of CFRP sheets, the side external strengthened for self – compacting RC continuous beams in negative moment region or positive moment region give less increment in ultimate load capacities compared to top or bottom external strengthened, but it is an effective method for increasing cracking load capacities and eliminating number and width of flexure cracks.

7. References

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