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

**Sabih Z. Al-Sarraf** **Dhiyaa Hamoodi Mohammed**
*Building and Construction Engineering Department, University of Technology*
**Mustafa Mohammed Raheem Al-Kashan**
*Engineering Department,University of Technology*
dhiyaa_hamoudi@yahoo.com

## 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 اعتاب خرسانية ذاتية الرص مسلحة مستمرة مكونة من فضائين كل فضاء بطول 1500 مليمتر بابعاد (150*250). تم تقوية سبعة من هذه العتبات الخرسانية المسلحة خارجيا باستخدام شرائح من الياف الكربون البوليمرية مع استعمال او بدون استعمال الارساء الخارجي. المتغيرات الرئيسية تضمنت موقع شرائح الياف الكربون البوليمرية ونوع الارساء في النهائيات. 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 الاولي 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.

***I 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 90º 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.

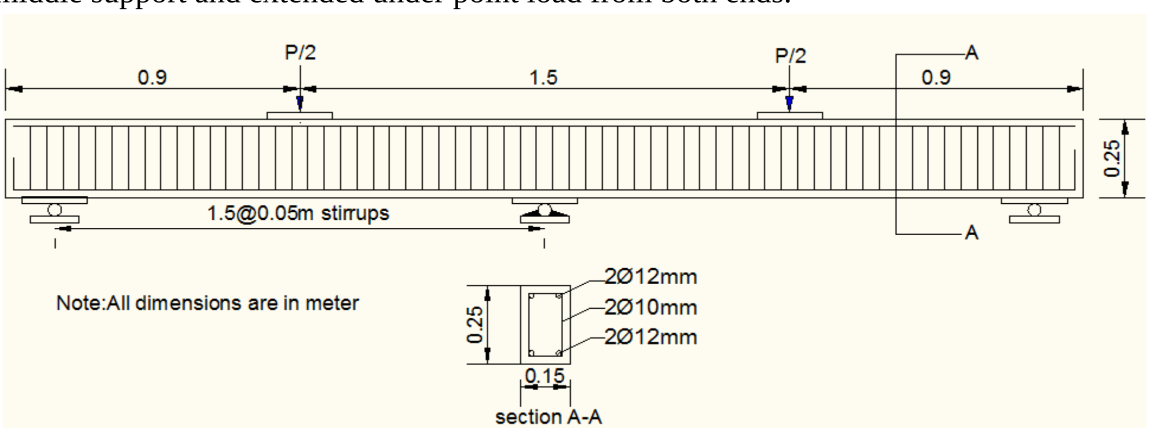


**Figure (1) Reinforcement details of tested beams**

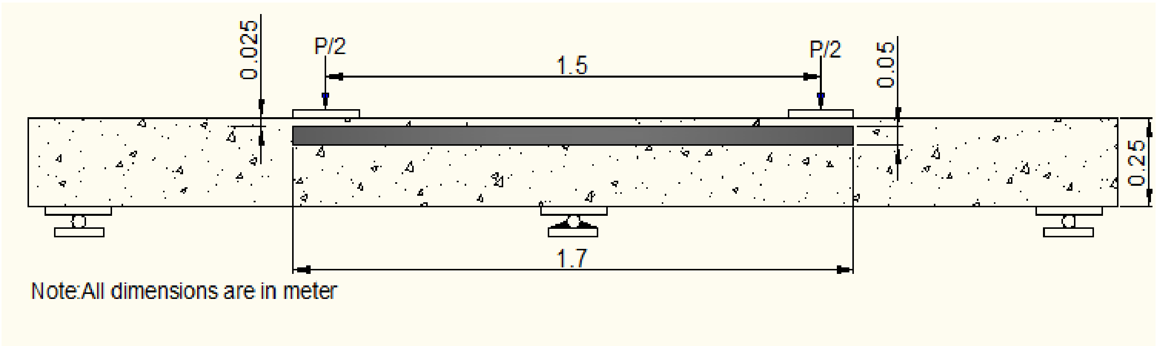


**Figure (2) Specification and details of CFRP locations of beam B2**

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 instilled. The CFRP anchors (which used in this search) in ach 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).

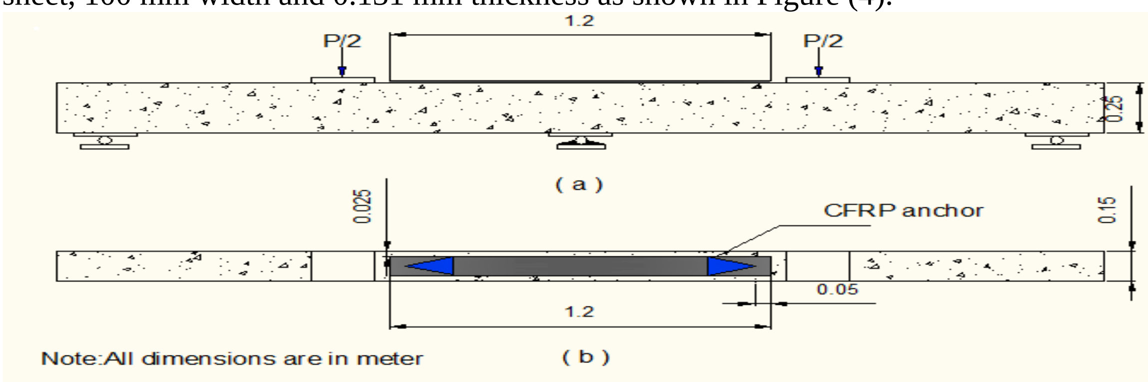


**Figure (3) Specification and details of CFRP locations of beam B4**
**(a) Front side view (b) Top side view**

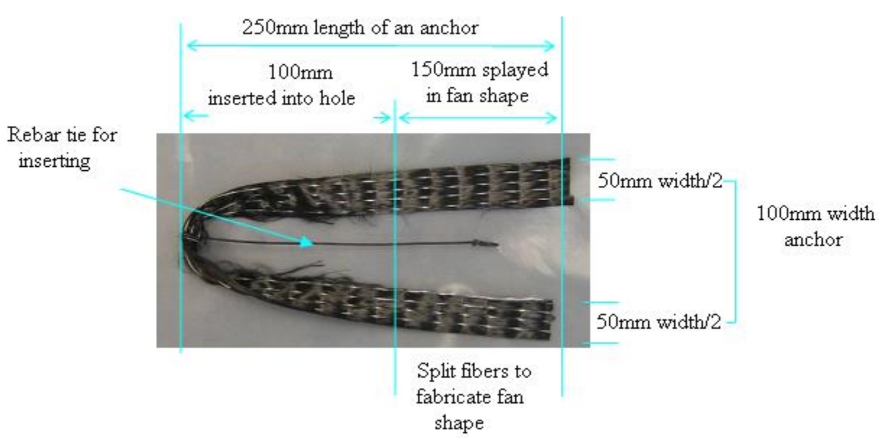


**Figure (4) Specification and details of CFRP anchors**

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 instilled at each ends as shown in Figure (5).

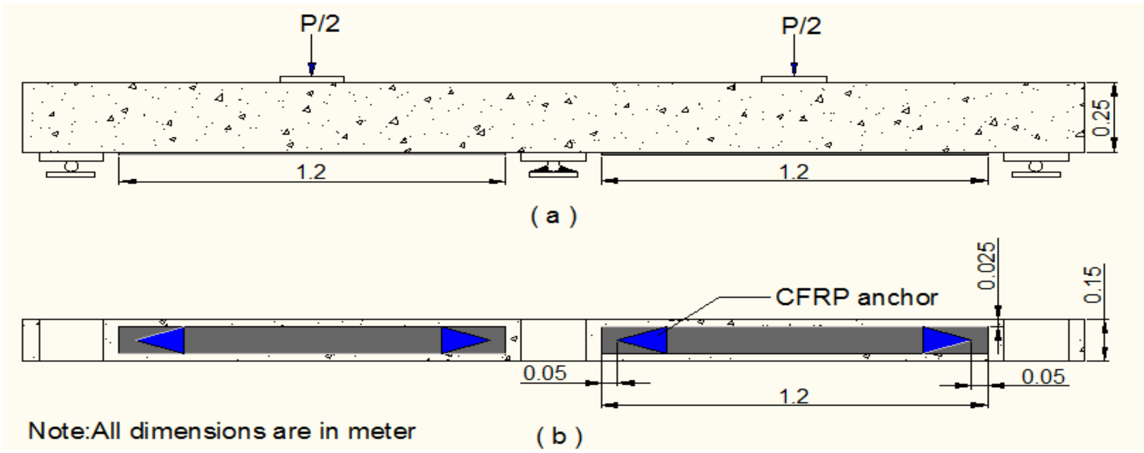


**Figure (5) Specification and details of CFRP locations of beam B6**
**(a) Front side view (b) Bottom side view**

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).

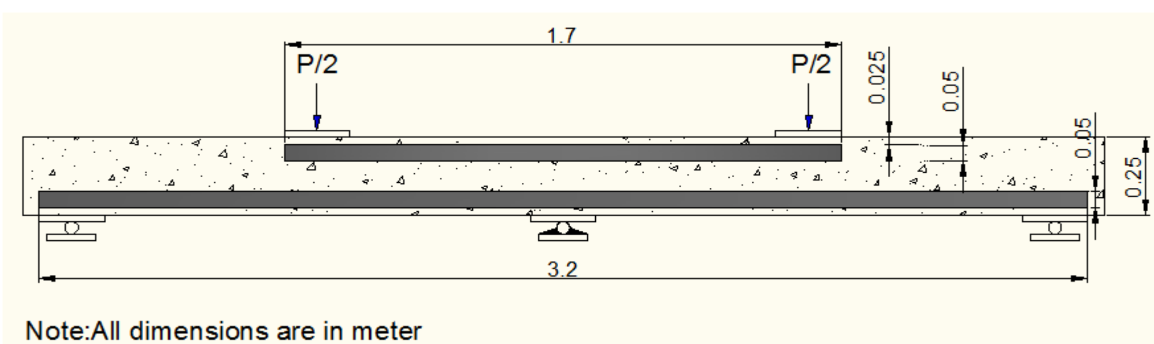

**Figure (6) Specification and details of CFRP locations of beam B7**

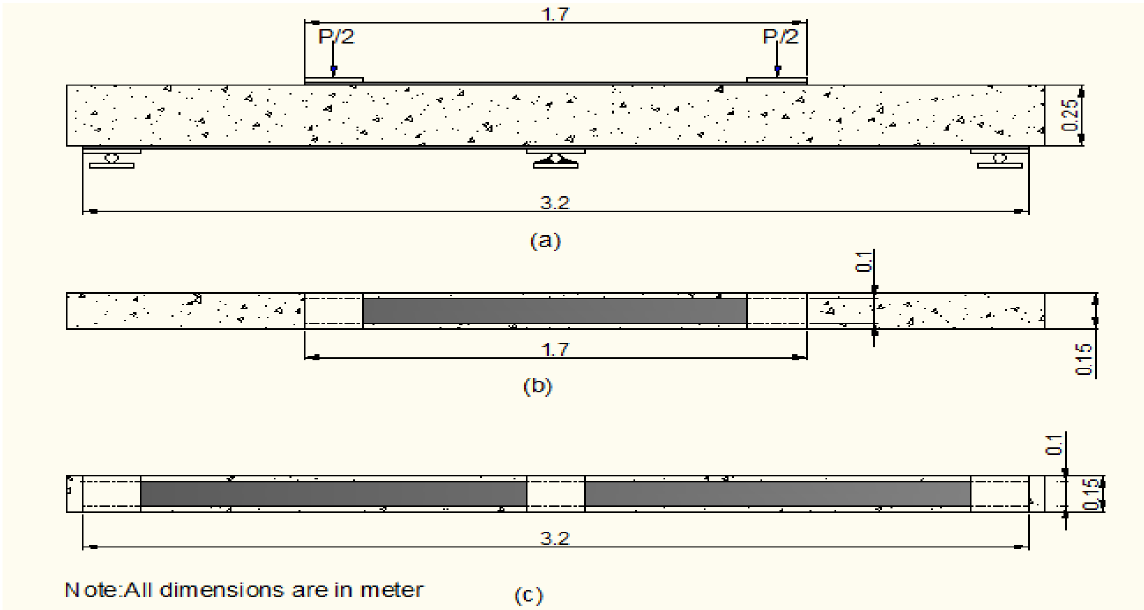


**Figure (7) Specification and details of CFRP locations of beam B8**
**(a) Front side view (b) Top side view (c) Bottom side view**

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 (Ø 10 mm, Ø 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/cm³) | 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.

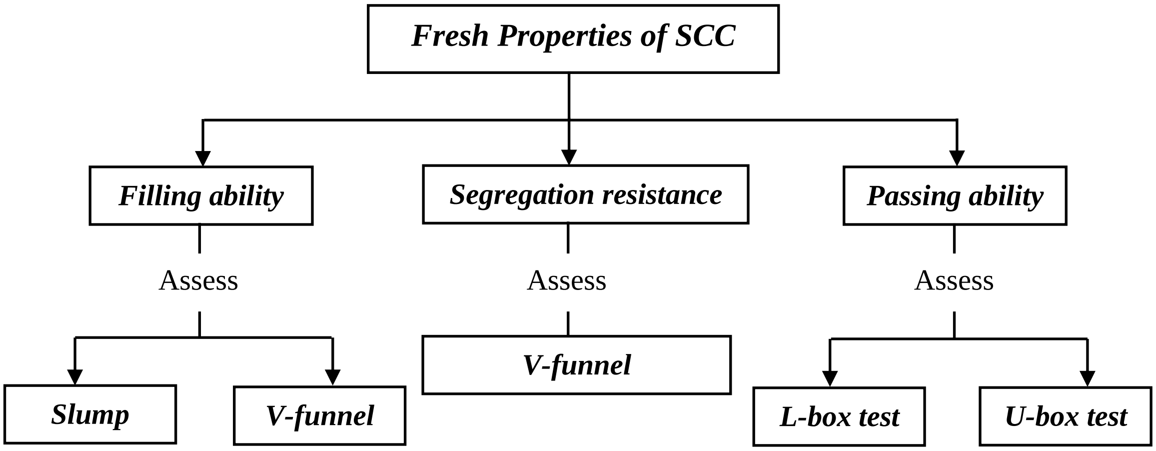


**Figure (9) Details of self-compacting concrete fresh experimental program**

## 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 (fct) 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

***I Load Deflection Curves***

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

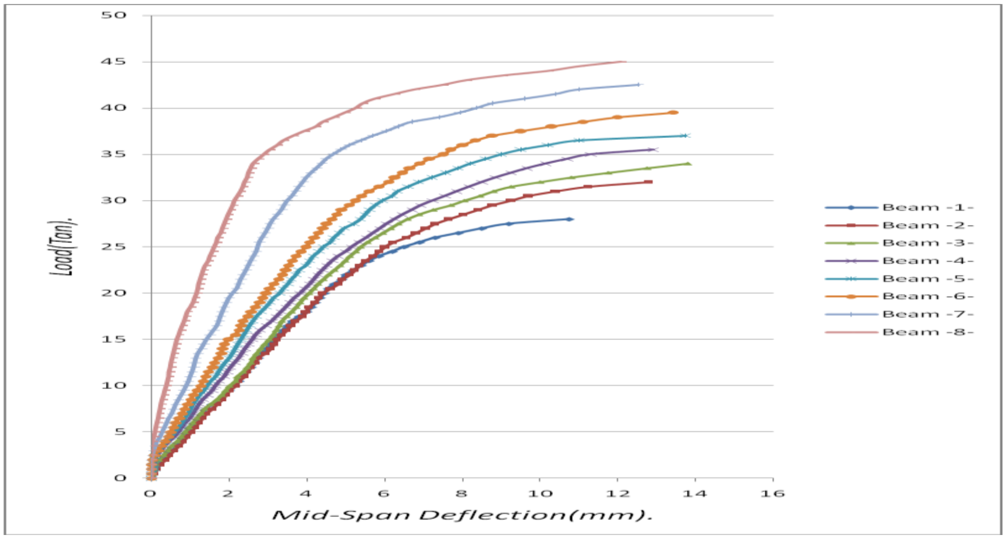


**Figure (10) Load – mid span deflection curve for tested beams**

### *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

ACI Committee 318M-08, 2008 , “Building Code Requirements for Structural Concrete and Commentary (ACI 318M-08)” American Concrete Institute, Farmington Hills, Michigan, USA.

American Society for Testing and Material "Standard specification for testing method and definitions for mechanical testing of steel products" A370-05a, 2000 Annual Book of ASTM Standards, Vol.1.01, pp248-287.

American Society for Testing and Materials, 2004,"Standard Test Method for Splitting Tensile Strength for Cylindrical Concrete Specimens", ASTM C496.

American Society for Testing and Materials,2002, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression", ASTM C469.

Ashour A F, El-Refaie S A, Garrity S W, 2004, "Flexural strengthening of RC continuous beams using CFRP laminates". Cement & Concrete Composite, pp.( 765-775).

EFNARC, May 2005,: The European Federation of Specialist Construction and Concrete System "The European Guidelines for Self-Compacting Concrete; Specification, Production and Use".

Okamura, H. and Ouchi, M. , April 2003, "Self-Compacting Concrete", Journal of Advanced Concrete Technology, Japan, Vol.1, No.1, pp.(5-15).

Sika, 2005, “SikaWarp®- 230C Woven carbon fiber fabric for structural strengthening”, Technical Data Sheet, Edition 2.