Experimental Studyof Reactive Powder Reinforced Concrete Beams Strengthened withCFRP for Critical Shear Zones

Dr. Kaiss F. Sarsam
Building and Construction Engineering Department, University of Technology/ Baghdad
Email:kaisssarsam@yahoo.com
Dr. Shakir .A. Al-Mishhadani
Building and Construction Engineering Department, University of Technology/ Baghdad
Email:uot_magaz@yahoo.com
Alaa M. Al-Habbobi
Civil Engineering Department, College of Engineering, University of Kufa/ An Najaf
Email:ms_cv_engalaa@yahoo.com

Received on: 10/8/2014 & Accepted on: 4/12/2014

ABSTRACT

The behavior and shear strength characteristics of eight SFRHSC beams strengthened with CFRP strips subjected to combined bending and shear are studied in the present research (in addition to a 9^{th} control beam without CFRP strengthening). The studied variables were shear span to effective depth ratio (a/d) and the deep beam effect, the effect of end anchorage of the CFRP strips with the beams, and effect of the amount of wrapping (width and spacing of the CFRP strips).Tests show that the presence of end anchorage for the strips increases the shear capacity of the beams by 12%for beams with the same properties regardless to the compressive strength.

Keywords: high strength concrete, steel fiber, reactive powder concrete, CFRP strips, end anchorage effect

الدراسة العملية لعتبات خرسانة المساحيق الفعالة المسلحة والمقوّاة بألياف الكاربون البوليمرية لمناطق القص الحرجة

تم في هذا البحث دراسة خصائص السلوك ومقاومة القص لثمانية اعتاب من الخرسانة عالية المقاومة المسلحة بألياف الحديد والمقواة للقص باشرطة الياف الكاربون البوليمريةالمعرضة الى الانحناء والقص (بالاضافة الى عتب التنظيم التاسع بدون تقوية بالياف الكاربون). المتغيرات التي تمت دراستها هي نسبة فضاء القص الى العمق الفعال (a/d) وتأثير العتب العميق، تأثير تثبيت نهايات اشرطة ألياف الكاربون البوليمرية مع العتب، تاثير كمية اللف (العرض والمسافات البينية لأشرطة ألياف الكاربون البوليمرية).اظهرت الفحوصات ان وجود التثبيت لنهايات الاشرطة يزيد مقاومة القص بمقدار 12% للاعتاب ذات المواصفات المتشابهة بغض النظر عن قيمة مقاومة الانضغاط.

https://doi.org/10.30684/etj.33.1A.12
2412-0758/University of Technology-Iraq, Baghdad, Iraq

INTRODUCTION

Carbon fiber reinforced polymer (CFRP) composites are currently used to reinforce concrete in an attempt to overcome the corrosion issue encountered with ordinary steel.In order to exploit more efficiently their tensile capacity, it is interesting to use CFRP as shear strengthening strips. The advantageous characteristics of steel fiber reinforced high strength concrete (SFRHSC kind of fibrous reactive powder concrete FRPC with f'_c up to 150 MPa), such as high strength, good ductility and durability, mean that a SFRHSC structure strengthened in shear with CFRP strips may be lighter and require less maintenance compared with conventional RC.

One way to increase both lifetime and strength is upgrading(1).SFRHSC is a cementitious composite material that consists of the distinctive characteristics of the reactive powder concrete and high tensile strength steel fibers(2). Its superior strength combined with higher shear capacity results in significant dead load reduction and less limited shapes of structural members. SFRHSC can be used with elimination the need for supplemental shear and other auxiliary reinforcing bars compared with ordinary concrete(3).Jungwirth(4), concluded that metallic fibers have a significant role in improving flexural and tensile resistance of RPC by carrying the load well after first cracking. Ridha(5), concluded that the amount of fibers in RPC mixture did not significantly affect the cracking load but did have an influence on the rate of crack growth and on crack width. Fibers also changed the mode of failure to a more ductile one.Kwak, et al.(6), concluded that the nominal stress at shear cracking and the ultimate shear strength increased with increasing fiber volume, decreasing shear span to effective depth ratio, and increasing concrete compressive strength. As the fiber content increased, the failure mode changed from shear to flexure.Sarsam and Al-Musawi(7), concluded that, the HSC beams are likely to be more slender than NSC beams. Oh and Shin(8), concluded that, the addition of horizontal shear reinforcement does not improve the ultimate shear strength with decreasing (a/d) ratio in a deep beams of high strength concrete.Shah and Mishra(9), indicated by experimental investigation that the concrete deep beams reinforced with steel fibers exhibited large deflection at failure which indicates high ductility and energy absorption.Madan et al(10), showed that steel fibers can replace the conventional web reinforcement in reinforced concrete deep beams.

CFRP has many advantages including light weight, being noncorrosive, ease of applications in confined areas, etc. The normal strength concrete is the weakest material compared to the epoxy and the CFRP strip and the epoxy is the lesser in thickness (rigidity)(1). So in the case of using the high strength materials like the SFRHSC, the end anchorage is very important to insure transmitting the stresses from the SFRHSC to the CFRP.Uji(11), tested eight beams with continuous FRP strips on sides or fully wrapped. From the tests it was observed that FRP substantially increases the shear capacity of beams without stirrups. Sato et al.(12),concluded that the FRP strain along the major shear crack was not uniform; and the FRP strain is large at the middle of the shear crack, small at the end of the crack.Taerwe et al.(13), concluded that the position and the distribution of the FRP plays important roles on the shear strengthening. They suggested that FRP increases the shear capacity in a way similar to that of internal stirrups. Izzet(1),concluded that the end anchor system proved its effectiveness in carrying the applied shear force. It was found that CFRP strain (and, therefore, resistance to loading) only starts after diagonal cracking. Also the use of CFRP is significantly influenced by the spacing of the strips and the shear

https://doi.org/10.30684/etj.33.1A.12
2412-0758/University of Technology-Iraq, Baghdad, Iraq

spanto effective depth ratio (a/d).Chajes et al.[14], suggested the bond strength is proportional to $\sqrt{f'_c}$.They showed that there is a bond development length of the CFRP strip beyond which no further increase in load force can be achieved.It has been found that total wrap or U-wrap with end anchor is the alternative solution for U-wrap if debonding is to be avoided[15]. However, total wrap is not practical from a constructability standpoint.Bousselham and Chaallal[16], concluded that, the shear capacity gain due to the CFRP was greater for deep specimens than for slender specimens.

Experimental Program

The properties of the component materials, mixing procedures and curing used for the production of SFRHSCbeams and their control specimensare detailed below.The experimental details of the behavior and load carrying capacity of SFRHSC beams strengthened in their shear zone with CFRP are also presented.Some beams are tested to illustrate the effect of anchoring the end of CFRP strips.

Materials

The properties of cement, sand, reinforcing steel, steel fiber, silica fume, high range water reduction (HRWR) admixture, carbon fiber reinforced polymer CFRP, epoxy and the resulting SFRHSC used in this investigation are presented in this section.

Cement

Ordinary Portland cement Tasluja LAFARGE satisfying the experimental property No.5 / 1984[17], and manufactured in Iraq was used throughout this work. The laboratory testing of this type of cement illustrates its physical properties as: The compressive Strength at 3 days and 7 days are 22.86 MPa and 25.46 MPa respectively.

Fine Aggregate

Natural sand from BAHR EL-NAJAF region in Iraq was used for concrete mixes of this study. The fine aggregate was passing from sieve No.40 (450 µm) maximum size; and remaining on sieve No.100 (150 µm). The main properties for the fine sand used are: The sulfate content is 0.47%, Specific gravity is 2.75, Absorption is 0.63%.

Silica Fume

Micro silica (MS) is a densified powder which is a highly active pozzolanic material (reactive powder).The chemical composition of micro silica used in this investigation is shown in Table (1). The micro silica used in this work conforms to the chemical and physical requirements of ASTM C1240-03[18] as shown in Tables (2) and (3) respectively.The benefits that result from adding silica fume are related to changes in the microstructure of concrete. These changes result from two different but equally important processes:-

I- Physical contribution; Adding silica fume brings millions of very small particles to a concrete mixture, it fills in the spaces between cement grains.

II- Chemical contribution;When the concrete hydration releases calcium hydroxide. The silica fume reacts with this calcium hydroxide with the presence of water to form additional binder material (calcium silicate hydrate (C-S-H))**.**

Mixing Water

Ordinary tap water was used for mixing and curing all the concrete specimens used in this work.

High Range Water Reducing Admixture (HRWR)

A high performance concrete superplasticiser based on modified polycarboxylic ether manufactured and supplied by BASF® under the commercial name Degussa GLENIUM 54 was used as a water reducing admixture with nominal dosage of 6 % of cement weight. GLENIUM 54 is almost free from chlorides and complies with ASTM C494(19) Type A and F.

Steel Fiber

The steel fibers used in this test program were straight steel fibers manufactured by Bekaert Corporation. The fibers have the propertiessupplied by the manufacturer: Length, Diameter, Density, Tensile strength, Aspect ratio are 13 mm, 0.2 mm, 7800 kg/m^3, 2600 MPa, 65 respectively.

Reinforcing Steel bars

Ukrainian reinforcing steel bars wereused to reinforce the flexural tension zone for the beams. The properties of the bars :Bar diameter (mm), Modulus of elasticity (GPa), Yield stress (MPa), Ultimate Stress (MPa) are 16, 245.03, 612, 727.9 respectively.

Steel plates

Mild steel plates (2mm thick) were used to make the end anchorage of CFRP strips. The properties of the plates Modulus of elasticity (GPa), Yield stress (MPa), Ultimate stress (MPa) are 200, 240, 340 respectively.

Anchoring Bolts Properties

Specimens of the anchoring bolts were tested according to ASTM A370-05a(20) and the resulting properties: Bolt diameter (mm), Modulus of elasticity (GPa), Yield stress (MPa), Ultimate stress (MPa) are 6.9, 200, 623, 761 respectively.

Carbon Fiber Fabric (CFRP)

The SikaWrap® 230C is a unidirectional woven carbon fiber fabric used for strengthening the shear zones of the beams in the present work. All information related to this system is summarized in Table (4).

Adhesive (Sikadur-330) Properties

A two part, solvent free, thixotropic epoxy based impregnating resin / adhesive less viscous paste manufactured by Sika Company, was used for bonding the carbon fiber reinforced polymers laminate to the surface of reinforced concrete beam specimens.The properties of this resin which is taken from manufacturer's specification are tabulated in Table (5).

SFRHSC Mix Design

The dominant mix proportioning (by weight) for all beams and their reference specimens is 1:1:0.15 cement : fine sand : silica fume with water/cement ratio 0.24. 6 % by weight of cement of superplasticizer, and 2% volume fraction steel fibers.

Mixing and curing of Concrete Batches

The mixing of all the batches are in the following steps[(21)]:

- The desired quantity of silica fume was mixed in dry state with the sand for 2 minutes.
- The cement was loaded into the mixer and mixed for another 2 minutes.
- The superplasticizer was dissolved in water and the solution was added to the rotary mixer and whole mix ingredients were mixed for about 5 minutes.
- Steel fibers were uniformly distributed into the mix slowly in 5 minutes during mixing process, and then the mixing process continued for additional 3 minutes.

The hardened specimens were demolded after 24 hours. They were cured at about (50 – 80) C^o for 7 days in a fabricated water bath tank. After that the samples were left to be cooled at room temperature. Then all specimens were kept in a normal water tank up to 28 days age.

Beams Details

In this work nine shear tests of SFRHSC beams without steel stirrups and strengthened with CFRP strips are reported. Beams were designed to have extra strength in flexure to ensure shear failure. The beam details are presented in Fig.(1) and Table (6). For all beam specimens, the cross section was 100 mm wide and 180 mm in depth. The overall length was 1250 mm, with clear span 1150 mm.All beams (except beam B1 which is the control beam without any strengthening for shear) were strengthened using U-wrap CFRP strips which were bonded to the beams by epoxy and without stirrups. The strengthened beams were divided into two groups according to the anchorage of the CFRP strip end or not.

Strengthening with CFRP

The strengthening system used in this work comprised of fiber strips, epoxy, connectors (bolts) and small steel plates (anchorage). All the strengthening processes were done after 28 days of moist curing for the beam specimens. The strengthening process is detailed in (ref. 24) see Figs.(2).

Strengthening Schemes

Only the first specimen (B1) was kept without strengthening as control specimen, whereas the other eight beam specimens were strengthened with externally applied CFRP strips with or without end anchorage. The following different schemes illustrate the technique of this strengthening as shown in Figs. (3) to (6).

Test Measurement and Instrumentation

All specimens were tested as simply supported beams using two-point loading with shear span to effective depth ratio (a/d) equal to 1.5 and 3. Fig.(7) shows the details and instrumentation used for testing the beam specimens. The measurements includes:

- The central deflections were measured by using a dial gage of 0.01mm/div. sensitivity.
- A demec strain device was used on a length of 200 mm to measure the surface strains at the tension and compression zones. These demec points were fixed at specific positions as shown in Fig.(8).
- The strain of the CFRP U-wrap strips was measured at center of each strip with the 100 mm demec gage along the CFRP strip on the specimen side [see Fig.(8)].

Shear Strength results

Table (7) represents the shear strength at the appearance of diagonal crack (diagonal cracking loads) for SFRHSC beams without stirrups and strengthened in shear zones with CFRP, along with the ultimate shear failure loads, as measured during testing. In this study the diagonal cracking load is defined as the shear load at the time when the critical diagonal crack formed within the shear span propagated to the mid-depth of the beam. Also the failure types of the CFRP strips are shown in Table (7).

The effects of several parameters on shear behavior of SFRHSC beams containing shear strengthening with CFRP were studied in the present study were:
1. Effect of shear span to effective depth ratio (a/d).
2. Effect of the anchorage of the ends of CFRP strips with the beams.
3. Effect of the amount and distribution of the wrapping (width and spacing of the CFRP strips).
The experimental results for each parameter are discussed below:

Effect of Shear Span to Effective Depth Ratio (a/d)

The diagonal cracking and ultimate shear failure loads of the tested SFRHSC beams decrease with the increase of (a/d) ratio. However, the values of the ultimate load in all tested beams with the variation of (a/d) ratio is much more pronounced than those of the diagonal cracking loads.

It can be clearly seen from Table (7) and Fig.(9) that by increasing the (a/d) ratio from 1.5 in B2 and B9 (deep beams) to 3 in B5 and B7 respectively, the diagonal cracking load decreased by 100 kN, 25 kN respectively, which represents a decrease ratio of 40 %, 14.28 % respectively. Also for the same increase in the (a/d) ratio the ultimate shear strength decreases by 175kN, 141kN respectively, which represents a decrease of 43.2 %, 39.6 % respectively. The test results for shear failure of the beams have shown that for (a/d) of 1.5, shear failure due to arch action (deep beam effect) is dominant; whereas in the region with (a/d) of 3 the beam action due to concrete teeth (beam action) is more effective.

Effect of End Anchorage of the CFRP Strips

Anchorage the ends of the CFRP strips decreases the required development length for the bonding with concrete, this is more effective for the limited depth girders(22). In this work, the strengthening of beams in shear is with U-wrap CFRP strips, and with two methods, the first group is with end anchorage for beams B2, B3, B4 and B5, while the second is without anchorage, for beams B6, B7, B8 and B9 (see Table 6).

Table (7) clearly shows the increase in the ultimate load of beams due to the end anchorage of the strips. For example, B2 and B3 had a failure load increased by 49 kN and 10 kN respectively compared with B9 and B8 due to the strip ends anchorage. Also the end anchorage of the CFRP leads to increasing the diagonal cracking load for the same beams by 75 kN and 50 kN respectively.

It is obvious from the results of the tested beams, in case of using the mechanical fixing technique of CFRP (using the end anchorage) the overall length of the CFRP strip works as a link between the top zone (concrete compressive cord) and the bottom zone (main reinforcement tension cord) similar to the steel stirrups function. This is by preventing cracks widening and propagation to the compression zone, which leads to a more uncracked concrete sections.

Effect of Width and Spacing of the CFRP Strips

The type of failure of the CFRP strips depends on the values of the bond stress (produced between the FRP and the concrete) and its resultant bond force that are normal to the crack, and these values depend on the spacing and active bond area of FRP (active bond area = FRP effective width × FRP effective length)(23). The failure shape and the design of the FRP depend on the quantity and distribution of CFRP strips used in shear strengthening or repairing of the beams(24).

As it is mentioned in Table (6), the beams in this work were fabricated in two groups. The first group, beams B2, B5, B7 and B9 were strengthened with CFRP strips of 40 mm width with a spacing of 100 mm center to center. While in the second group, beams B3, B4, B6 and B8 were strengthened with CFRP strips of 75 mm width spacing at 200 mm.

It can be clearly observed from Table (7), that beams B4, B6 and B8 from the second group have larger ultimate loads than their analogous beams B5, B7 and B9 respectively from the first group, by 20 kN, 10 kN and 4 kN respectively. The results showed approximately equal values of diagonal cracking loads for these beams from both groups. this may be attributed to the delay of the response of CFRP strips to resist the stresses transported from the concrete.

Crack Patterns

Two types of cracks may be observed in the tested beams; the flexural cracks resulting from flexural tensile stresses at the region of the simple beam cross-section below the neutral axis, and the shear cracks which are formed as a result of the inclined or "principal" tensile stresses acting on the beam at regions of combined moment and shear(2).

The type of failure that occurs depends mainly on the (a/d) ratio. In normal concrete beams, diagonal tension failure generally occurs when this ratio is between 2.5 and 6.0. While shear-compression failure generally occurs when this ratio is between 1.0 and 2.5 (deep beam effect). However, there is no distinct boundary between these two failure types and either type may occur when (a/d) ratio is in the range between 2.0 and 3.0(25).

The CFRP strips did not affect the basic mechanism, nor did they affect starting of cracking or the angle of diagonal compression which formed. The effect of the CFRP strips was noticed once the crack began to open up and propagate, at which time they began to influence the behavior of the member(22).

Fig.(10) shows photographs of the crack patterns after the failure of the tested beams of this work. The numbers shown beside the crack indicate the load when the crack penetrated to that position.

The behavior of the control beam B1 specimen supports the idea which states that, the SFRHSC tends to be more slender (beam action is dominant) compared with NSC beams, through the mode of failure was flexural mode with the absence of shear reinforcement. However, its obvious from table (7) and Fig.(10) that CFRP strips did not effect the mode of failure of the specimens,especially when end anchorage was not used.In addition,concrete crushing in the compressive zones was dominant due to the high values of tensile reinforcement ratio and volume fraction of the steel fibers.

Load-Deflection Behavior

The load-midspan deflection curves of the tested SFRHSC beams are plotted in groups having beams differing in the parameters considered with the other variables being kept constant as shown in Figs.(11) to (14). The load deflection of the control beam B1 is plotted in the Figs.(13) and (14) to show the effect of the CFRP strengthening and the (a/d) ratio on the behavior of SFRHSC beams.Comparisons among the load-deflection relationships of all tested SFRHSC beams will be discussed and related to major characteristic items. These are the deflection characteristics at ultimate load, and the ductility ratio as shown in Table (8).

Effect of Shear Span to Effective Depth Ratio (a/d) on The Load – Deflection

The load-midspan deflection curves for SFRHSC beams, Figs.(11) and (12), show that for a given load level at early stages of loading, the deflection increases with increasing shear span to effective depth ratio (a/d). Also, it is evident from these figures and Table (8) that the final deflection at ultimate load decreases with the increase of (a/d) ratio. As shown by the results of SFRHSC beams with and without anchoring the CFRP strips, the increase in (a/d) ratio from 1.5 to 3 causes a decrease in the ultimate deflection by about 50.6% for beams with anchored 40 mm CFRP strips with 100 mm spacing, and 26.52% for beams with anchored CFRP of 75 mm width @ 200 mm spacing as shown in Fig.(11).

For beams without anchored CFRP strips the increase in (a/d) ratio from 1.5 to 3 causes a decrease in the ultimate deflection by about 51.45% for beams with CFRP of 40 mm width @ 100 mm spacing, and 13.1% for beams with CFRP of 75 mm width @ 200 mm spacing as shown in Fig.(12).It is clear from Table (8) that the ductility ratio decreases with increasing shear span to effective depth ratio (a/d). With varying (a/d) ratio from 1.5 to 3, the ductility ratio decreases by 55.34% and 57.93% for the beams with anchorage end CFRP of 40 mm @ 100 mm and of 75 mm @ 200 mm respectively. This ratio decreases by 68.84% and 68.38% for the beams without anchorage CFRP of 40 mm @ 100 mm and of 75 mm @ 200 mm respectively.

Effect of End Anchorage of the CFRP on The Load – Deflection

Regardless of the values of compressive strengths of the SFRHSC, it is observed that, the ends anchorage effect of the CFRP strips on the behavior of the tested beams, one can generally say that, the ends anchorage of the CFRP strips leads to a significant decrease in the ultimate deflections of the SFRHSC tested beams. However, Figs.(13), (14) and Table (8), show the effect of end anchorage on the ultimate deflections and the ductility ratio.

Fig.(13) shows that for the same (a/d)=1.5 and amount of strengthening with CFRP (the width and spacing of strips), there is an increase in the ultimate deflection of the beams at the ultimate load when the end anchorage exists. This increase is of about 14% and 5.3% for the beams strengthened with 40 mm CFRP strips spacing at 100 mm and of 75 mm @ 200 mm respectively.

Also, Fig.(14) shows that, for (a/d) =3 an increase by 15.48% was observed in the ultimate deflection due to the end anchorage for the beams strengthened with CFRP of 40 mm @ 100 mm. While the same figure shows that the varying values of ultimate deflections due to the end anchorage is decreased by 12% for the beams strengthened with CFRP of 75 mm @ 200 mm. Despite that the overall behavior of the beam B4 had a proper line which gives less deflection values for all loading stages than the behavior of its analogous beam B6 and an increase in the ultimate load. This may be due to the difference in the nature of failure in the two beams.

Effect of Width and Spacing of the CFRP Strips

From observing Figs.(13) and (14), one can conclude that approximately in general, increasing the width and the spacing of the CFRP strips leads to increased the stiffness of the strengthened beams. However, with increasing width and spacing of the strips the ductility ratio increased by 13.4% and 8% for the beams with ends anchorage having (a/d) 1.5 and 3 respectively, while for the beams without anchorage the ratio increased by 6.92% for the (a/d = 1.5).

FRP Strain

The load-vertical FRP strains (in the direction of the fibers orientation) measured at the center of the strips are shown in Figs (15) to (22). The vertical strains of single-layer of FRP strips are for the outside of the strips and there is no relation of these measured strains with the epoxy or the concrete under the strips. It is clear that the strain of the FRP increased at strips which crossed the diagonal cracks.Approximately in all beams the initial loading stages show compressive or zero strains for the strips, and when the cracks formed, the shear stresses were redistributed along the shear spans of the beams and the CFRP strips started to respond for this stress redistribution and generating the CFRP strains. However, the test results show that the first two strips near the supports have the major strains compared with the other strips.

CONCLUSIONS

1. Experimental tests of the eight SFRHSC beams strengthened by CFRP strips indicate that the presence of end anchorage for the strips increases the shear capacity of the beams by 12%.
2. The amount and distribution (width and spacing) of the CFRP strips show an influence on the behavior and shear capacity *V* of the SFRHSC beams. In the present work, there is an increase in the ultimate shear capacity by 8%, 4.4% and 1.1% for beams B4, B6 and B8 (having the wider width and larger spacing of strips) respectively.
3. Approximately, for all tested SFRHSC beams there is a small difference in the values of the diagonal cracking strength even for beam B1 without strengthening, this may be attributed to the retardation of the CFRP strips to response and resisting the tensile stresses transported from the concrete due to forming the micro diagonal cracks.

Despite the presence of deep beam effect (a/d< 2) in beam B9, the beam failed by flexure. This means that, the CFRP strips play a role similar to stirrups as vertical web reinforcement, while the steel fibers replaced the horizontal web reinforcement.

Table (1): Chemical Composition of Micro Silica (MS)

Oxide composition	Oxide content %
SiO_2	95.95
Al_2O_3	0.02
Fe_2O_3	0.01
Na_2O	0.00
K_2O	0.07
CaO	1.21
MgO	0.01
SO_3	0.22
L.O.I.	2.5

Manufacturer Properties

Table (2): Chemical Requirements of Micro Silica ASTM C 1240-03[18]

Oxide composition	Micro silica	Limit of specification requirement ASTM C 1240
SiO_2	95.95	> 85.0 %
Moisture Content	0.8	< 3.0 %
Loss on Ignition	2.5	< 6.0 %

Table (3): Physical Requirements of Micro Silica ASTM C 1240-03[18]

Physical properties	Micro silica	Limit of specification requirement ASTM C 1240
Retained on 45-µm (No.325) Sieve	7	< 10 %
Accelerated Pozzolanic Strength Activity Index with Portland Cement at 7 days	128.6	> 105 %
Specific Surface, Min, (m^2/g)	20	> 15

Table (4) Details of Sika-Wrap 230 C/45 (Carbon Fiber Fabric) *

Fiber type	Mid strength carbon fibers.
Fiber orientation	0◦ (unidirectional). The fabric is unidirectional woven carbon fiber fabric for the dry application process.
Areal weight	225 g/m2
Fabric design thickness	0.131 mm (based on total area of carbon fibers)
Tensile strength of fibers	4300 MPa
Tensile E – modulus of fibers	230 GPa
Elongation at break	1.5 %
Fabric length/roll	≥ 45.7 m
Fabric width	500 mm
Fiber Density	1.76 g/cm3

Supplied by the manufacturer

Table (5) Details of Sikadur 330 Resins properties*

Tensile bond strength (MPa)	30 (7 days at +23°C)
Elongation at Break	0.9% (7 days at +23°C)
Elastic modulus (MPa)	Flexural: 3800 (7 days at +23°C) Tensile: 4500 (7 days at +23°C)
Curing	7 days (+10°C to +53°C)
Density of Mixed Resin	1.31 kg/lt (at +23°C)
Appearance / Colours	Resin part. A: white Hardener part B: grey Part A+B mixed: light grey
Thermal Expansion Coefficient	45 x 10-6 per °C (-10°C to +40°C)
Mixing Time	at least 3 minutes with a mixing spindle attached to a slow speedelectric drill (max. 600 rpm)

Supplied by the manufacturer

Table (6): Details of the reinforcement and U-wrap strips

Beams	a/d	Reinfor-cment amount	ρw	CFRP Width (mm)	CFRP Spacing (mm)	CFRP ends anchorage Status
B1	2.5	2Ø16 mm	0.0268	….	….	….
B2	1.5	2Ø16 mm	0.0268	40	100	Anchored
B3	1.5	2Ø16 mm	0.0268	75	200	Anchored
B4	3	3Ø16 mm	0.0402	75	200	Anchored
B5	3	3Ø16 mm	0.0402	40	100	Anchored
B6	3	3Ø16 mm	0.0402	75	200	Without
B7	3	3Ø16 mm	0.0402	40	100	Without
B8	1.5	2Ø16 mm	0.0268	75	200	Without
B9	1.5	2Ø16 mm	0.0268	40	100	Without

Table (7) : Details of Cracking and Ultimate Shear Strength for Tested Beams.

Beams	f'_{cf} (MPa)	CFRP mode failure	Shear Strength		$\frac{P_{u\ exp.}}{P_{cr\ exp.}}$	Mode of Failure
			Diagonal CrackingPcr(kN)	Ultimate Pu (kN)		
B1	119	……	175	270	1.54	SC
B2	108.3	R+D	250	405	1.62	DT
B3	93.8	R+D	200	370	1.85	DT
B4	100.1	none	150	250	1.67	SC
B5	99.7	none	150	230	1.53	SC
B6	111.6	D	125	225	1.8	DT
B7	103.4	D	150	215	1.43	S+F
B8	102.4	D	150	360	2.4	DT
B9	102.4	D	175	356	2.03	S+F

R: Rupturing the CFRP strip, D: Debonding the CFRP strip.
DT: diagonal tension failure, S+F: shear-flexure failure, SC: shear compression failure.

Table (8) Deflection at First Crack and Ultimate Load and the Ductility Ratio for Tested SFRHSC Beams.

SFRHSC Beams	Def. at First Crack Load (mm)	Def. at Ultimate Load (mm)	Ductility Ratio
B1	4.5	12.93	2.87
B2	3.7	20.8	5.62
B3	2.15	13.95	6.49
B4	3.75	10.25	2.73
B5	4.085	10.27	2.51
B6	5.19	11.48	2.21
B7	3.7	8.68	2.34
B8	1.89	13.21	6.99
B9	2.38	17.88	7.51

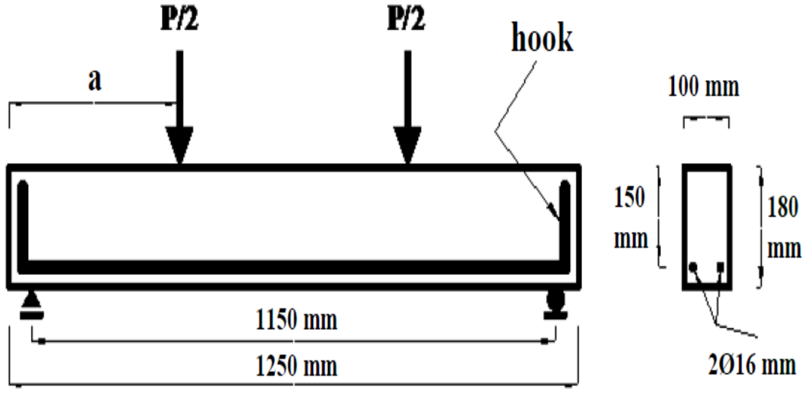


Figure (1) Details of Typical Tested Beams[21]

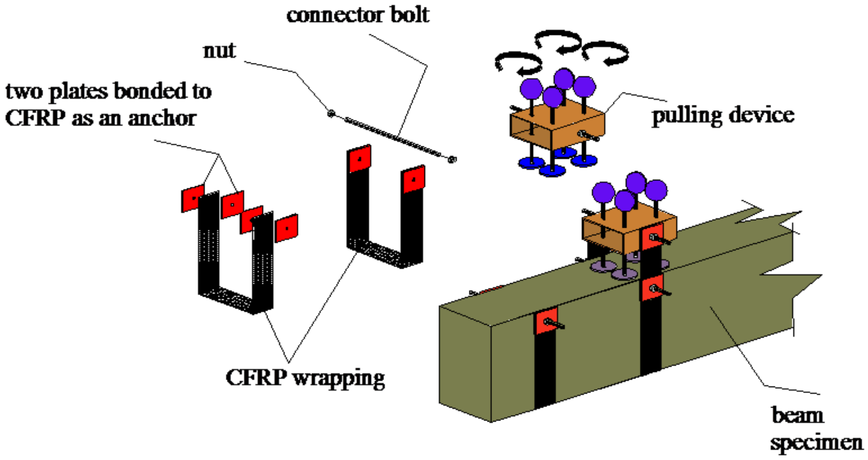


Figure (2) Details of Preparing and Fixing System of the U-wrapCFRP and Devices[21]

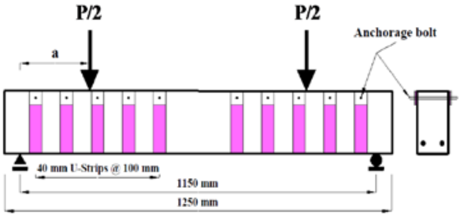


Figure (3) Shear Strengthening with End AnchoringB2 and B5[21]

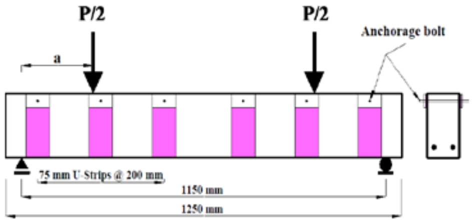


Figure (4) Shear Strengthening with End Anchoring B3 and B4[21]

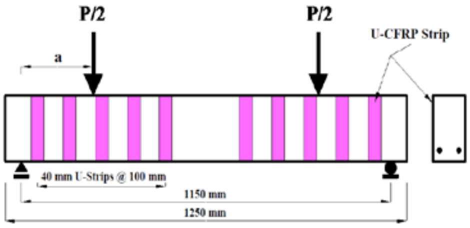
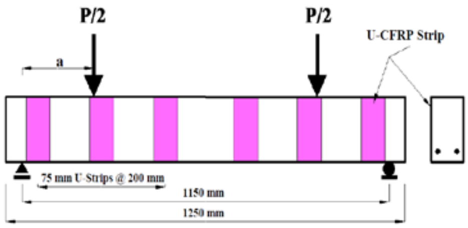


Figure. (5) Shear Strengthening without End Anchoring B7 and B9[21]



Figure(6) Shear Strengthening without End Anchoring B6 and B8

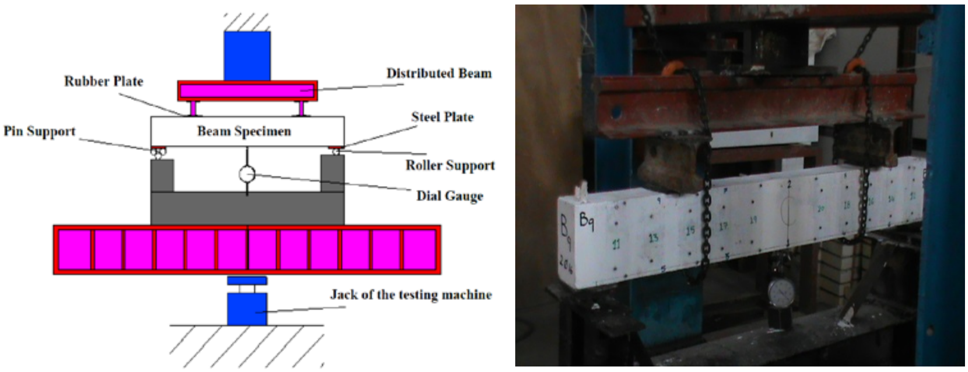


Figure (7) Beams Testing Machine Details[21]

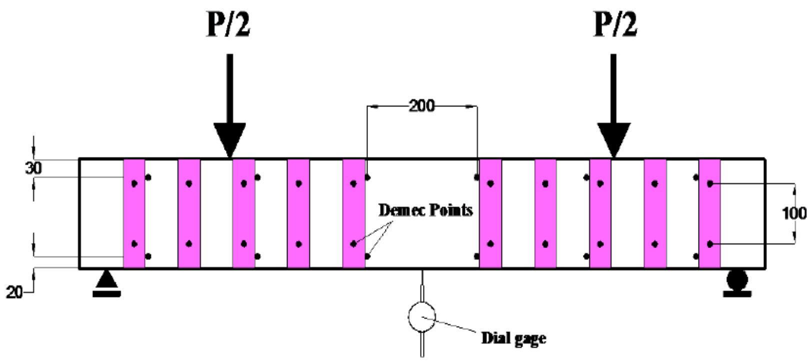
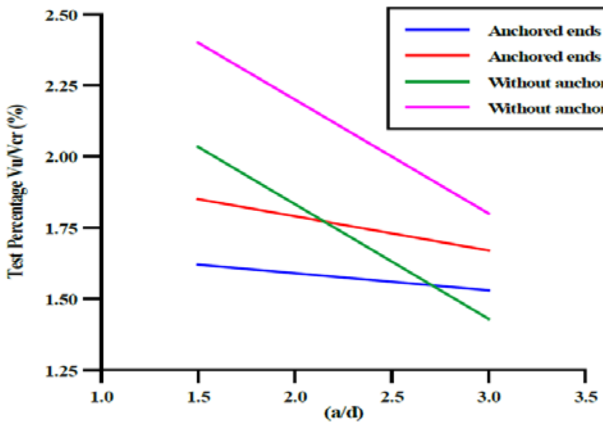


Figure. (8) Details and Instrumentation of Specimen[21]



Figure(9):Effect of (a/d) Ratio on the Percentage Decrease in Shear Strength of SFRHSC Beams[21].

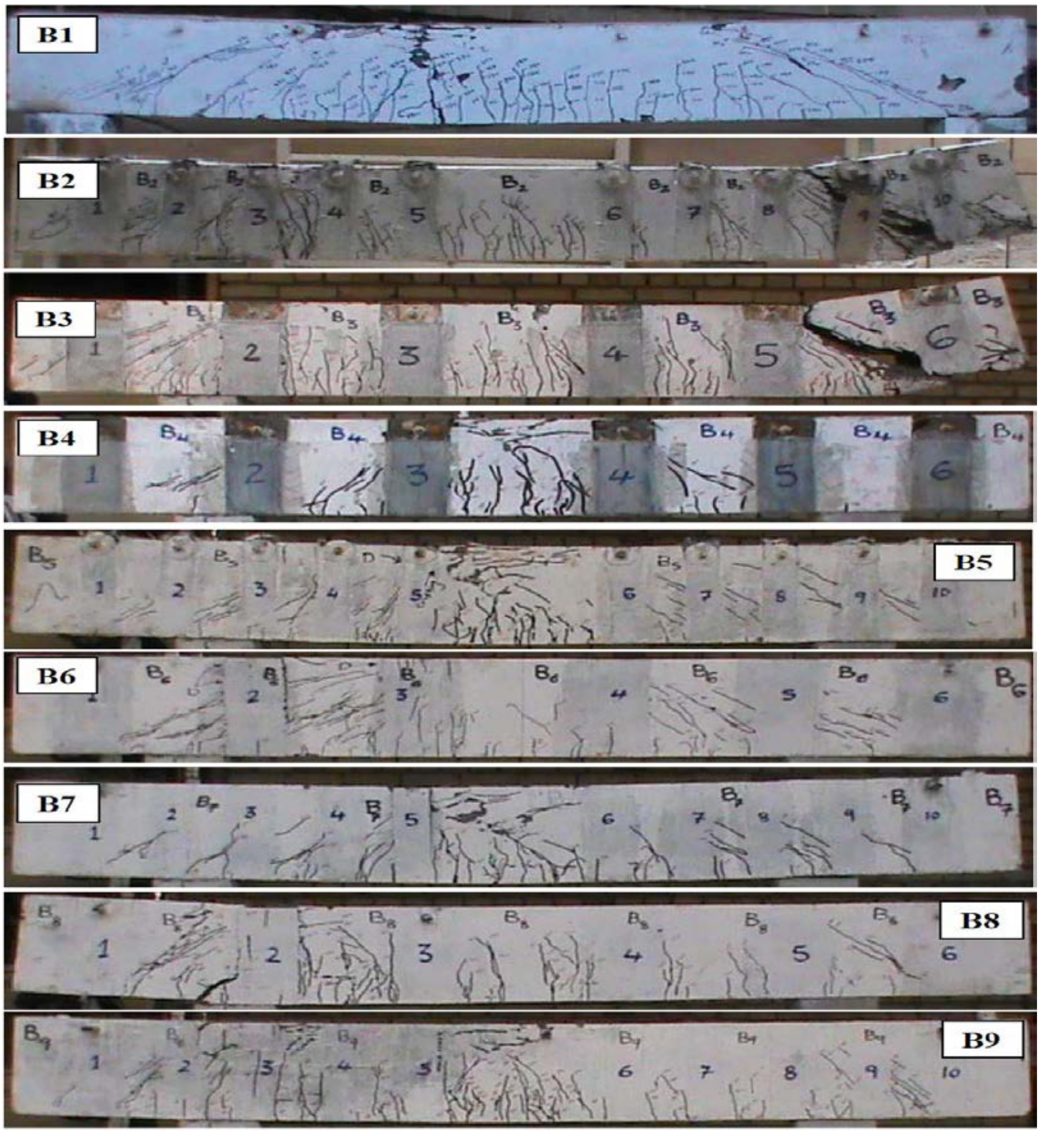
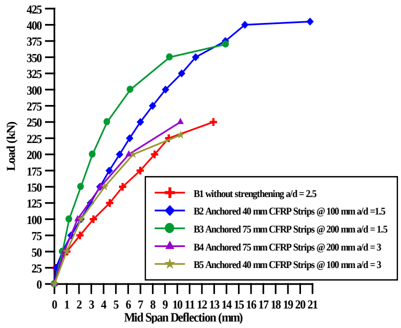
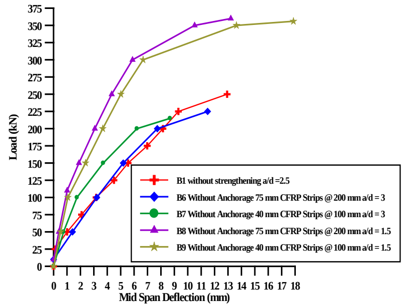


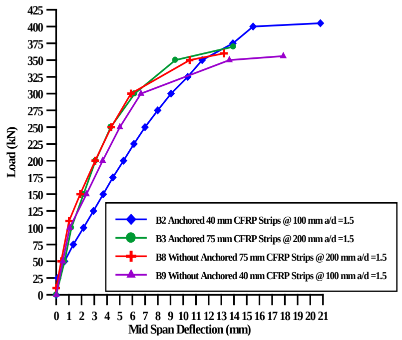
Figure. (10) Crack Patterns for tested Beams[21]



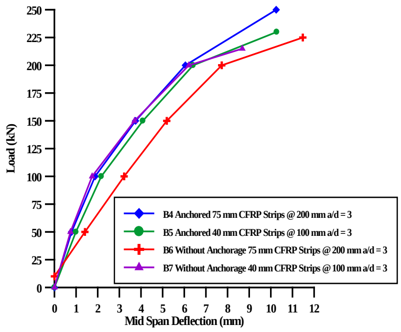
Figure(11): Effect of Varying a/d Ratio on The Load- Deflection of The Beams With Anchorage End



Figure(12): Effect of Varying a/d Ratio on The Load- Deflection of The Beams Without Anchorage End



Figure(13):Effect of The CFRP End Anchorage on the Load-Deflection of The Beams With (a/d



Figure(14):Effect of The CFRP End Anchorage on the Load-Deflection of The Beams With

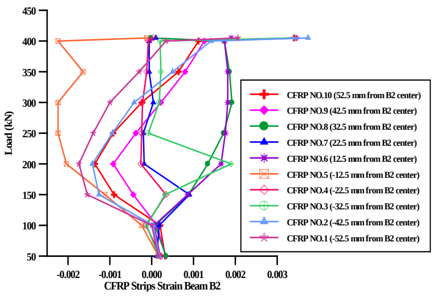
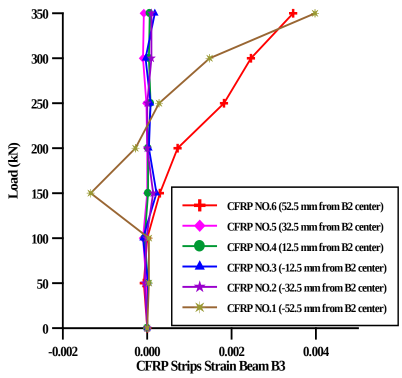


Figure (15) Applied load - CFRP Strain for Beam B2(21)



Figure(16) Applied load - CFRP Strain for Beam B3(21)

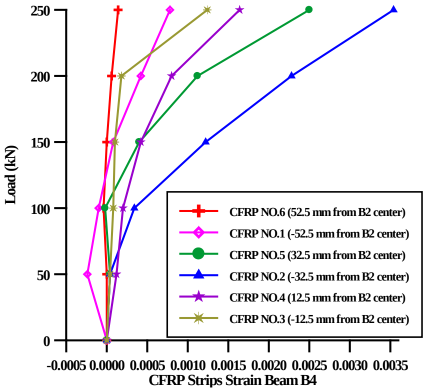


Figure (17) Applied load - CFRP Strain for Beam B4[21]

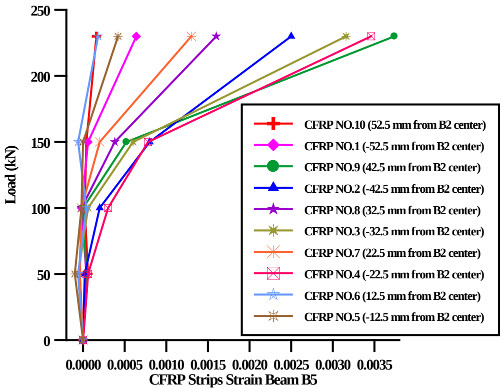


Figure (18) Applied load - CFRP Strain for Beam B5[21]

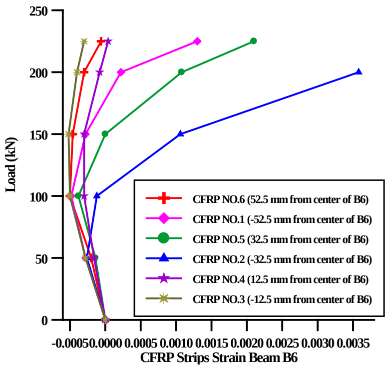


Figure (19) Applied load - CFRP Strain for Beam B6[21]

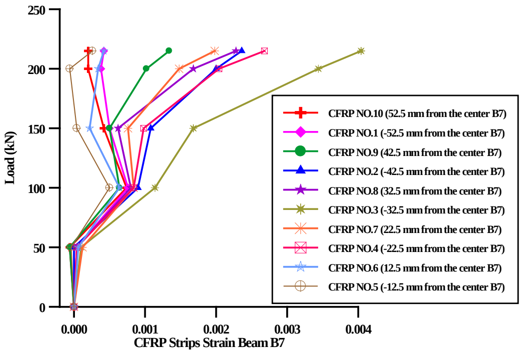


Figure (20) Applied load - CFRP Strain for Beam B7[21]

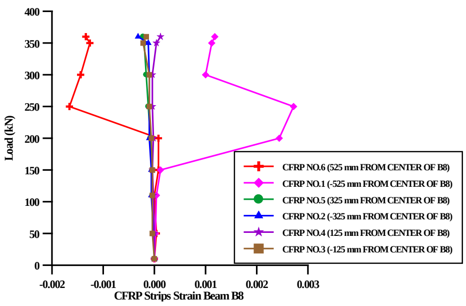


Figure (21) Applied load - CFRP Strain for Beam B8[21]

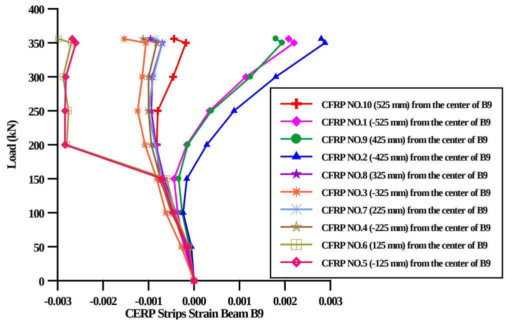


Figure (22) Applied load - CFRP Strain for Beam B9[21]

REFERENCES

[1].Izzet, A. F., "Retrofit of Shear Critical R.C. Beams with Carbon Fiber Reinforced Polymer Sheets",PhD. Thesis, University of Technology, Baghdad, 2008, 152 pp.

[2].Nematollahi, B., Saifulnaz, R., Jaafer, M.S. and Voo, Y.L.,"A Review on Ultra High Performance Ductile Concrete (UHPdC) Technology",International Journal of Civil and Structural Engineering, Vol.2, No.3, 2012, PP.1003-1018.

[3].O'Neil, E.F. and Dowd, W.H., "Reactive Powder Concrete: A New Material for the Construction Industry" Third National Concrete and Masonry Engineering Conference, June 15-17, 1995, San Francisco, CA, PP. 43-50.

[4].Jungwirth, J., "Underespanned Bridge Structures in Reactive Powder Concrete (RPC)", France, Janvier, 2002, Email: Jorg. Jungwirth @ epfl.ch.

[5].Ridha, M. M., "Shear Behavior of Reactive Powder Concrete Beams ", PhD. Thesis, University of Technology, Baghdad, 2010, 205 pp.

[6].Kwak, Y., Eberhard, M. O., and Kim, J., "Shear Strength of Steel Fiber-Reinforced Concrete Beams without Stirrups", ACI Structural Journal, V.99, No.4, July-August 2002, PP.530-538.

[7].Sarsam, K.F. and Al-Musawi, J.M.S., "Shear Design of High and Normal Strength Concrete Beams with Web Reinforcement", ACI Structural Journal of Concrete Vol. 89 No.6, Nov.-Dec. 1992, PP. 659–664.

[8].Oh, J. K., and Shin, S. W., "Shear Strength of Reinforced High-Strength Concrete Deep Beams",ACI Structural Journal, Vol.98, No.2, March-April, 2001, PP. 164-173.

[9].Shah, R. H., and Mishra, S. V., "Crack and Deformation of SFRC Deep Beams,"IE (I) Journal –CV, July, 2004, PP. 44-48.

[10].Madan, S. K., Kumar, G. R., and Singh, S. P., "Steel Fibers as Replacement of Web Reinforcement for RCC Deep Beams in Shear"Asian Journal of Civil Engineering Vol.8, No.5, 2007, PP. 479-489.

[11].Uji, K., 1992"Improving Shear Capacity of Existing Reinforced Concrete Members By Applying Carbon Fiber Sheets" Transactions of the Japan Concrete Institute, Vol.14 , PP 253-266.

[12].Sato, Y., Ueda, T., Kakuta, Y., Tanaka, T., (1996)"Shear Reinforcing Effect of Carbon Fiber Sheet Attached to Side of Reinforced Concrete Beams"Advanced Composite Materials in Bridges and Structures (2 International Conference). Edited by M.M.EL-Babry. Published by the Canadian Society for Civil Engineering Montreal, Quebec, Canada. PP.621-628.

[13].Taerwe, L., Khalil, H., Matthys, S., (1997)"Behavior of RC Beams Strengthened in Shear By External CFRP Sheets"Proceedings of the Third International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures, Published by Japan Concrete Institute, Tokyo, Japan, Vol.1, PP. 483-490.

[14].Chajes, M. J., Finch, w., Jamuszka, T. F., and Thomson, T. A., (1996) "Bond and Force Transfer of Composite Material Plates Bonded to Concrete", ACI Structural Journal. Vol.93, No.2, March-April, PP 208-217.

[15].Araki, N., Mastsuzaki,Y., Nakano, K.,Kataoka, T., Fukuyama, H., (1997) "Shear Capacity of Retrofitted RC Members with Continuous Fiber Sheets", Proceedings of the Third International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures, Published by Japan Concrete Institute, Tokyo, Japan, Vol.1, PP. 515-522.

[16].Bousselham, A. and Chaallal, O. "Behavior of Reinforced Concrete T-Beams Strengthened in Shear with Carbon Fiber-Reinforced Polymer An Experimental Study"ACI Structural Journal, V. 103, No. 3, May-June 2006 PP. 339-347.
[17]. المواصفة القياسية العراقية 5\1984، " الاسمنت البورتلاندي "، (وزارة التخطيط الجهاز المركزي للتقييس والسيطرة النوعية).
[18].ASTM C 1240 – 2003, "Standard Specification for Use of Silica Fume as a Mineral Admixture in Hydraulic-Cement Concrete, Mortar, and Grout", Vol. 04.02, 2003, PP.1-6.
[19].ASTM C 494/C 494M – 1999a, "Standard Specification for Chemical Admixtures for Concrete", Vol. 04.02, 1999, PP.1-9.
[2o].ASTM Designation A370-05a, "Standard Specification for Testing Method and Definitions for Mechanical Testing of Steel Products", 2000 Annual Book of ASTM Standards, American Society for Testing and Material, Philadelphia, Pennsylvania,section1, Vol.1.01, PP.248-287.
[21].Al-Habbobi, A. M., "The Use of CFRP for Shear Strengthening of Reactive Powder Concrete Beams", PhD. Thesis, University of Basrah, Basrah, 2014, 207 pp.
[22].Drimoussis,E.H., Cheng, J.J.R., "Shear Strengthening of Concrete Girders Using Carbon Fiber Reinforced Plastic" Structural Engineering Report No. 205,Department of Civil and Environmental Engineering, University of Alberta, 1994.
[23].Brandon, E. R.,"Analytical Modeling and Standardized Testing of Concrete Beams with Web Bonded FRP Shear Reinforcement", M.Sc. Thesis , University of Wyoming, Laramie, 2002, 64 pp.
[24].Ali, D.,D.,"Experimental and Theoretical Investigation of the Behavior of Reinforced Concrete Beams Strengthened by Fiber Reinforced Polymer", PhD. Thesis, Civil Engineering Department, University of Baghdad, Baghdad, 2007, 188 pp.
[25].Bresler, B. and Mac Gregor, J. G., "Review of Concrete Beams Failing in Shear", J. Struct. Divis. , ASCE , 93 , 1967, PP.343-372.