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Behaviour of Segmental Concrete Beams Reinforced by Pultruded CFRP Plates: An Experimental Study

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ABSTRACT

The research aims to develop an innovative technique for segmental beam fabrication using plain concrete blocks and externally bonded Carbon Fiber Reinforced Polymers Laminates (CFRP) as a main flexural reinforcement. Six beams designed and tested under two-point loadings. Several parameters included in the fabrication of segmental beam were studied such as; bonding length of carbon fiber reinforced polymers, the surface-to-surface condition of concrete segments, interface condition of the bonding surface and thickness of epoxy resin layers. Test results of the segmental beams specimens compared with that gained from testing reinforced concrete beam have similar dimensions for validations. The results display the effectiveness of the developed fabrication method of segmental beams. The modified design procedure for externally bonded carbon fiber reinforced polymers ACI 440.2R-17 was developed for designing segmental beams. The experimental test values also compared with design values, and it was 93.3% and 105.8% of the design values, which indicates the effectiveness of the developed procedure.

Keyword: segmental beam, plain concrete, carbon fiber reinforced polymers (CFRP) laminates, reinforced concrete, design procedure.

سلوك العتبات الخرسانية المصنعة من أجزاء القطع الخرسانية وصفائح البوليمر المسلحة بألياف الكاربون: دراسة عملية

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الخلاصة

الهدف من البحث هو أبتكار تقنية جديدة لتصنيع العتبات المكونة من أجزاء والمصنعة من القطع الخرسانية والمسلحة بصفائح البوليمر المعززة بألياف الكاربون والتي أعتمدت تسليح رئيسي لمقاومة قوى الأنحناء. تم تصميم وتصنيع ستة عتبات من هذا النوع وتم تعريضها لحملين مركزيين. تم دراسة مجموعة متغيرات ومنها طريقة التصنيع حيث تضمنت طول الصفائح الكاربونية وحالة الربط بين القطع الخرسانية وحالة سطح الربط للصفائح الكاربونية وسمك الراتنجات الايبوكسية الرابطة ومدى تأثيرها على مقدار تحمل العتبات ومقدار الهطول في منتصف فضاء العتبة وأيضاً تم مقارنة النتائج العملية مع عتبة خرسانية مسلحة تم تصنيعها بذات الأبعاد. بينت النتائج العملية كفاءة العتبات المبتكرة المكونة من أجزاء بالمقارنة مع العتبات الخرسانية المسلحة.

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أيضاً تم أعتماد طريقة معدلة لدليل التصنيع ACI 440.2R-17 والخاص بتعزيز العتبات الخرسانية المسلحة. تم مقارنة النتائج العملية للعتبات الخرسانية المكونة من أجزاء مع الطريقة المعدلة للتصميم المذكور وكانت النتائج تتراوح 93.3 % - 105.8 % مع الطريقة المعدلة مما يدل على كفاءة الطريقة المعدلة.

الكلمات الرئيسية: العتبة المصنعة من أجزاء، الخرسانة غير المسلحة، صفائح الياف الكاربون، الخرسانة المسلحة، طريقة التصميم

1. INTRODUCTION

A segmental beam may be defined as a structural beam which consists of multi-segments that are prefabricated commonly from concrete in or out of the field, and later they were gathered to form structural beams. Two methods nowadays are adopted in the segmental forming of beams which corresponds to the purpose of application or usage. The first one used cast-in-situ concrete in segmental forms, and the other used precast concrete segments which are either pre-tensioned or post-tensioned reinforced concrete construction. The segmental construction procedure relying on pre-stressed reinforced concrete (PRC) is fast, not exposed to danger or risk, and economical. Hence, it is widely adopted in bridge construction overall in the world**, Al-Sherrawi, et al., 2018.** Structural construction joints between segments may be free from moisture or liquid, in other words, the joints are directly dry and they may also be wet or may be indirectly coated or (epoxy-joints) and with or without any interlocking keys. Joints were chosen according to the prevailing condition by which the structural-interaction system will be fully utilized, **Dong-Hui, et al., 2016.** Since the 1950s, some researchers did some researches on the mechanical behavior of joints in segmental beams. The studies, according to their path, could be classified into two categories or failure modes. First one is the shear behavior of segmental joints subjected to direct shear (**Zhou, et al., 2005)**. Other researchers were conducted on bending failure under compression and shear actions, namely diagonal-compression mode **Angel, et al., 2002** and **Jiang, et al., 2018.**

Strengthening and retrofitting of reinforced concrete structures (RCS) were exceedingly discussed and studied for the last two decades. Existing structures need rehabilitation or strengthening due to many reasons such as improper design or construction; exceeded design loads, damage due to accidents or environmental attacks and subjected to seismic, **Pellegrino and Sena, 2016**. Many systems were developed to strengthen existing structures for any of the above reasons such as the replacement of structural members, by adding modern materials to improve the structural performance of individual elements and using post-tension rebar, **Said, and Abdulwahed, 2018.** These modern techniques are very efficient and widely adopted, but unfortunately, they may be expensive in some cases. Using fiber reinforced polymers (FRP) is considered as cost-effective in the application for rehabilitation of existing structural members compared with traditional strengthening methods. Considerable attention in the worldwide for using FRP composites for strengthening purpose due to its high mechanical properties and as mentioned low cost. Fiber reinforced polymers composites consist of relatively high strength fibers such as carbon, glass, and aramid. Strengthening with CFRP composites are utilized to structural members on its surface using especially resins usually epoxy resins. FRP composites could be implemented through two well-known techniques used in the strengthening of structural elements. These techniques are either external bonded (EBR) to element surface, or it is near surface mounted (NSM). The first method is performed by directly applying the FRP on element surface with the aid of epoxy resin while the second uses making grove near element surface on which the FRP composite to be placed and the grove to be filled with an epoxy resin material. FRP composites are intended to resist tensile stresses as the composite matrix (FRP and epoxy resin) transfer tensile forces to substrate concrete to support, **Hashemi, S. and Al-Mahaidi**, **2012** and **Ghernouti, et al., 2014**.

From a practical point of view, FRP is easy to install, and many researchers recorded structural load carrying capacity increased when using FRP composites, **Yang, et al., 2018** and **Hanoon, et al., 2017**. Another interesting issue is that FRP has a high strength to fiber weight ratio. Hence, many reasons encourage the use of FRP composite for structural retrofitting. Some of the design procedures and guidelines concern both EBR and NSM composites are issued by;

- The American Concrete Institute guide, **ACI 440.2R-2017**.
- The Federation International of Concrete procedure, **FIB, 2001**.
- Italian National Research Council procedure, **CNR, 2004**.

2. RESEARCH SIGNIFICANCE

The innovative construction technique is used in this experimental work by utilization of EBR-CFRP composite as flexural reinforcement for segmental beams fabrications. Six segmental beams reinforced with CFRP composites were studied and compared with reference ordinary RC beam. A modified design procedure of ACI 440.2R-17 was developed and adopted in the design of the segmental beams manufactured from plain concrete have a rectangular cross-section reinforced by EBR CFRP composites.

3. EXPERIMENTAL PROGRAM

3.1 Specimen Details and Materials Characteristics

A total of seven test beams were cast from concrete with a specified compressive strength of 50 MPa at 28 days. Among these beams, six of them are small-scale prototype segmental beams reinforced with EBR-CFRP composite and one reference ordinary reinforced concrete beam. The layouts of both types of beams are shown in **Fig. 1**, and **Fig. 2**; respectively. All of these beams have a cross-sectional dimension of (100mm ×100mm) and have a clear span and total span of 1000 mm and 1100mm, respectively. The segmental beams consist of 7 segments; two segments have a length of 300 mm with four deformed steel bars have 8mm diameter (as flexural reinforcement) and D8 @100mm as shear reinforcement. These two segments were over-reinforced. The remaining five segments made from plain concrete have a length of 100 mm. Beams dimensions, EBR-CFRP layout, and steel reinforcements layout are shown in **Fig. 1**. To designate the segmental and control beams, the sample designation system is shown in **Fig. 3**.

For the segmental beams, the end segments are designed to have slightly more than the minimum ratio of flexural reinforcement specified by American Concrete Institute, **ACI-318M, 2014** in this study to simulate deficiency in flexural reinforcements in these two end segments under extreme loadings. The concrete mix was designed to have a minimum compressive strength of 50 MPa at 28 days of concrete cubes. Concrete mixing was done using electric mixer have a drum capacity of 180 liters.

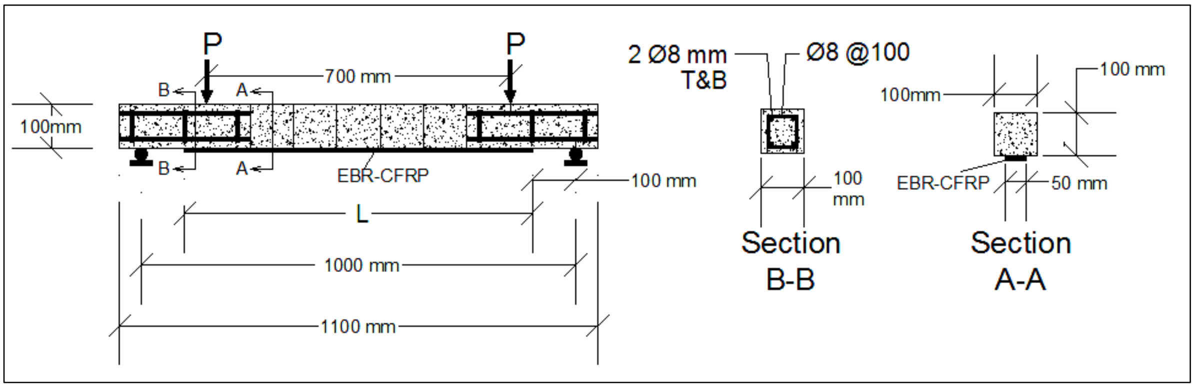


Figure 1. Typical segmental beam layout

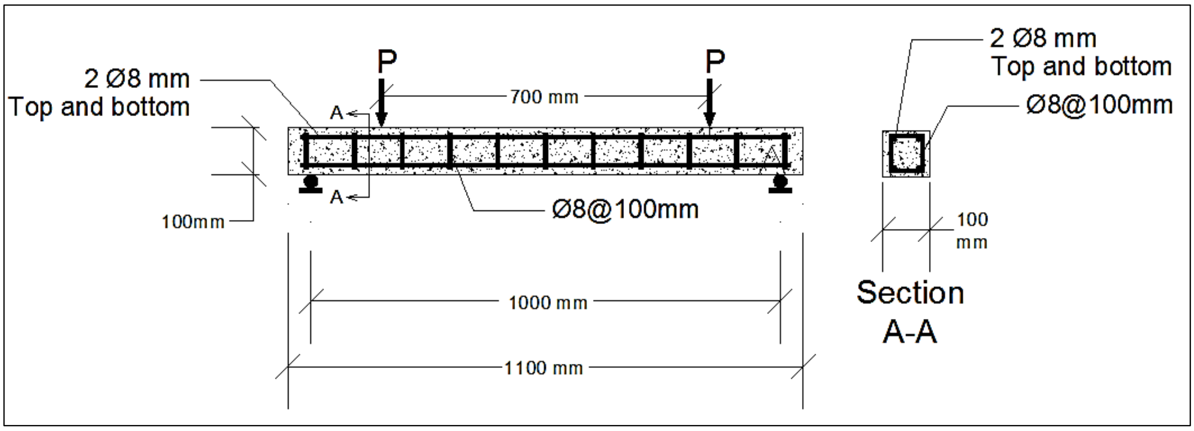


Figure 2. Reference beam layout.

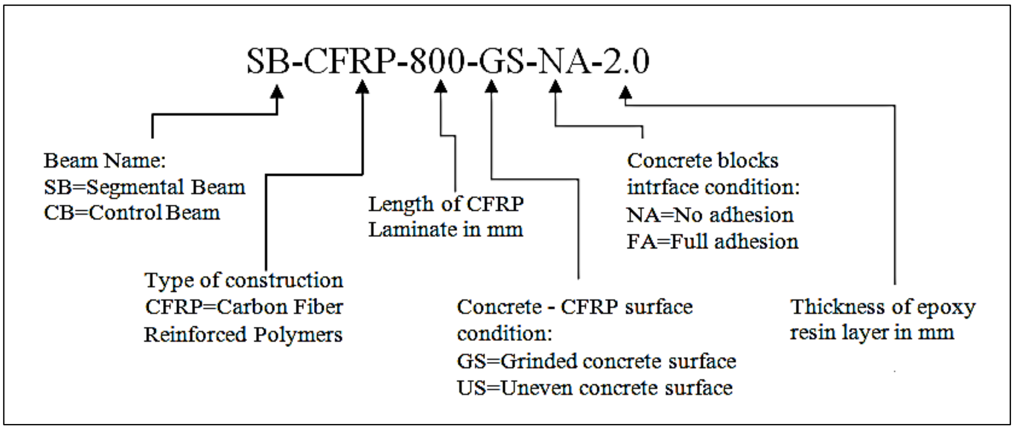


Figure 3. Specimen designation system.

Concrete samples (cubes and cylinders) were taken from the same patches of segmental beams so as a reference (control) beam, i.e., under the same condition. Wooden molds were fabricated to cast beam segments. Beam segments so as testing specimens were cured for 28 days before assemblage and testing. Steel reinforcement used in the fabrication of the control beam was tested according to the Iraqi Standard Specifications, **I.Q.S 2091, 1999** and the American Society for Testing and Materials Standard, **ASTM-A615, 2018**. The testing performed in the structural lab of Civil Engineering Department/College of Engineering/ University of Baghdad. The average of three test specimens for the used steel reinforcement with diameters of 8mm and 10mm was found to be 495 MPa and 440 MPa, respectively. Test results of steel reinforcement complied both of the specifications as mentioned above for tensile requirements of steel reinforcement with Grade 400 as indexed in **Table 1**. Concrete mix details are given in **Table 2,** which illustrate the components and the proportions of the used concrete mix.

Table 1. Steel reinforcement test.

Diameter, mm	Specimen no.	Yield Strength, MPa	Average Yield Strength, MPa	Tensile Strength, MPa	Average Tensile Strength, MPa	I.Q.S 2091, 1999 (Grade 400)		ASTM-A615, 2018 (Grade 420)	
						Yield Strength, MPa	Tensile Strength, MPa	Yield Strength, MPa	Tensile Strength, MPa
8	S8-01	448	440	662	656	400	600	-	-
	S8-02	437		655					
	S8-03	435		652					
10	S10-01	494	495	678	680	400	600	420	620
	S10-02	502		693					
	S10-03	489		669					

Table 2. Concrete mix components.

Parameter	Ratios
Water/cement ratio	0.36
Water (kg/m^3)	190
Cement (kg/m^3)	525
Fine aggregate (kg/m^3)	840
Coarse aggregate (kg/m^3)	850
Superplasticizer (l/m^3)	6

EBR CFRP pultruded laminates from **Sika Group, 2009** used as main reinforcement for segmental beams construction. CFRP laminates have a width of 50 mm and thickness of 1.4mm. Thixotropic adhesive epoxy resins for bonding pultruded CFRP reinforcement was used in this study also from **Sika Group, 2017** as recommended in the technical data sheet of the laminates**.** The epoxy resin is a structural 2-component adhesive (A and B) with a mixing ratio 3:1 and pot-life of 60min at temperature 25°C. This type of adhesive specially designed for use at high temperatures exposures. The manufacturer provides specifications for both CFRP laminates and epoxy resin as indexed in **Table 3**.

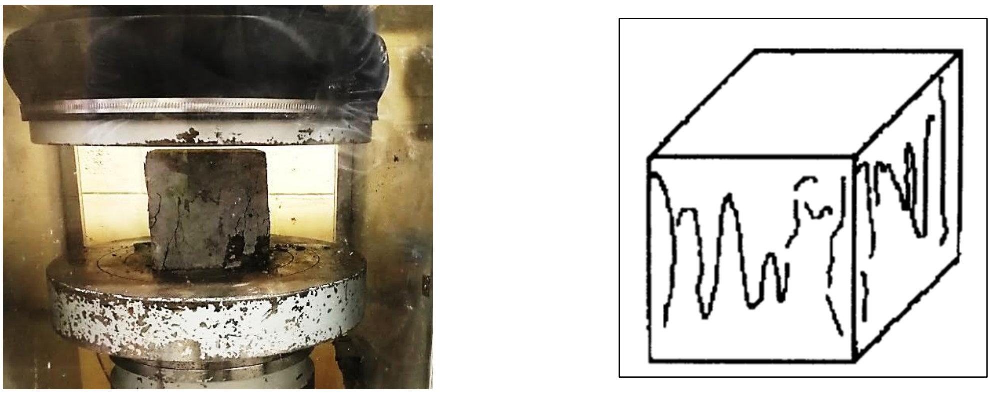
Table 3. CFRP laminates and epoxy resin properties.

Property	CFRP Laminate	Epoxy Resin
Density	1600 Kg/m^3	1.65 Kg/l
Tensile strength (min.) (N/mm^2)	2800	25*
Modulus of elasticity (min.) (N/mm^2)	165000	10000**
Strain at break (min. value)	> 1.70%	-

* Value for curing period seven days and at temp. +25°C
** Value at temp. +25°C

3.2 Testing Concrete Specimens

The compressive strength was determined by testing both concrete cubes with a side dimension of 100mm and also with concrete cylinders have 100 diameters and 200mm height. The compressive strength tests performed to six standard cubes and six standard cylindrical specimens at 7 and 28 days ages of hardened concrete. Test results for both ages of plain concrete samples are listed in **Table 4**. The test results for both cubes and cylindrical concrete specimens were performed according to the British Standards **BS 1881-116, 1983)** and **ASTM C39/C39M, 2018,** respectively. The compression failure mode of all cubes concrete specimens was satisfactory according to the aforementioned standards and specifications, as shown in **Fig. 4.**



(a) Testing concrete cubes

(b) Satisfactory failure mode according to BS 1881-116, 1983

Figure 4. Compression test of concrete cubes.

Table 4. Compressive test results of concrete specimens.

Sample No.	Standard Cylinders Compressive strength, according to ASTM C39/C39M (2018), MPa		Sample No.	Standard Cubes Compressive strength according to BS 1881-116 (1983), MPa	
	7 days	28 days		7 days	28 days
Cy-50-01	33.15	-	Cu-50-01	40.65	-
Cy-50-02	33.67	-	Cu-50-02	39.28	-

Cy-50-03	33.91	-	Cu-50-03	39.15	-
Cy-50-04	-	44.65	Cu-50-04	-	54.53
Cy-50-05	-	45.25	Cu-50-05	-	54.94
Cy-50-06	-	45.98	Cu-50-06	-	53.92
Average	33.58	45.29	Average	39.69	54.46

3.3 Segmental Beam Assemblage

Segmental beams assemblage were conducted after 28 days from casting concrete segments following the process displayed in **Fig. 5**. The assemblage of beam's segments initiated by placing the seven segments on thick and level timber formwork by considering the straight longitudinal alignments of the beams (in some beams, the interface or substrate surface of the concrete was grinded and in another left to be uneven). Then, an insulation tape was applied on segments joints to ensure no penetration of epoxy raisin, and hence, the segments were not agglutinated as shown in **Fig. 5 (a)**. After that, segments were tightened with the particular mechanism to minimize the thickness of the void between adjacent concrete segments. Next step, CFRP laminate with a specific length (L) was placed on the segments temporarily after marking its longitudinal position on concrete segments as shown in **Fig. 5 (b)**. Later on, epoxy resin was mixed using slow speed electric drill with a maximum speed of 300 rpm with mixer spindle attached and according to manufacturer recommendations for at least 3 min to ensure a homogeneous epoxy resin as shown in **Fig. 5 (c)**.

Next, epoxy resin was applied using 50mm width trowel within marked margins, which have a specific layer thickness, as shown in **Fig. 5 (d)** (noting that the thickness of the epoxy resin is one of the parameters considered in this study). Last step, the CFRP laminate with a specific length was laid on the epoxy resin layer and pressed firmly by special rubber roller, as shown in **Fig. 5 (e)**. The completed segmental beam left into position for more than 24 hours and avoided any vibrations, as shown in **Fig. 5 (f)**.

3.4 Control Beam Fabrication

Reference RC beam was cast from the same concrete patches of concrete segments used in the assemblage of the segmental beam. Control beam clear span is 1000 mm, and the overall span length is 1100 mm and with rectangular cross-section 100mm x 100mm. The beam was left for curing for 28 days before testing.

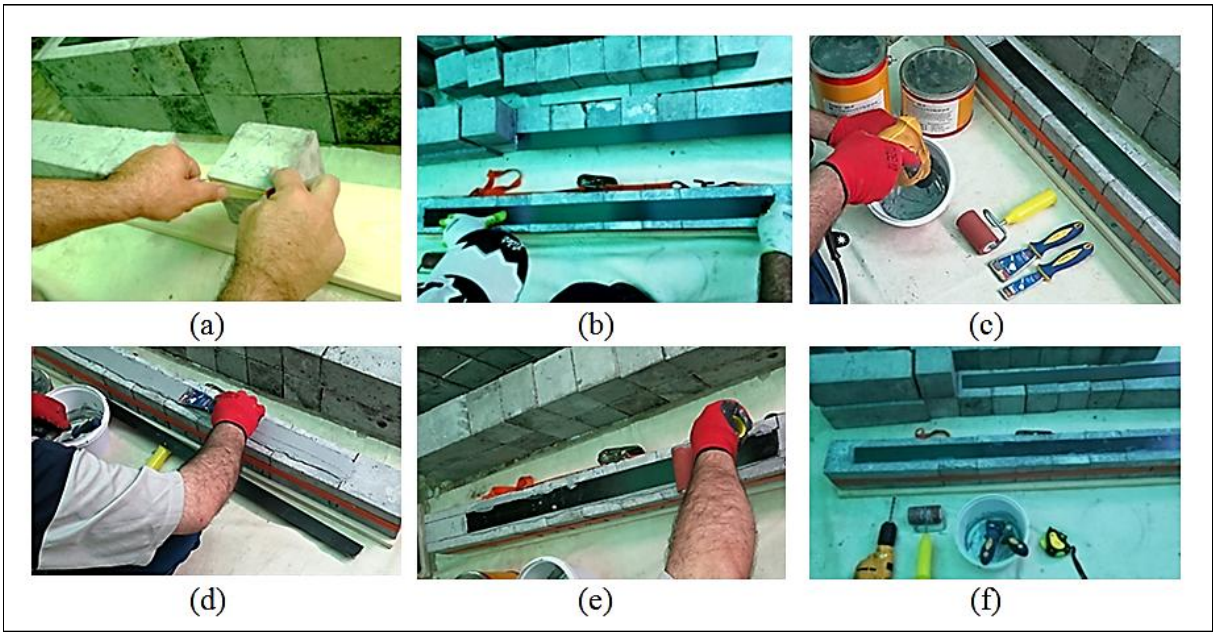


Figure 5. Segmental beams assemblage process.

3.5 Test Setup and Instrumentations

Testing of pultruded EBR CFRP reinforced segmental beams conducted in the Structural Lab of Civil Engineering Department/ College of Engineering / University of Baghdad. The segmental beam was subjected to two points of load testing. The span of loading changed for each case of studied segmental beams. The point loads in all cases were within the outer prism segments to obtain a larger pure bending span. Two simply supports were positioned and spaced 1000 mm were used to support segmental beams. Load cell with a capacity of 5-ton force was placed under the manually operated hydraulic jack and at the center of steel beam IPE180. The steel beam was selected to be rigid to spread and transfer load from the manually operated hydraulic jack to the testing specimens. Dial gauge with a capacity of 25 mm and precision of 0.01 mm was placed under the beam to measure mid-span deflection. The advantage of the test setup is that by applying a single vertical load, so the steel beam will be subdivided into two point loads and hence the specimen is subjected to pure bending as shown in **Fig. 6 (a)**. The similar test setup was repeated for RC reference beam as shown in **Fig. 6 (b)**.


(a) (b)

Figure 6. Specimens testing, (a) segmental beams (b) reference beam.

4. MODIFIED ACI 440.2R-17 DESIGN PROCEDURE OF EBR FRP SYSTEMS

Two assumptions were used to apply ACI 440.2R-17 [20] procedure in the design of segmental beams reinforced with EBR CFRP laminates, and to calculate the ultimate load carrying capacity of beams;

- **a.** The segmental beams will consider being continuous with cross-section dimensions (0.1m x 0.1m).
- **b.** Debonding controls ultimate strength analysis of the FRP system.

The first assumptions were applicable to segmental beams with full adhered adjacent segments at the interface between them (this case was studied and will be illustrated in details) while the second assumption applies to all studied cases. This was proved from the design calculations, which resulted in a design failure load to be 31.67 KN and will be compared with the experimental results later on.

5. RESULTS AND DISCUSSION

Six simple-supported segmental beams were experimentally tested to study the flexural behavior of pultruded segmental beams and compared with the seventh RC control beam. The studied parameters are the development length of CFRP laminates, substrate condition (whether it is grinded or rough substrate), the thickness of epoxy resin layer (the thickness of epoxy layer measured by using microscope), and segments interface condition (whether completely adhered with epoxy resin or not adhered) as listed in details in **Table 5**.

Table 5. Details of tested beams

Beam Designation	Length of EBR CFRP laminate (mm)	Substrate surface condition	Segments interface condition	The thickness of epoxy resin (mm)
CB1-ORCB	0	NA	NA	NA
SB1-CFRP-800-US-NA-2.0	800	Rough	No adhesion	2.0
SB2-CFRP-800-GS-NA-2.0	800	Grinded	No adhesion	2.0

SB3-CFRP-800-GS-NA-2.5	800	Grinded	No adhesion	2.5
SB4-CFRP-800-GS-FA-2.0	800	Grinded	Full adhesion	2.0
SB5-CFRP-950-GS-NA-2.0	950	Grinded	No adhesion	2.0
SB6-CFRP-950-GS-FA-2.0	950	Grinded	Full adhesion	2.0

The first cracking load, ultimate load, mid-span deflection corresponds to first cracking load, and maximum mid-span deflection was recorded to all segmental beams in addition to control beam and indexed in **Table 6**. Furthermore, the decreasing percentage of first cracking and ultimate loads regarding the control beam is also highlighted in **Table 6.**

Table 6. Specimens test results.

Beam Designation	First cracking load, KN	Decreasing of first cracking load, (%)	Ultimate load, KN	Decreasing of ultimate load, (%)	Mid-span deflection at first cracking load, mm	Maximum mid-span deflection, mm
CB1-ORCB	34.34	Ref.	38.95	Ref.	5.01	13.75
SB1-CFRP-800-US-NA-2.0	13.92	59	19.12	51	4.67	7.05
SB2-CFRP-800-GS-NA-2.0	15.73	54	21	46	4.16	6.66
SB3-CFRP-800-GS-NA-2.5	15.77	54	21.64	44	3.94	6.5
SB4-CFRP-800-GS-FA-2.0	22.66	34	29.56	24	3.12	4.65
SB5-CFRP-950-GS-NA-2.0	20.87	39	29.18	25	3.96	5. 4
SB6-CFRP-950-GS-FA-2.0	26.38	23	33.51	14	2.95	4.4

5.1 Failure Modes

As all segmental beams and the control beam specimens are symmetrical and subject to two point loads. Furthermore, all the beams were monitored, and the load corresponds to the first crack, and the ultimate load was recorded. Moreover, the width of the 1st crack which corresponded to cracking load also measured by using crack width ruler as shown in **Fig. 7.**

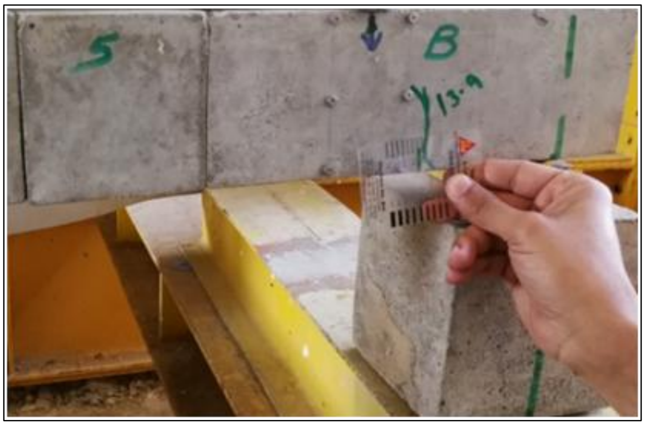


Figure 7. Measurement of first crack width

5.1.1 Tension cracks initiation

The tension cracks initiate in control beam with designation CB1-ORCB at the soffit and precisely at the mid-span. With loading progress, several cracks appeared (tension, diagonal tension) and extended towards the compression zone, as shown in **Fig. 8**. In contrary, no tension cracks were developed in the segmental beam specimens. This due to the existence of EBR-CFRP laminates, which is bonded at the extreme tension fibers and prevents the formation of flexural cracks in the segmental beams. Furthermore, the tensile strength of EBR-CFRP laminates is much more than four times than conventional steel reinforcement, and this causes the propagation of diagonal shear cracks at the verge of EBR-CFRP laminates which will be discussed in the next section.

Figure 8. Cracks Propagation in control beam specimen.

5.1.2 Diagonal shear cracks initiation

During the test, diagonal shear cracks were generated symmetrically for all beams. The diagonal shear cracks were initiated from specimen soffit and specifically at the verge of EBR CFRP laminates in both of 1st and 2nd segments which are expected as these extremities blocks were unreinforced completely with EBR CFRP laminate and in the region of application of loading as shown in **Fig. 9**.

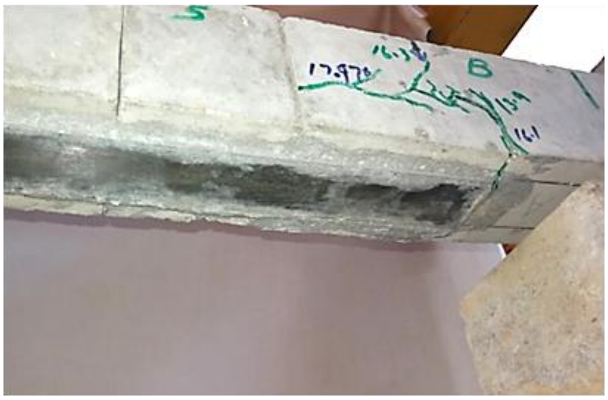


Figure 9. Cracks initiation in segmental beams at the verge of EBR CFRP laminates.

In four of the segmental beam specimens namely (SB1-CFRP-800-US-NA-2.0, SB2-CFRP-800-GS-NA-2.0, SB3-CFRP-800-GS-NA-2.5, SB5-CFRP-950-GS-NA-2.0), diagonal shear cracks were propagated diagonally towards the adjacent segment which is the weakest nearby region (no bond over the depth between them except the EBR CFRP laminate which is at specimen soffit) as shown in **Fig. 10**.

In the other two specimens, namely SB4-CFRP-800-GS-FA-2.0 and SB6-CFRP-950-GS-FA-2.0, where there was full adhesion between all concrete segments, the propagation of cracks is different. The diagonal shear cracks were inclined following a single path, and it was extended from beam soffit (at the verge of EBR CFRP laminates) towards the point load only which was due to the extra strength added by adhering concrete segments which change the failure cracking pattern and as shown in **Fig. 11.**

Figure 10. Cracks propagation and failure mode of beams with no adhesion at segments interface.

Figure 11. Cracks propagation and failure mode of beams with full adhesion at segments interface.

The initiation of first cracks in all specimens and the corresponding loading condition is shown in **Fig. 12**. The overall behavior of segmental beams indicates the increase of first cracking loading with the increase of the length EBR CFRP laminates which means the increasing of bond length to a sufficient value, in general, will increase the load carrying capacity. The increase was in bond length not necessary leads to an increase in the anchorage force and hence increasing load carrying capacity which is an important concept and in good agreements with previous researchers by **Meier, 1995** and by **Hosseini and Mostofinejad, 2014.**

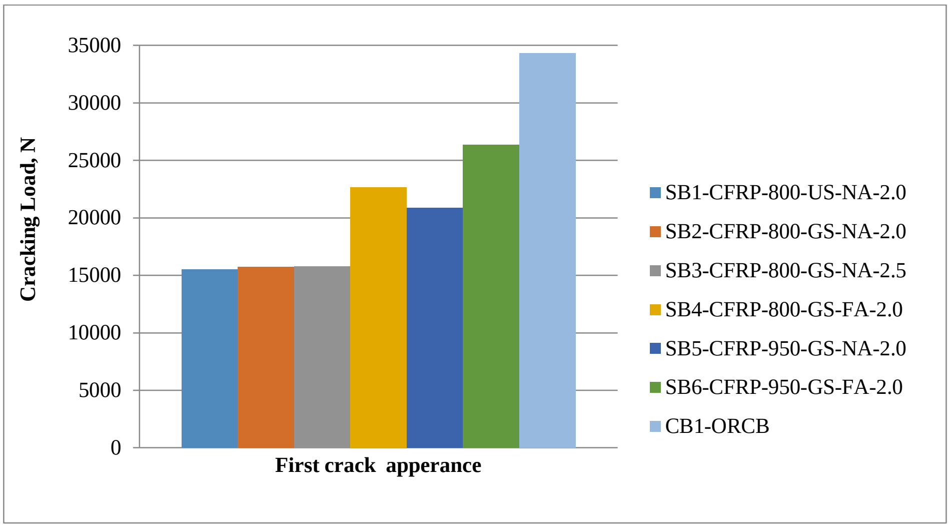


Figure 12. Cracks initiation vs. cracking load.

5.2 Effects of Fabrication Parameters on the Behaviour of Segmental Beams

5.2.1 Effect of surface grinding of concrete blocks

The effect of grinding the bonding surface between concrete segments and EBR CFRP laminates (grinded or un-grinded "rough" surface of concrete segments) was also focused. Segmental beam SB2-CFRP-800-GS-NA-2.0 slightly exhibited high resistance against cracks initiation under both service loads and ultimate loads than SB1-CFRP-800-US-NA-2.0. The increase in service and ultimate strength of segmental beam specimen SB2-CFRP-800-GS-NA-2.0 is about 13% and 9.8% than SB1-CFRP-800-RS-NA-2.0, respectively. The grinding of the bonding surface removes the unevenness in concrete blocks and hence the achievement of a laitance and open-textured surface, which enhanced the bonding of EBR CFRP fabrics. However, the enhancement in the load carrying capacity by grinding bonded surface beam was so limited.

5.2.2 Effect of increasing epoxy resin thickness

The increasing of epoxy resin thickness was also studied in this research. It is noticed that the increasing of epoxy thickness from 2.0mm to 2.5mm as in beams specimens SB2-CFRP-800-GS-NA-2.0 and SB3-CFRP-800-GS-NA-2.5, respectively does not give a noticeable change in service loads and it was limited to 0.25% only. However, under ultimate loads, the case was slightly different, and the increase in ultimate carrying capacity due to the change in this parameter is about 3%. Moreover, no debonding of EBR CFRP laminates take place in both considered segmental beams. This behavior is explained as the failure of segmental beams is not related to epoxy resin thickness, and slight change may result when using a thicker layer of epoxy which verified from the failure mode without debonding of EBR CFRP laminates. Even though, and for both loading stages, the results give good agreement with previous findings by **Triantafillou, 199** and **Choi, et al., 2007.**

5.2.3 Effect of adhering of segmental blocks

Moreover, it noted that the adhering of concrete segments would delay the initiation of shear cracks in addition to an increase in both service and ultimate loads. For example, segmental beams SB2-CFRP-800-GS-NA-2.0 in comparison with SB4-CFRP-800-GS-FA-2.0, the later exhibited considerable increase in strength which was about 44% and 40.76% greater than the prior under both of service and ultimate loading stages, respectively. Noting that, both of the beams are identical except adhering segments interfaces for the segmental beam SB4-CFRP-800-GS-FA-2.0. Similarly, if compared segmental beams specimens SB5-CFRP-950-GS-NA-2.0 and SB6-CFRP-950-GS-FA-2.0, the increases of service and ultimate loads in the last beam about 26.4% and 16.34%, respectively than the prior segmental beam.

5.2.4 Effect of bonding length of EBR CFRP laminates

The effect of the bonding length of CFRP was also studied. The first case by considering designated specimens SB2-CFRP-800-GS-NA-2.0 and SB5-CFRP-950-GS-NA-2.0. Both beams fabricated with no adhering between concrete segments, and CFRP bonding surface was grinded except the bonding length was increased 18% in SB5-CFRP-950-GS-NA-2.0. The test indicated an enhancement in the first crack load and failure load about 32% and 39%, respectively.

The second studied case by considering segmental beams SB4-CFRP-800-GS-FA-2.0 and SB6-CFRP-950-GS-FA-2.0. Both beams fabricated with no adhering between concrete segments, and CFRP bonding surface was grinded except the bonding length was increased 18% in SB6-CFRP-950-GS-FA-2.0. The test increased the first crack load and failure load about 16.4% and 13.36%, respectively.

For both cases above, increasing the bonding length to 950 mm will limit the unbonded zone to be only 25 mm from the face of supports (as the precise span of segmental beams is 1000 mm length). Therefore, the enhancement in both cases is explained by liming the zone of cracks initiation as it was shifted to the support, which provided an extra shear resistance against cracking. Reminding that diagonal shear cracks in segmental beams initiated at the end of EBR CFRP laminates.

5.2.5 Efficiency of bonding length of EBR CFRP laminates vs. the adhering of concrete segments

The significant thing among all of the tested parameters is the comparison of service and ultimate loads of specimen SB4-CFRP-800-GS-FA-2.0 and SB5-CFRP-950-GS-NA-2.0. The prior segmental beam SB4-CFRP-800-GS-FA-2.0 carried higher service load about 8.6% and higher ultimate load about 1.3% than SB5-CFRP-950-GS-NA-2.0 despite that the later have longer EBR CFRP laminates about 18% longer. That means the characteristic property of full adhesion of the interface of concrete segments in segmental beam SB4-CFRP-800-GS-FA-2.0 exceeds the characteristic property of longer EBR CFRP laminates.

From **Fig. 12** and **Fig. 13**, it is seen that ordinary RC control beam specimen CB1-ORCB sustains higher service and ultimate loads until failure. The service load carrying capacity of RC control beam is in the range of (30.17% - 146%) of segmental beam specimens while the ultimate load carrying capacity of RC control beam is in the range of (16.3 %- 103.7 %).

As stated previously, the ultimate design load by modified ACI 440.2R-17 design and construction procedure of EBR FRP systems will be compared with the experimental results of testing segmental beams specimens. The modified design value was 31.67 KN, while the resulted test values varied according to several studied parameters. When focusing on both results of segmental beams, namely SB4-CFRP-800-GS-FA-2.0 and SB6-CFRP-950-GS-FA-2.0 as they resist an ultimate load of 29.56 KN and 33.51 KN, respectively, as these cases comply all of the modified design assumptions. Segmental beam SB4-CFRP-800-GS-FA-2.0 test resulted in 93.3% from the design value, and hence it is considered an upper bound, and segmental beam SB6-CFRP-950-GS-FA-2.0 test resulted in 105.8% from the design value, and thus it is regarded as a lower bound or conservative and safe value.

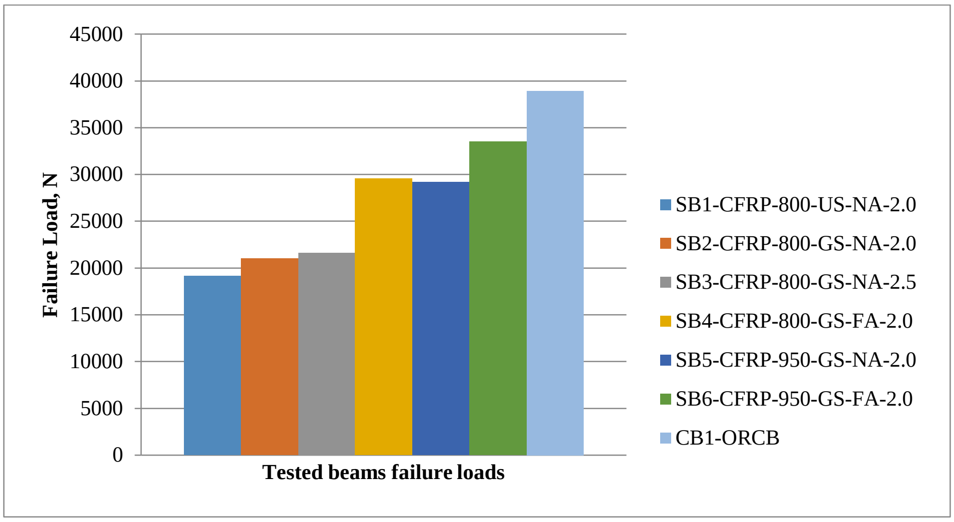


Figure 13. Ultimate failure loading for beams specimen.

5.3 Debonding of EBR CFRP Reinforcing Laminates

Debonding of EBR CFRP laminate also monitored, and it noticed that partial debonding happened at the interface between the hardened epoxy resin and concrete segments (specifically on the interface between first and second segmental portions) of beam SB5-CFRP-950-GS-NA-2.0 as shown in **Fig. 14**. This case was unique among all tested segmental beams specimens, and it recorded at a loading value about 20.5 KN, which is very close to the cracking load value 20.87 KN. The debonding of EBR CFRP laminate may interpret from the aforementioned significant note concern this beam when compared with segmental beam SB4-CFRP-800-GS-FA-2.0 in section 5.1.

Figure 14. Partial debonding of EBR-CFRP in beam SB5-CFRP-950-GS-NA-2.0.

5.4 Load Vs. Deflection Behavior of Beams Specimens

The response of all specimen beams under loading until the failure is shown in **Fig. 15**. The values of ultimate loads and the corresponding mid-span deflection were listed previously in **Table 5**. All of the segmental beams behave linearly until ultimate loadings. From **Fig. 15**, it is also noticed that the RC control beam CB1-ORCB exhibited a ductile behavior on the contrary of segmental beam specimens which does not show any ductility. This explained from the failure mode as the propagations of tension cracks in the control beam result the ductile behavior. On the other hand, the existence of EBR CFRP laminates in segmental beams prevents tension cracks formation and resulted in the propagation of diagonal shear cracks, which leads to beams failure and hence limited the ductile behavior. However, this is expected due to materials individual behavior of composite segmental beam section as both of plain concrete and CFRP composites are brittle and this is reflected on the behavior of segmental beam specimens in this study.

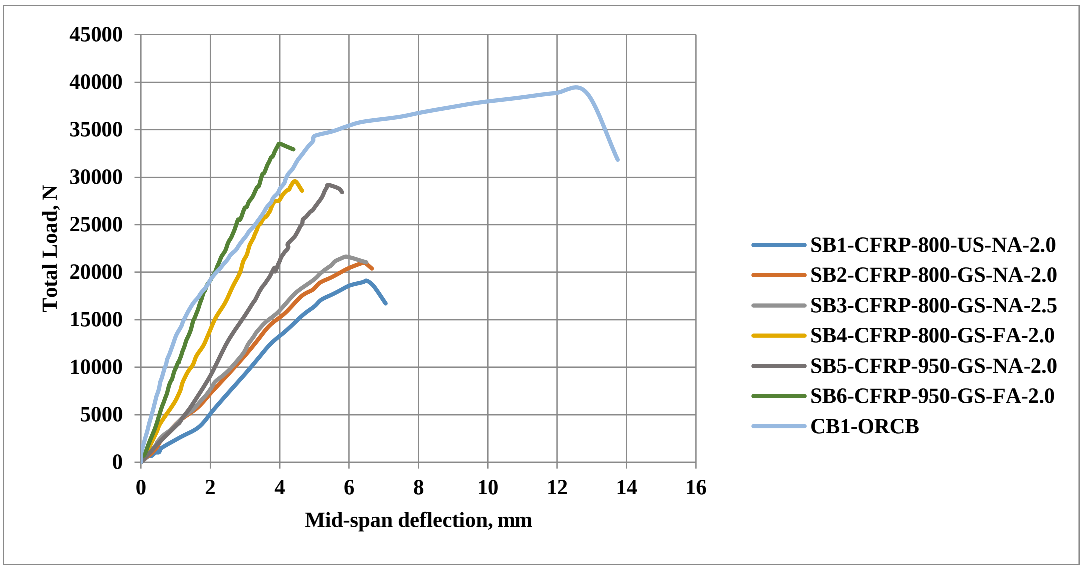


Figure 15. Load-displacement response for tested beams specimens.

6. CONCLUSIONS AND RECOMMENDATIONS

Results obtained from this experimental study indicated that the external composite system performed by using EBR CFRP laminates as a main flexural reinforcement is effective and successful. That means using EBR CFRP laminates is not limited to only strengthening and retrofitting purposes. Also, the failure mode of small scale segmental beams is different from ordinary RC beams. No flexural cracks appeared in the segmental beams while it initially formed in RC beams for the studied cases. Regarding the studied parameters, it is concluded that increasing epoxy resin thickness for bonding CFRP laminates about 25% did not considerably affect the load carrying capacity of segmental beams as it was limited to 13%. Additionally, increase bonding length of EBR CFRP laminates about 18% enhanced beam carrying capacity within the range (12-39) %. Moreover, the efficiency of adhering segments-to-segment interface was the most significant parameter and considerably enhanced the load carrying capacity of about 40 %.

Further researches on segmental beams are recommended. Also, more experimental and analytical investigations to be conducted to measure extra parameters such as using EBR CFRP laminate in the extreme top fibers in addition to the soffit and studying large-scale segmental beams.

REFERENCES

- Al-Sherrawi, M.A., Allawi, A.A., Al-Bayati, B. H., and El-Zohairy, A., 2018, *Behavior of precast prestressed concrete segmental beams*, Civil Engineering Journal, 4(3), 488-496.

- American Concrete Institute ACI 318M-14, 2014, *Building Code Requirements for Structural Concrete and Commentary*, Farmington Hills, MI 48331.

- American Concrete Institute ACI-440.2R-17, 2017, *Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures*, Farmington Hills, MI 48331.

- American Society for Testing and Materials ASTM A615 / A615M - 18e1, 2018, *Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement,* West Conshohocken, PA 19428-2959, United States of America.

- American Society for Testing and Materials ASTM C39 / C39M – 18, 2018, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*, West Conshohocken, PA, United States of America.

- Angel, C. A., Ramos, G., and Juan, R. C., 2002, *Testing of externally prestressed concrete beams*, Engineering Structures, 24, 73–84.

- British Standards BS 1881-116, 1983, *Part 116: Method for Determination of Compressive Strength of Concrete Cubes*, BSI.

- Central Organization for Standardization and Control Quality I.Q.S 2091, 1999, *Carbon Steel Bars for the Reinforcement of Concrete*, Baghdad, Iraq.

- Choi, K., Meshgin, P., and Taha, M. M. R., 2007, *Shear creep of epoxy at the concrete–FRP interfaces,* Composites Part B: Engineering, 38, 772–780.

- Dong-Hui, Yang and Ting-Hua, Yi, 2016, *Combined shear and bending behavior of joints in precast concrete segmental beams with external tendons*, The 2016 structures congress (structures16), Korea.

- Federation International of Concrete FIB, 2001, *Externally bonded FRP reinforcement for RC structures*, Bulletin 14, Lausanne, Switzerland.

- Ghernouti, Y., Rabehi, B., Benhamna, A. and Hadj, M. A., 2014, *Strengthening of concrete beams by CFRP Experimental study and finite element analysis*, Journal of Building Materials and Structures, 1, 47-57.

- Jiang, H., Li, Y., Liu, A., John, Z., ASCE, F., Chen, L., and Chen, Y., 2018, *Shear Behavior of Precast Concrete Segmental Beams with External Tendons,* Journal of Bridge Engineering, 23(8), 1-16.

- Hanoon, A. N., Jaafar, M. S., Hejazi, F., & Aziz, F. N. A., 2017, *Strut-and-tie model for externally bonded CFRP-strengthened reinforced concrete deep beams based on particle swarm optimization algorithm: CFRP debonding and rupture,* Construction and Building Materials, 147, 428-447.

- Hashemi, S. and Al-Mahaidi, R., 2014, *Strengthening of concrete beams by CFRP: Experimental study and finite element analysis*, The Third Asia-Pacific Conference on FRP in Structures (APFIS), 1, 47-57.

- Hosseini, A., and Mostofinejad, D., 2014, *Effective bond length of FRP-to-concrete adhesively-bonded joints: Experimental evaluation of existing models*, International Journal of Adhesion & Adhesives, 48, 150–158.

- Italian National Research Council CNR-DT200, 2004, *Guide for the design and construction of externally bonded FRP systems for strengthening existing structures*, Rome.

- Meier, U., 1995, *Strengthening of structures using carbon fibre/epoxy composites*, Construction and Building Materials, 9(6), 341-351.

- Pellegrino, C, and Sena-Cruz, J., 2016, *Design Procedures for the Use of Composites in Strengthening of Reinforced Concrete Structures*, *RILEM State-of-the-Art Reports*, *Technical Committee 234-DUC*, Springer Dordrecht Heidelberg New York.

- Said, A. I, and Abdulwahed, L. R., 2018, *Experimental evaluation of tendon stress in externally prestressed composite ultra-high performance concrete-steel girder,* ARPN Journal of Engineering and Applied Sciences, 13(18), 4840-4849.

- Sika Group, 2009. *Sika CarboDur Plates Pultruded carbon fiber plates for structural strengthening.* Available: https://irn.sika.com/dms/getdocument.get/Carbodur.pdf.

- Sika Group, 2017. *Sikadur-30 LP - Thixotropic adhesive for bonding reinforcement*. Available: https://gcc.sika.com/dms/getdocument.get/Sikadur-30LP_PDS.pdf

- Triantafillou, T. C., 1998. *Strengthening of masonry structures using epoxy-bonded FRP laminates*, Journal of Composites for Construction. 2(2), 96-104.

- Xu Yang, Wan-Yang Gao, Jian-Guo Dai, Zhou-Dao Lu, Ke-Quan Yu., 2018, *Flexural strengthening of RC beams with CFRP grid-reinforced ECC matrix*, Composite Structures, 189, 9–26.

- Zhou, X., Mickleborough, N., and Li, Z., 2005, *Shear strength of joints in precast concrete segmental bridges*, ACI Structural Journal, 102-S01, 3-11.