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Investigation the bond between concrete and FRP strip/sheet by using pull-out test to enhancement the External bonded System

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الملخص العربى :

توضح هذه الدراسة العمليه خصائص التماسك من خلال اختبار الشد للعينات التى تمت تقويتها بالتدعيم الخارجى. نظرا لمميزات هذه الطريقة مثل سهولة وسرعة التطبيق على الرغم من وجود ظاهرة عدم التماسك بين الفيبر وسطح الخرسانة لهذه الطريقة . حديثا يتم عمل حفر فى الخرسانة ثم يتم عمل التدعيم بدلا من وضع الفيبر على سطح الخرسانة مباشرا. قد اثبتت هذة التقنية (التدعيم الخارجى للعناصر الخرسانية بعد عمل حفر فى الطبقة السطحية للخرسانة) تحسين فى السعة التحميلية او تأخير فصل الفيبر عن سطح الخرسانة. لذللك يتم استخدام هذة التقنية فى الدراسة الحالية البرنامج العملى لهذة الدراسة يحتوى على ستة كمرات خرسانية ويتم تدعيمها بألواح وشيتات من الفيبر الكاربونى والزجاجى وايضا البازلتى ثم يتم اختبار الشد للعينات وحيث يتم مقارنة النتائج المعملية بنتائج الدراسة التحليلية (التحليل بالعناصر المحددة الغير خطية). اثبتت الدراسة المعملية ان تقنية التدعيم بحفر الخرسانة بفاعليتها القوية فى زيادة التماسك بين الفيبر وسطح الخرسانة وبالتالى تزيد السعة التحيلية للعناصر الانشائية المقواة بالفيبر.

Abstract

This paper presents an experimental bond investigation through pullout testing by externally bonded reinforcement (EBR) technique for strengthening of reinforced concrete (RC) structure. The technique has certain benefits such as simple and rapid installation; therefore the main problem is premature deponding of FRP composite from concrete substrate. Recently, grooving method (GM) has been introduced as an alternative to conventional EBR technique. Grooving with the technique of externally bonded strengthening on grooves (EBROG) has enhanced the results in load capacity or, in some cases, completely elimination of undesirable debonding failure in flexural/shear strengthened RC beams. Consequently, the technique of externally bonded reinforcement on grooves (EBROG) used in the current study, sex concrete prism were adhered by CFRP strip and Carbon, Glass, Basalt sheet, then the specimens were subjected to pull-out test and the results were compared between experimental and analytical result (ANSYS program). Experimental results of the current study strongly verify the capability of GM for strengthening RC members to completely

elimination the debonding failure and increase the bond between the FRP and concrete surface thus increase the load capacity.

1. Introduction

Many old concrete structures need strengthening due to new codes' requirements as ACI 440-17[1] and increasing of allowable loads. The technique of externally bonding FRP laminates is applied more due to simple and rapid installation, and becomes an attractive solution for strengthening the RC structures [2, 3, 4]. Bonding FRP sheets or strips to the tension face of a RC flexural member with fibers oriented along the length of the member will provide an increase in flexural strength. The primary deficiency of externally bonded FRP is the premature debonding of the FRP laminates from the concrete substrate prior to the development of the full strength of the FRP fibers [5–6]. When applying this strengthening technique to enhance the flexural capacity, using grooving method (GM) must be applied to avoid the premature debonding and enhancing from transfers the load carried by the FRP laminates directly into the structure [7]. Grooving method (GM) consisted of cutting grooves into tension face of concrete beams, filling them with proper epoxy resin and bonding FRP sheets or strips on the member's surface over the filled grooves, has been recently introduced by Mostofinejad and Mahmoudabadi [8], which increase the ultimate loads up to 80% compared with conventional EBR strengthened specimens [8]. Grooving method in its original form was later referred as externally bonded reinforcement on grooves (EBROG) technique; and its performance for flexural strengthening of RC beams using multilayer CFRP sheets was more investigated by Mostofinejad et al. [8] and promising results were reported in completely elimination of debonding failure and, subsequently, reaching full capacity of composite materials. Recently, Mostofinejad and Tabatabaei Kashani [9] investigated the performance of EBROG technique for shear strengthening of RC beams. Based on their experimental study, using vertical grooves as a substitute to conventional EBR technique prior to shear strengthening of beams by CFRP sheets changed the failure mode from shear to flexural and increased ultimate load capacity of the beams up to 15 percent compared to EBR strengthened specimens; while no debonding was reported in CFRP shear reinforcements [9].

Despite certain benefits of the GM for flexural/shear strengthening of RC members by FRP sheets such as obviate the need for costly and time-consuming traditional surface preparation and, reduce the cost of strengthening projects due to postponing or, in some cases, completely elimination of debonding; no research has been conducted up to now to investigate bond behavior of FRP sheets attached to concrete using GM in the form of EBROG technique. Consequently, the main intention of the current study is to experimentally investigate the FRP-to-concrete bond behavior in GM by means of single-shear bond tests.

2. Experimental program

2.1 Test specimens

Ten concrete prisms with dimension of 150x150x300mm were cast and tested at structural laboratory of Helwan University Fig (1). To obtain a compressive strength of about 25MPa, to measure the compressive strength of the concrete, three 150x150x150mm cub specimens were also cast and tested after 28dayes. The specimens were designed as per standard conditions ASTM C192 and ASTM D3039 [10, 11] specimens details are shown in Table1.

2.2 Material properties

- Concrete: the concrete mix was prepared at the laboratory to provide nominal strength of 25MPa using type-1- Portland cement. The maximum aggregate size was 20mm to ensure good workability.
- Strengthening laminate: the strengthening laminate and sheet used in the current study are illustrated in Fig 2 and the mechanical properties are given in Table 2. Carbon fiber laminates of 50 mm width and 1.2 mm thickness were used in this research. The CFRP laminates used have an ultimate tensile strength of 3100MPa, modulus of elasticity of 165 GPa and ultimate strain of 1.4%.
- Epoxy adhesive: the manufacturer(sika) provides the mechanical properties of the epoxy, a two-component epoxy adhesive, Sikadur 330, was used for bonding FRP composite to the concrete substrate as well as for matrix phase of the FRP composite. Laminate adhesive with tensile strength and Young’s modulus of 32 MPa and 10 GPa, respectively. Mechanical properties of carbon fibers and epoxy resin utilized in this research are provided in Table 1 according to the manufacturer’s catalogue.

Table. 1. Specimens Details

Prism	Strengthening type	Strengthening Thickness(mm)	Effective length
P1	Carbon strips	1.2	200
P2	Carbon sheet	0.3	200
P3	Glass sheet	0.3	200
P4	Glass sheet	0.3	150
P5	Basalt sheet	0.3	200

Table 2 Mechanical properties of materials

Material	Strength		Modulus of elasticity	Ultimate strain
	Type	MPa	GPa	
Concrete	Compressive strength	25	20	0.003
Carbon laminate	Tensile strength	3100	165	0.0140
Carbon sheet	Tensile strength	3500	230	0.0167
Glass sheet	Tensile strength	3450	90	0.0214
Basalt sheet	Tensile strength	2700	95	0.0267

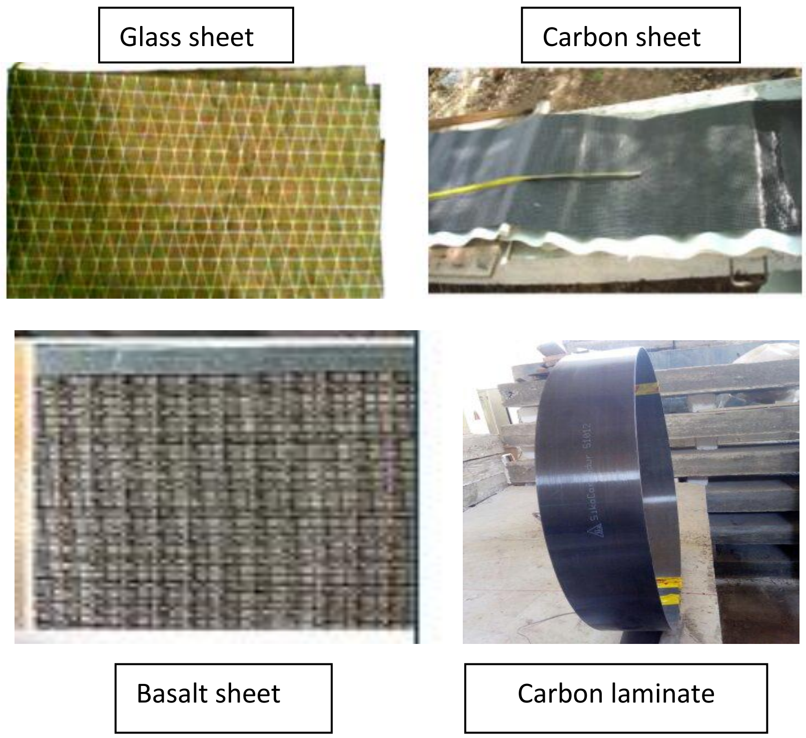


Fig. 2. Different strengthening laminates and sheets used in the current study

2.3 Testing layout and strengthening methods

Ten prism specimens were strengthened using GM in the form of EBROG technique and one specimen was strengthened by conventional EBR technique.

1- The factor considered in the present test program
2- - strengthening method.
3- - strengthening material type.
4- - Bond length150, 200mm.
5- - Increase FRP thicknes.

Strengthening method of EBROG technique

1-Mark the width and length groove.

2-Removed the first weak layer of the concrete surface by grinding hammer machine in selected size to achieve good bonding between the adhesive and the concrete Fig(3).

3-Cleaned the concrete surface with air jet or wire brush to remove dust.

4-Cutting the FRP sheet or strips by mechanical cutter, and the surface on each sides of the plate was cleaned with sika colma cleaner and white cloth to remove contaminates and carbon dust.

5-Put the FRP strips or sheet into the selected size and adhered to concrete surface using epoxy resin in wet layup procedure and supported it Fig(3).

Afterwards, all specimens were cured for at least 7 days in laboratorial condition before testing.

a. Marking line on prism b. Grinding and grinding tools c. Surface cleaning with the brush and hover

d. CFRP Surface preparation e. Adhered CFRP to concrete f. Supported CFRP

Figure (3): Strengthening method of EBROG technique

2.4 Test setup and instrumentation

All strengthened specimens were subjected to single-shear test by means of a 300 kN displacement control hydraulic jack, specially designed for single-shear bond test in structural laboratory of Hellwan University. All specimens supported by test setup special with pull out test machine, as shown in Fig (4). In order to eliminate stress concentration at the loaded edge of the concrete prism, a 50 mm unbonded zone was introduced along the interface between the CFRP sheet and the concrete surface. Similar setups for eliminating stress concentration in single-shear bond tests have been reported by other researches [12,13].

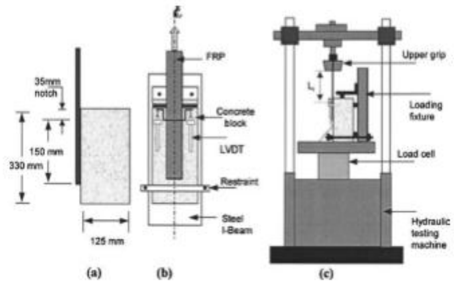


Figure (4) Specimen geometry and loading arrangement:(a)specimen dimentions;(b) loading fixture ; and (c) test setup

3 Results and Analysis

The failure modes of each specimen, as well as ultimate load and CFRP bond length are presented in Table 3. Moreover, since the relative displacement (slip) between CFRP reinforcement and concrete substrate is a key factor affecting FRP-to-concrete bond behavior, ultimate slip at loaded end of CFRP reinforcements for all tested specimens are also presented in Table 3.

Table 3. Result and analysis specimens

Prism labels	Prism cross section	Strengthening details	Ultimate load (KN)	Relative displacement(mm)	Failure mode
P1		Carbon laminate (GOM)	53.87	11.8	FRP- Rupture And debonding
P2		Carbon laminate (EBM)	23	11.78	FRP-debonding
P3		Carbon sheet	52.5	10.2	FRP-debonding
P4		Glass sheet (L=200mm)	51	11	FRP-debonding
P5		Glass sheet (L=150mm)	50	11.2	FRP-debonding
P6		Basalt sheet	52	10.5	FRP-Rupture

3.1Failure mode

EBR strengthened specimen failed due to debonding while all GM strengthened specimens failed by FRP rupture (Fig. 6), which strongly shows the excellent performance of GM. It was observed that EBR strengthened specimens failed due to concrete failure adjacent to the adhesive-concrete interface while a thin layer of concrete was attached to the debonded FRP strip. This type of failure is assumed not to be a strict ‘‘debonding’’ as failure occurs in concrete

Figure (6) failure mode of prisms

3.2 Load–slip behavior

Longer FRP bond length increases the ultimate load slip of the bonded joint and leads to a more ductile failure, however not observed increasing in the ultimate debonding load. As it is plotted in Fig (6), two major zones can be considered in load–slip diagrams. The first zone as a linear part from beginning of loading process up to a load of approximately 10 kN for specimens with EBR method and 12.6 kN for specimens with GM. The second zone for EBR specimens is where the load is approximately constant up to debonding. This zone for the specimens strengthened by GM linearly continues upward with a lower stiffness compared to that of the first zone, up to FRP rupture around a load of 53 kN.

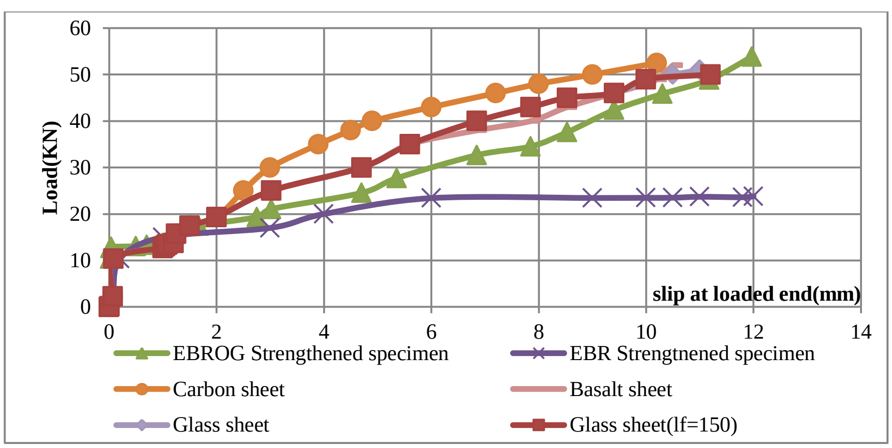


Figure (6): load-slip behavior

3.3Slip and strain profiles along CFRP reinforcements

Both EBR and GM specimens reached a maximum slip of 11.8 mm at their maximum load level, Pmax, which were equal to 23.8 kN and 53.87 kN, respectively. After Pmax, however, the CFRP strip which was externally bonded to EBR specimen experienced higher slip values along the whole bond length under approximately constant load (Fig. 7), and finally debonded from the concrete substrate. In GM specimen, however, only the first 90 mm of the CFRP strip experienced deformations and the slip profiles gradually increased up to FRP rupture at maximum load level, Pmax = 53.87 kN (Fig. 8). It can be concluded from Fig.(8) that due to high strength bond between CFRP strip and concrete substrate when using GM, the slip values sharply decrease toward the free end of the strip.

Strain profiles along bonded length of CFRP reinforcements are presented in Figs. 7 and 8 for specimens EBR and, respectively. The strain values are derived from slip profiles obtained LVDT analyses for the whole length of CFRP strips; except for the start point of bond length (x = 0) which were deduced directly from applied load values. It is due to local stress concentration at this point as previously mentioned by Yao et al. [14]. As it is illustrated in Fig. 7, upon reaching Pmax, only a limited length of the CFRP strip (about 70 mm) in EBR specimen resisted the applied load which strongly verifies the concept of effective bond length. However, after reaching Pmax, debonding rapidly propagated toward the free end of CFRP strip causing strain redistribution along the strip (Fig. 7). It may be noted here that similar strain profiles for EBR specimens were presented by Yao et al. [14].

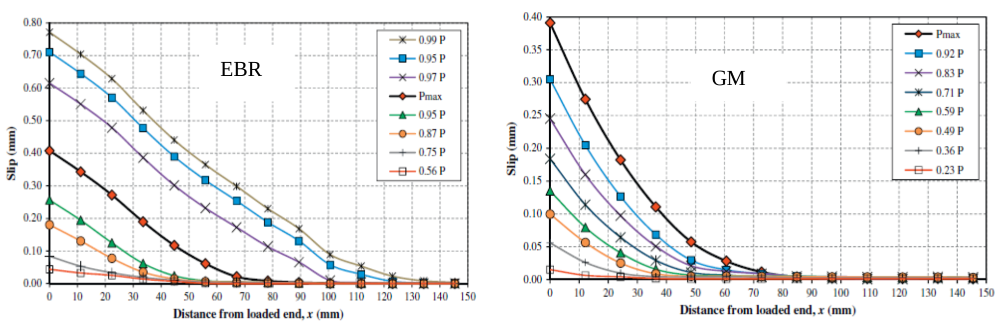


Figure (7): slip profiles corresponding to different load levels for specimen EBR and GM

4. Finite Element Analysis (Numerical modeling) Yao et al. [14]

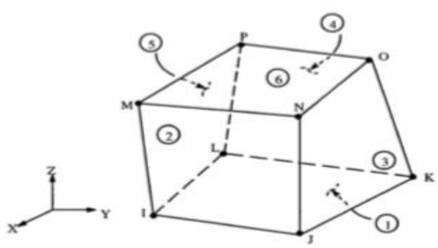
The main purpose of the numerical simulation is the representation of the concrete prism pull out test when conducted in slip control mode. Two different parameter strengthening material type and thickness, effective length, and were investigated by numerical modeling.

4.1 Element Type and Meshing (three dimensional model of the prism pull out test)

The finite element (FE) code ANSYS (2019) was used in this study. The experimental results were used to calibrate the FE models.

Concrete and resin was modeled using 3D 8-node solid elements (SOLID65). The main feature of this element is the ability to account for material nonlinearity. This element is capable of considering cracking in three perpendicular directions, plastic deformation and crushing, and creep. The element is defined by eight nodes having three translation degrees of freedom at each node in the x, y and z directions as shown in Fig. (9).

The SOLID185 element is used for modeling the CFRP composite. This element is defined by eight nodes having three degrees of freedom at each node; translations in the nodal x, y, and z directions. The element is capable of plasticity, hyper elasticity, stress stiffening, creep, large deflection, and large strain capabilities. SOLID185 element uses enhanced strain formulation, simplified enhanced strain formulation, or uniform reduced integration. The SOLID185 in the form of homogeneous structural solid is used in this study to model the Carbon fiber plate as shown in Fig. (10).



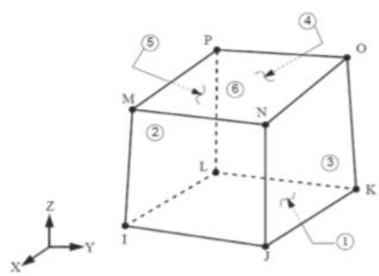


Figure (9): Solid 65 3D reinforced concrete solid element   Figure (10): Solid 185 3D Homogeneous Structural solid element, ANSYS (2019)

3. NUMERICAL (ANSYS) RESULTS OF LOAD-DEFLECTION BEHAVIOUR

FEA software ANSYS is adopted for predicting the load displacement response of the control and strengthened beams numerically. The mesh model defined 375 nodes and 47 elements. The program offers solid 65 for concrete prism element (Fig. 9) and solid185 for CFRP fabric element [11]. The element description, loading pattern and boundary conditions in FEA model (ANSYS) concrete prism is shown in Fig. (11). Comparisons of ultimate loads for experimental and numerical (ANSYS) results are shown in Table 4.

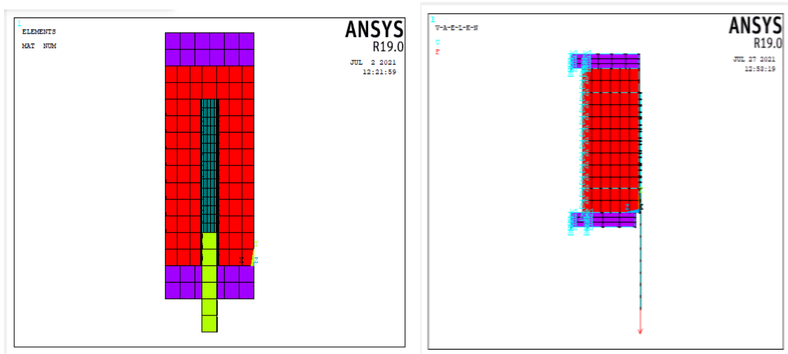


Figure (11): Element description, load pattern and boundary condition

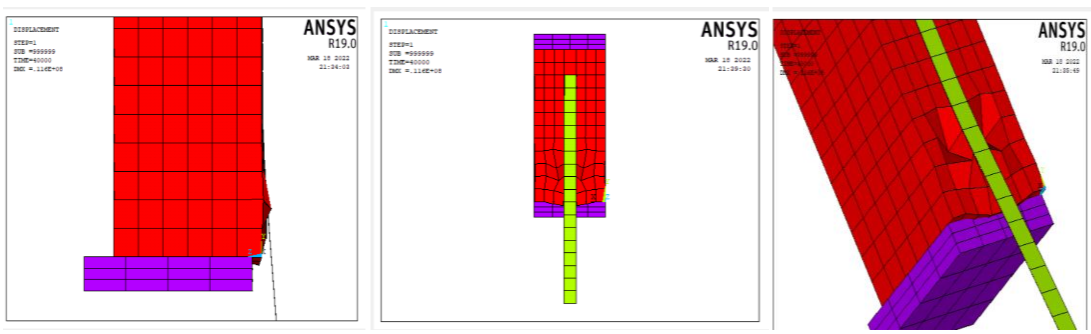
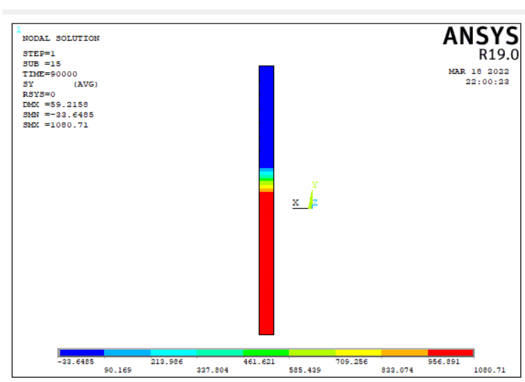


Figure (12): Mode failure



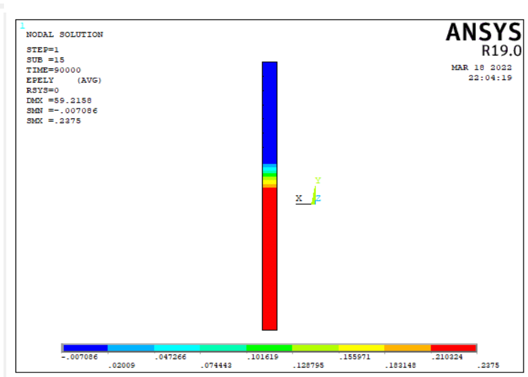


Figure (13) FRP Stress

Figure (13) FRP Strain

Table 4. Comparisons of ultimate loads for experimental and numerical (ANSYS) results

Prisms samples	Experimental	numerical	Ex/en
Pr1	53.87	55	0.98
Pr2	23.8	25	0.95
Pr3	52.5	54	0.97
Pr4	52	53	0.98
Pr5	51	52	0.98
Pr6	50	51	0.98

5. Conclusions

Performance of grooving method (GM) in the form of EBROG as an alternative to conventional EBR technique for bonding CFRP Sheets and strips to concrete surface was evaluated in this research. Ten concrete prisms were strengthened using EBR and EBROG techniques, and the strengthened specimens were subjected to single-shear bond test were used to investigate FRP-to-concrete bond behavior of strengthened specimens. Based on the experimental and ANSYS analyses results of the current study, the following conclusions can be drawn:

1-An average increase of 55.5% in ultimate load capacity of CFRP sheets attached to concrete prism specimens using GM was observed compared with those attached using conventional EBR technique. Furthermore, debonding failure was completely eliminated when EBROG technique was used, and all GM specimens failed due to FRP rupture regardless of grooves length. Conventional EBR strengthened specimen's failed due to debonding failure.

2. Cutting two 5 x 10 x 200 mm (width _ depth _ length) grooves into the concrete surface to surface preparation and also made the bond of FRP to concrete strong enough that the FRP composite reached its full tensile capacity.

3- With increasing the thickness of CFRP, the displacement decrease by 15%. But the ultimate bond loads not affect appear.

4- The bond load increase when use the higher stiffness of CFRP materials, but the displacement decrease.

5- The effective length (L_f=200mm) is adequate than (L_f=150mm).

6. Obtained strain profiles and strain fields in different load levels implied that debonding rapidly propagated along the CFRP strip after reaching ultimate load level in specimens strengthened by EBR technique. However, due to high stiffness bond of FRP to concrete when GM was used, only a limited length of the bonded CFRP strip experienced strain up to FRP rupture.

7-The three-dimensional nonlinear finite element model presented in this study by using the computer program (ANSYS V.19.1) is able to simulate the behavior of reinforced concrete slabs strengthened in flexural with EBR-CFRP. The numerical results were in good agreement.

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