

FLEXURAL STRENGTH OF RC CONTINUOUS BEAMS STRENGTHENED BY CFRP USING EBR AND EBROG METHODS: EXPERIMENTAL AND ANALYTICAL STUDY

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Abstract

Recently, a new proposed technique named; Externally Bonded Reinforcement on Grooves (EBROG) has been presented as a strengthening method to postpone or eliminate the undesirable debonding failure mode that is accompanying to Externally Bonded Reinforcement (EBR) method. This paper introduces an experimental and analytical study to evaluate the validity and accuracy of the formulas that were introduced by the standard codes and researchers, in estimating the ultimate load of RC continuous beams strengthened with carbon fiber reinforced polymer (CFRP) sheets in flexure. The experimental program includes testing of ten RC beams with cross section of (200×130) mm and two equal spans, each span has a 1050 mm length. The comparison between the ultimate load collected from the test results and that predicted using ten different analytical models is conducted. It is found that the ACI 440.2R-17 and most of other analytical models well predicted the ultimate load of RC beams strengthening with one layer of CFRP sheets using EBR, but most of these models significantly underestimate the ultimate load of tested beams that were strengthened using EBROG method. ACI, Shehata et al., and Teng et al. models give close predicted load to the experimental results in case of EBR beams strengthened with two layers.

Keywords:

Continuous RC Beams;
 Flexural Behavior;
 Strengthening Techniques;
 EBROG;
 EBR;
 CFRP Sheets;
 Analytical Models.

1 Introduction

Continuous are the widely used type of beams, which are utilized in the girder concrete bridges and also in the structures located in severe environments or in zones subjected to high levels of seismic. This may be related to exploiting the reserve strength due to the moments redistribution that occurs in case of the continuous beams, because of its structural redundancy. As the other structural concrete elements, the reinforced concrete beams need repair or strengthening during the serviceability life to improve their ability in supporting additional loads and enhance the deformation capacities. The reasons of requirement to this repairment including; insufficient reinforcement, utilizing low strength concrete, deteriorating the used materials in the reinforced concrete members, updating the initial design, and enhancing of the structure strength as a result of accidents, or earthquakes. At the few latest years, particularly since 2000s, the strengthening with external fiber reinforced polymer (FRP) plate/sheets can be utilized as a one of the available strengthening techniques. The FRP composites are available in many types, where the most common one is CFRP sheets, which can significantly enhance the flexural and shear load capacity of strengthened members[1]–[5].

In case of using the externally bonded reinforcement (EBR) as strengthening technique, the FRP sheets debonding was noted as the most common failure mode of strengthening members, that happens into two different forms; either end debonding or intermediate crack (IC) debonding[6]–[9] as in Figure (1). In the end debonding mode, the failure firstly occurs at the end of the FRP sheets due to highly concentration of bending and shear stresses, which then extends to the middle of the sheets[10]. In other hand, creating of flexural-shear cracks in the beam leads to initiating of IC debonding [11]. So that, a new technique had been proposed to overcome of de-bonding of FRP sheets. Externally bonded reinforcement on grooves (EBROG) technique has been developed by Mostofinejad & Mahmoudabadi

(2010) [12] to delay or sometime eliminate the FRP debonding because of the good contact between FRP and concrete surface [13]–[15].

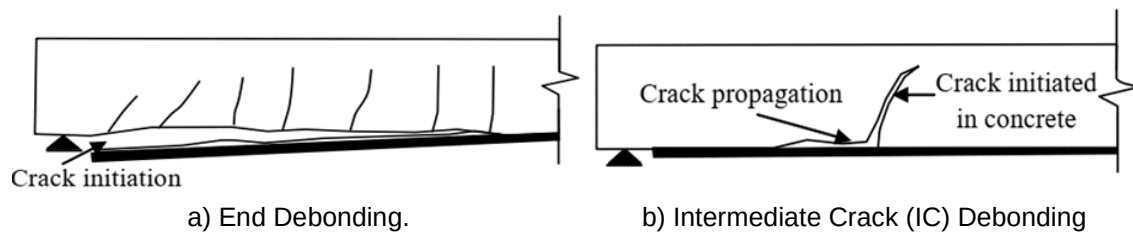


Fig. 1: Types of Debonding Mode of Failure.[16], [17].

Many experimental studies in which the tested specimens failed with debonding mode of failure, were presented by the researchers [18]–[22]. But, most of these researches investigated only load-displacement curves, while very limited ones interested to study the distribution of FRP strain during the testing duration and the sudden changes in the strain value of FRP sheets at the initiating cracks, in spite of the importance of them in the predicting of the loading capacity of RC members strengthened with FRP sheets. It seems difficult to locate the strain gauges along the FRP sheets length to collect the comprehensive strain data. So that, the finite element (FE) models are more applicable for this purpose. Up to now, large numbers of introduced studies used the FE models to more understand of the distribution of debonding strain of RC members strengthened with FRP sheets [23], [24].

Many of analytical models were presented and adopted by design codes [10];[23], [25]–[29], based on the available experimental and FE data. These models can be divided into two groups; the first one is an empirical formula, in which the needed parameters are corrected using experimental results, for this, it cannot reveal the behavior of debonding. The second group depends on the strain distribution along the FRP sheets that are collected from testing and FE data, these models seem inaccurate enough because of limitations of the testing data and the imperfections in the FE models [25], [28].

Generally, most of the design codes and previous analytical studied [30], [31] focused on simply supported beams strengthening with external FPR laminates although the many applications of this types of concrete members in situ. So that, much additional research is still necessary to have a full understanding on the structural behavior of continuous beams strengthening with external reinforcement under the effects of different factors. In this research, the comparison between the tested and predicted load carrying capacity using different analytical models to check the validity of these model to estimate the flexural load capacities of two-span continuous beams strengthening with CFRP sheets using ERPOG technique these tested in this study.

2 Debonding Strain of FRP System

The external bonding reinforcement can be used in enhancing of either flexural or shear strength of RC beams. In bending strengthening, the CFRP sheets bond on the tension face of RC beam, while the sheets lay along the beams sides in case of shear strengthening. In case of flexural strengthening, the beams fail in many different modes based on the combination of many factors as; member size, concrete compressive strength, tension reinforcement bars ratio, FRP characteristics, and strengthening techniques. The failure happens either due to the concrete crushing as a result to reaching the concrete strain (ϵ_c) at the extreme compression fiber to its ultimate value ($\epsilon_c = \epsilon_{cu} = 0.0035$), or the strain of CFRP sheets (ϵ_f) at the extreme tension fiber reaches to ultimate stress ($\epsilon_f = \epsilon_{fu}$) and CFRP rupture happen. But the most dominant failure mode usually is debonding of the FRP sheets [32]–[34]. Most proposed models assume that the bond capacity of FRP system as a function of the maximum transferable load [35]–[37]. The IC debonding strains can be predicted using plane sections analysis, which consider that the plane section remains plane after bending and also there is a full bond between composite materials. According to ACI 440.2R-17 [27], the effective strain in FRP sheets should be limited to that at the debonding.

3 The Analytical Models of RC Beams Flexural Strengthening with CFRP sheets

The bearing capacity of RC beam strengthening with FRP system, can be calculated by superimpose the contribution of the CFRP sheets to that of tension steel bars, Figure (2).

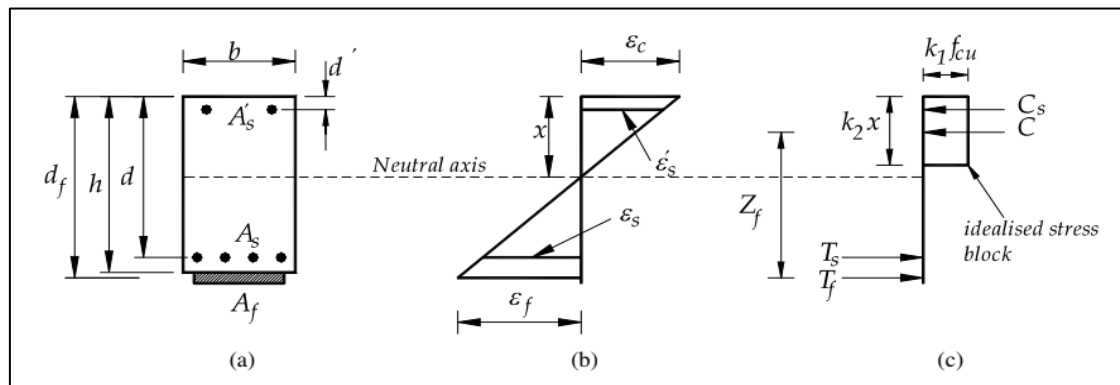


Fig. 2: (a) Cross section of RC with CFRP Sheets; (b) Strain Distribution; (c) Stress Distribution [38].

The flexural capacity, M_u , can be estimated by taking moments of internal forces about the level of tensile reinforcement bars as in Eq. (1):

$$M_u = k_1 k_2 f_c' b x \left(d - \frac{k_2 x}{2} \right) + A_s' f_s' (d - d') + A_f f_f (d_f - d) \quad (1)$$

In which:

k_1 and k_2 are two factors define the concrete block.

However, the RC beams strengthening with FRP sheets can be analyze and designed using different analytical models. The load of failure of these types of RC beams can be easily predicted by the analytical methods, which based on the analysis of cross section.

3.1 ACI-440.2R-17 Analytical Model

The ACI 440.2R-17 [27] presented two approaches to estimate the RC beams strengthened with CFRP sheets using either EBR or NSM FRP reinforcement. The flexural moment capacity of RC beams strengthening with FRP sheets depends on the type of failure. The ultimate moment can be predicted using Eq. (2), when the beams show a FRP debonding failure mode.

$$M_u = A_s f_s \left(d - \frac{\beta_1 c}{2} \right) + \psi_f A_f f_{fd} \left(d_f - \frac{\beta_1 c}{2} \right) + A_s' f_s' \left(\frac{\beta_1 c}{2} - d' \right) \quad (2)$$

Where:

M_n is the nominal bending moment, and ψ_f is the reduction parameter that is created by FRP, that is taken to equal to 0.85. β_1 is the ratio of rectangular stress block depth to the that to the neutral axis, β_1 is considered equal to 0.85 for concrete compressive strength (f_c') ranged from 17 MPa to 27 MPa In case of concrete compressive strength greater than 27 MPa, then it should be reduced the β_1 factor by 0.05 for each 7 MPa increasing value. Generally, β_1 must not be more than 0.65. *The effective FRP stress (f_{fe}) given by:

$$f_{fe} = E_f \epsilon_{fe} \quad (3)$$

In which:

the effective strain (ϵ_{fe}) can be calculated from:

$$\epsilon_{fe} = \epsilon_{cu} \left(\frac{d_f - c}{c} \right) - \epsilon_{bi} \leq \epsilon_{fd} \quad (4)$$

ϵ_{cu} is the ultimate concrete strain ($\epsilon_{cu} = 0.003$), ϵ_{bi} is the initial strain which can be calculated from an elastic analysis of the strengthening member, due to the effect of the loads applied at the duration of installation of the FRP sheets.

$$\varepsilon_{fd} = 0.41 \sqrt{\frac{f'_c}{nE_f t_f}} \leq 0.9\varepsilon_{fu} \quad (5)$$

Also, the concrete and steel strain can be calculated from:

$$\varepsilon_c = (\varepsilon_{fe} - \varepsilon_{bi}) \left(\frac{c}{d_f - c} \right), \quad \text{and} \quad (6)$$

$$\varepsilon_s = (\varepsilon_{fe} - \varepsilon_{bi}) \left(\frac{c}{d_f - c} \right) \quad (7)$$

The design process for structural members enhanced using the NSM-FRP technology is also provided by this guidance. The maximum value of the FRP strain is suggested by the guideline to be:

$$\varepsilon_{fd} = 0.7\varepsilon_{fu} \quad (8)$$

3.2 Said and Wu Analytical Model

A new analytical model was proposed by Said and Wu [31], to predict the flexural capacity of RC beams externally strengthening with FRP sheets. It was assumed that the analytical specimens fail with de-bonding mode after reaching to the yield point of main longitudinal steel reinforcement. In this model, the maximum strain of FRP sheets which was considered that one corresponding to the ultimate load (ε_{fd}), is given by:

$$\varepsilon_{fd} = 0.23 (f'_c)^{0.2} / (nE_f t_f)^{0.35} \quad (9)$$

Again, the ultimate moment (M_u) of analytical beams which occurs at de-bonding failure, can be estimated by:

$$M_u = 0.9A_s f_y d + 0.23 b_f (f'_c)^{0.2} (nE_f t_f)^{0.65} (0.9d + c^*) \quad (10)$$

In which:

c^* is the distance from the centroid of the tensile steel bars to that FRP sheets. In case of structural design, a strength reduction parameter of 0.75 is used as a safety factor.

3.3 Toutanji et. al. Analytical Model

The purposed model by Toutanji et. al. (2005) [39], consists of three stages to estimate the moment-deflection curve; crack, yield and ultimate phase. The ultimate moment is given by:

$$M_u = k_1 k_2 f'_c b c^2 + A'_s E_s \varepsilon_s (c - d') + A_s f_y (d - c) + A_f E_f \varepsilon_{ff} (h - c) \quad (11)$$

where:

ε_{ff} is effective strain of FRP sheets which is assumed to equal to ultimate value (ε_{fu}) in case of beams fail with yield of FRP sheets, but for beams fail with de-bonding mode the effective strain is given by:

$$\varepsilon_{ff} = k_m \varepsilon_{fu} \quad (12)$$

where:

k^m is a reduction factor of the ultimate strain:

$$k_m = \begin{cases} \frac{1}{60\varepsilon_{fu}} \left(1 - \frac{nE_f t_f}{360000} \right) \leq 0.90\varepsilon_{fu} & nE_f t_f \leq 180000 \\ \frac{1}{60\varepsilon_{fu}} \left(1 - \frac{90000}{nE_f t_f} \right) \leq 0.90\varepsilon_{fu} & nE_f t_f > 180000 \end{cases} \quad (13)$$

Again, k_1 and k_2 in Eq. (11), are two parameters define the concrete block:

$$k_1 = \frac{1}{f'_c \varepsilon_c} \int_0^{\varepsilon_c} f_c(\varepsilon) d\varepsilon = \frac{\varepsilon_c}{\varepsilon_0} \left(1 - \frac{\varepsilon_c}{3\varepsilon_0}\right), \quad \text{and} \quad (14)$$

$$k_2 = \frac{1}{\varepsilon_c} \frac{\int_0^{\varepsilon_c} f_c(\varepsilon) \varepsilon d\varepsilon}{\int_0^{\varepsilon_c} f_c(\varepsilon) d\varepsilon} = \frac{2}{3} \left[\frac{1 - \frac{3}{8}(\varepsilon_c/\varepsilon_0)}{1 - \frac{1}{3}(\varepsilon_c/\varepsilon_0)} \right] \quad (15)$$

Usually, ε_0 equal to 0.002 then:

$$k_1 = 500\varepsilon_c(1 - 166.7\varepsilon_c), \quad \text{and} \quad (16)$$

$$k_2 = \frac{2-375\varepsilon_c}{3-500\varepsilon_c} \quad (17)$$

The trial procedure is used to calculate the unknown parameters; k_1 , k_2 , c . Where:

$$Ac^2 + Bc + C = 0 \quad (18)$$

In which:

$$A = k_1 f'_c b, \quad B = \varepsilon_c (A'_s E_s + A_f E_f) - A_s f_y, \quad C = -\varepsilon_c (A'_s E_s d' + A_f E_f h)$$

Finally, the concrete strain given by:

$$\varepsilon_c = \left(\frac{c}{h-c} \right) \varepsilon_{ff} \leq 0.003 \quad (19)$$

3.4 Zhao Analytical Model

Analytical model was developed by Zhao (2005) [40], to calculate the FRP debonding strain in which the effect of the concrete in the compression zone, tensile reinforcement, and the FRP sheets were taken into consideration.

$$\varepsilon_{fd} = \begin{cases} \text{wet lay - up beams} & \begin{cases} 0.35 f'_c (E_f t_f)^{-0.65} & f'_c < 31.5 \text{ MPa} \\ 11.1 (E_f t_f)^{-0.65} & f'_c \geq 31.5 \text{ MPa} \end{cases} \\ \text{Pultruded plated beams} & \begin{cases} 0.08 f'_c (E_f t_f)^{-0.50} & f'_c < 31.5 \text{ MPa} \\ 2.51 (E_f t_f)^{-0.50} & f'_c \geq 31.5 \text{ MPa} \end{cases} \end{cases} \quad (20)$$

As in (3.3), the trial procedure is used to obtain the unknown parameters, k_1 , k_2 , c , and then the ultimate moment of strengthened beams predicated using Eq. (11).

3.5 Elsanadedy et. al. Analytical Model

The most important assumptions that were taken into consideration in Elsanadedy et. al. (2004) [23] model are; all beams and slabs are considered to be provided with longitudinal steel bars and externally strengthened with CFRP sheets. Also, the adopted mode of failure is IC debonding. The IC de-bonding strain of FRP-externally strengthened RC beams and slabs according to developed model is given by:

$$\varepsilon_{fd} = \left(\frac{2-b_f/b}{1+b_f/b} \right)^{0.1} \left(\frac{f_y}{n E_f t_f} \right)^{0.4} \left(6.5 + \frac{n E_f t_f}{135000} \right) \rho_s^{0.05} f'_c{}^{(0.1)} \quad (21)$$

Again, the moment capacity of RC members can be calculated from Eq. (11) using the trail procedure.

3.6 Lu et. al. Analytical Model

A simple strength model was presented by Lu et. al.[28] to obtain the IC debonding strain of FRP sheets *, which depends on the distribution of interfacial shear stress using new smeared crack FE model:

$$\varepsilon_{fd} = \frac{T}{E_f t_f b_f} = \frac{(1-\alpha)\tau_{max}L_{ee} + \alpha\tau_{max}L_d}{2E_f t_f} \quad (22)$$

In which, the unknown α is given by; $\alpha = 3.41L_{ee}/L_d$, whereas, $L_{ee} = 0.228\sqrt{E_f t_f}$, L_d is the distance from the loaded section to the end of the FRP sheets. While the max shear bond stress (τ_{max}) given by:

$$\tau_{max} = 1.5\beta_w f_t \quad (23)$$

where:

$$\beta_w = \sqrt{(2.25 - b_f/b)/(1.25 + b_f/b)}, \quad \text{and}$$

the concrete tensile strength can be calculated from; $f_t = 0.58\sqrt{f'_c}$.

Finally, the debonding strain can be calculated from:

$$\varepsilon_{fd} = 0.114(4.41 - \alpha)\tau_{max}/\sqrt{E_f t_f} \quad (24)$$

3.7 Teng et al. Analytical Model

The formula of IC debonding strain which was proposed by Teng et al. (2003) [41] depend on the effect of many factors including; *as follow:

$$\varepsilon_{fd} = \begin{cases} 0.48\beta_w \sqrt{f'_c/nE_f t_f} & \text{if } L_d \geq \sqrt{nE_f t_f/\sqrt{f'_c}} \\ 0.48 \sin \left[\pi L_d / \left(2 \sqrt{\frac{nE_f t_f}{f'_c}} \right) \right] \beta_w \sqrt{nE_f t_f/\sqrt{f'_c}} & \text{if } L_d < \sqrt{nE_f t_f/\sqrt{f'_c}} \end{cases} \quad (25)$$

where:

$$\beta_w = \sqrt{(2 - b_f/b)/(1 + b_f/b)} \quad (26)$$

The predicted moment capacity of RC beams can be calculated from Eq. (11).

3.8 Li and Wu Analytical Model

An empirical equation was proposed by Li and Wu [42], for estimating the debonding strain of FRP sheets, according to the net areas of the shear stress blocks predicted from FE analysis.

$$\varepsilon_{fd} = \frac{0.427\beta_w}{\sqrt{E_f t_f}} f_c'^{(0.25)} + \frac{1.28\beta_w}{\sqrt{E_f t_f}} \frac{f_t}{f_c'^{(0.30)}} \quad (27)$$

In which:

the tensile stress f_t can be found from; $f_t = 0.395 \left(\frac{f_c}{0.76} \right)^{0.55}$ and β_w is given by Eq. (26).

So that:

$$\varepsilon_{fd} = \frac{\beta_w}{\sqrt{E_f t_f}} (0.427 f_c'^{(0.25)} + 0.588 f_c'^{(0.30)}) \quad (28)$$

The same trial procedure in (3.3) is used to calculate the unknown parameters, and the ultimate moment of RC beam is estimated using Eq. (11).

3.9 Shehata et al. Analytical Model

In the model introduced by Shehata et al. (2001), the strengthened beam assumed to fail in flexure with FRP de-bonding mode, also, it was considered that the plane section remains plane after deformation. In the introduced model, a limitation on the concrete shear strength is taken to be $(\tau_{\max}) = 0.3f_t$, while FRP strain must be less than or equal to 0.005.

The moment capacity of RC strengthened beam can be achieved using:

$$M_u = A_s f_y (d - 0.4x_p) + A_f f_f (d_f - 0.4x_p) + A'_s f'_s (0.4x_p - d') \quad (29)$$

In which:

$$x_p = \frac{A_s f_y + A_f f_f + A'_s f'_s}{0.85 f'_c b}$$

4 Experimental Program

Ten RC beams continuous over two equal spans are designed based on the 318-ACI [43] and tested under the effect of one point load at middle of each span, to investigate the effect of external strengthening on the ultimate load, failure modes and load-deflection of tested specimens. All specimens have a 2300 mm as overall length with a (130×200) mm rectangular cross section, Figure (3). A (2Φ8 mm) steel bars, were used as longitudinal reinforcement at the tension and compression zones. While, Φ8mm rebars distribute at 60mm along the beam length as shear reinforcement. The beams geometric and distributed of the reinforcement bars are illustrated in Figure (3).

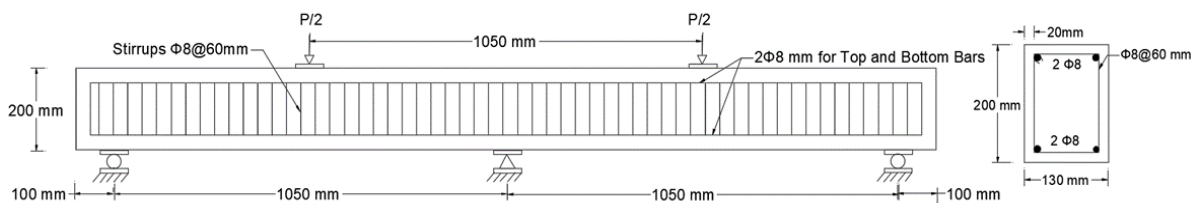


Fig. 3: The geometry of the beams and distributed of the reinforcement.

The first beam specimen (CB) has no CFRP sheets, which is selected as a control beam. The other nine beams were externally strengthened using CFRP sheets by two strengthening techniques (EBR and EBROG). In EBROG beams, the formed grooves were constructed with different length and number which located with varied directions in both sagging and hogging zones. The effect of the length and the layer numbers of CFRP sheets were also investigated. Table (1) and Figure (4) illustrate the strengthening details of all specimens.

Table 1: Details of Tested beam specimens.

Specimen	Groove Properties		CFRP sheet Configuration					Strengthening Technique
			Sagging Zones			Hogging Zone		
	Direction	Number	No. of layers	Length [L1] cm	Length [L3] cm	No. of layers	Length [L2] cm	
CB	-	-	-	-	-	-	-	-
E1L	-	-	1	85	85	1	76	EBR
E2L	-	-	2	85	85	2	76	EBR
O1L3G	Long.	3	1	85	85	1	76	EBROG
O2L3G	Long.	3	2	85	85	2	76	EBROG
O1L2G	Long	2	1	85	85	1	76	EBROG
O1LVD	Long.	3	1	85	85	1	76	EBROG
	Transverse (90°)	5						
O1L2D	Long.	3	1	85	85	1	76	EBROG
	Inclined	5						
O1LDG	Long. (45 cm) **	3	1	85	85	1	76	EBROG
O1LDL	Long.	3	1	85	45*	1	76	EBROG

L₁: Length of CFRP in Right Sagging zone, L₂: Length of CFRP in Hogging zone, L₃: Length of CFRP in Left Sagging zone.

* Length of grooves and CFRP sheets is 45 cm in O1LDL beam.

** Length of grooves only is 45 cm for all strengthening zones.

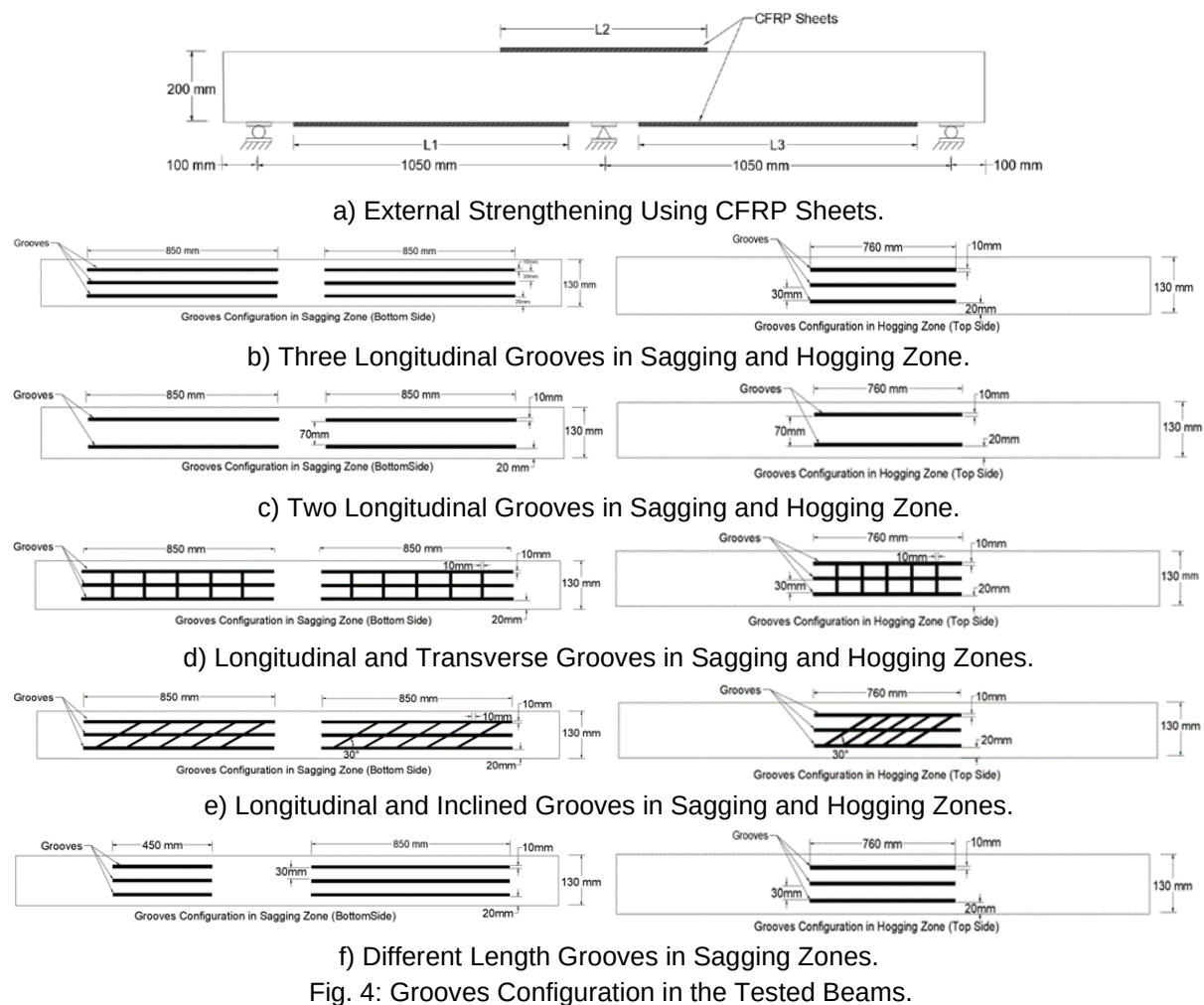


Fig. 4: Grooves Configuration in the Tested Beams.

The used materials; cement, sand, gravel, steel bars, CFRP, and Epoxy, in the cast of tested specimens, were tested at the laboratories of the university of Thi-Qar, according to ASTM specifications. The properties of materials are shown in Table 2.

Table 2: The properties of the used Materials in Tested Beam Specimens.

Material	Property Title	Magnitude
Concrete	Compressive strength of normal concrete [MPa]	37
	Tensile strength of normal concrete [MPa]	2.7
Steel rebar	Bar diameter [mm]	8
	Yield stress [MPa]	455
	Ultimate stress [MPa]	665
	Elongation [%]	15.5
CFRP	Thickness [mm/ply]	0.167
	Tensile strength [MPa]	3500
	Modulus of elasticity [GPa]	220
Epoxy Resin	Tensile strength [MPa]	30
	Tensile modulus [MPa]	4500
	Flexural modulus [MPa]	3800

5 Experimental and Analytical Results

The test results in term of load carrying capacity and deflection and also the predicted load using some of selected analytical models which were presented by standard codes and researchers, lists in Table (3).

Table 3: The experimental and Analytical results.

Specimen ID	P _{exp} [kN]	Def _{exp} [mm]	P _{pre} / P _{exp}										Mode of Failure *
			ACI-EBR	ACI-NSM	Said and Wu	Toutanji et. al.	Lu et. al.	Elsanadey et. al.	Zhao	Shehata et. al.	Teng et. al.	Li and Wu	
CB	125.4	31.1	-	-	-	-	-	-	-	-	-	-	F
E1L	143.2	11.5	0.98	0.94	1.03	1.19	1.01	0.97	1.05	0.77	0.86	1.18	CD
E2L	153.9	7.6	1.08	1.22	1.25	1.59	1.29	1.21	1.43	0.94	0.89	1.57	CD
O1L3G	178.1	8.6	0.79	0.76	0.83	0.96	0.82	0.78	0.85	0.62	0.69	0.95	CR
O2L3G	234.8	7.7	0.71	0.80	0.82	1.05	0.84	0.80	0.94	0.61	0.58	1.03	CCS
O1L2G	162.6	10.0	0.86	0.83	0.91	1.05	0.90	0.85	0.93	0.68	0.76	1.04	CR
O1LVD	190.3	8.6	0.74	0.71	0.78	0.90	0.76	0.73	0.79	0.58	0.65	0.89	CR
O1L2D	189.7	8.6	0.74	0.71	0.78	0.90	0.77	0.73	0.79	0.58	0.65	0.90	CR
O1LDG	164.1	8.6	0.86	0.82	0.90	1.04	0.88	0.84	0.92	0.67	0.75	1.03	CCS
O1LDL	145.4	14.1	0.97	0.93	1.02	1.17	1.00	0.95	1.03	0.76	0.85	1.16	CCS

*F: Flexural, CD: CFRP De-bonding, CR: CFRP Rupture, CCS: Concrete Cover Separation.

In this study, many types of the failure modes of strengthened continuous beams are observed; flexural (F), CFRP rupture (CR), CFRP debonding (CD), and concrete cover separation (CCS), as listed in Table (3) and presented in Figure (5). It can be said that the EBROG strengthening technique eliminate the debonding failure mode. According to that, the tested beams named; E1L and E2L, that were strengthened with single and double layers of CFRP sheets respectively using EBR strengthening method showed a CFRP debonding at failure. All other EBROG strengthened beams appeared either FRP rupture or concrete cover separation mode. There is also significant increasing in the ultimate load of tested beams when the EBROG is adopted as strengthening method.



a) Flexural Mode of Failure (CB).



b) De-bonding Mode of Failure (E1L and E2L).



c) Concrete Cover Separation (O2L3G, O1LDG and O1LDL).



d) CRFP Rupture Mode of Failure (O1L3G, O1L2G, O1LVD and O1L2).

Fig. 5: Failure Modes of Tested Beams.

To check the validity of the selected analytical models that are including; ACI440.2R, Said and Wu, Toutanji et. al., Lu et. al., Elsanadedy et. al., Zhao, Shehata el. al., Teng et al., and Li and Wu.; in estimating the load carrying capacity of continuous RC beams strengthening with CFRP sheets using both strengthening methods, the predicted ultimate load (P_{pre}) is compared with that resulted from the test (P_{exp}). The ultimate load of beam, E1L, which was strengthened with single layer of CFRP sheets using EBR method, successfully estimated by most of varied analytical models with low divergence ratio. Lu et. al. model is the closest one where the variation ratio between the calculated and tested load equal to (1%), while the ACI440.2R, Said and Wu, Elsanadedy et. al., and Zhao models also show have less than (5) % difference ratio. It is clear that the Toutanji et. al., and Li and Wu. Models overestimate the applied load with (19 and 18) %, respectively, while a (23 and 14) % are decreasing ratios in the predicted load using Shehata el. al. and Teng et al. models. Using two layers of CFRP sheets with EBR strengthening method in E2L specimens, leads to increase the difference between the calculated and tested results for most models. The best predicted load is achieved with adopted the models presented by ACI440.2R, Shehata el. al., and Teng et al., which have only (8, -6 and -11) % as variation ratio.

However, the highest difference between experimental and predicted load is noted for beams strengthening with one layer of CFRP sheets using the EBROG method, where three longitudinal grooves were formed in O1L3G, and also five transverse grooves in addition to three longitudinal grooves were used in O1LVD specimen beam and five inclined with 30o angle grooves with three longitudinal grooves were presented in O1L2D beam. The ACI440.2R, Said and WuLu et. al., Elsanadedy et. al., Zhao, Shehata el. al., and Teng et al. models underestimated the ultimate load with divergence ratio ranged from 15 to 42%. The models proposed by Toutanji et. al. and Li and Wu give the closer predicted values. The same trend with less variation ratio is observed in case of (O2L3G) which is provided with two layers of CFRP sheets along three longitudinal grooves. It is noted that the

Toutanji et. al., Zhao, and Li and Wu models are the appropriate ones to predicted the ultimate load of this type of beams, where a (5, -6, 3) % are the difference ratio, respectively for the three models.

The beam strengthened with single layer of CFRP along two longitudinal grooves, O1L2G, and that in which the length of grooves in the sagging zone reduced from (85 to 45) mm, O1LDG, show a P_{pre}/P_{exp} ranged from (0.84 to 1.03) for all the selected models excepted Shehata el. al., and Teng et al. model which highly underestimated the ultimate load with (33 and 25) %. Finally, the used models accurately estimated the load carrying capacity of O1LDL specimen in which the length of CFRP in sagging zone reduced from 85 cm to 45 cm, where Lu et al. model show 100% agreement with the testing load. But Shehata el. al. model still has farthest predicted load that reaches to (0.76) from experimental load.

6 Conclusion

A comparison between the experimental ultimate load of continues RC beams strengthening with CFRP sheets using two different strengthening techniques; EBR and EBROG and that predicated using the analytical models proposed by standard codes and many researchers, is presented in this paper to evaluate the effectiveness and validity of these models. The results can be summarized in the following:

- 1) The formula introduced by the ACI 440.2R-17 and other checked models are appropriating to estimate the ultimate load of the RC beams which are externally strengthened with single layer of CFRP sheets using EBR method, excepted Shehata el. al. model that underestimates the ultimate load by 23%.
- 2) Most of the used analytical model significantly underestimate the load carrying capacity of tested beams that were strengthened with one layer of CFRP sheets using grooving method that were layout in different directions, whereas Shehata el. al. model gave the larger difference ratio which reaches to 42%. But both Toutanji et. al., and Li and Wu models are preferred to use in estimating the ultimate load of these types of beams because it shows close predicted load to the experimental ones.
- 3) The ultimate load of RC beams strengthening with two layers of CFRP sheets using EBR method, that are predicted using ACI, Shehata el. al., and Teng et al. models are close to that collected from test program, while the other models show a greater than 20% divergence ratio. In other hand, Toutanji et. al., Zhao, Shehata el. al., and Li and Wu models are recommended to use in prediction the ultimate load of beams strengthening with two layers of CFRP sheet using EBROG method.
- 4) Most of the analytical models excepted Shehata el. al., and Teng et al. models, are assumed to be good in estimated the ultimate load of beams that are have less number and length of grooves.
- 5) ACI440.2R, Said and Wu, Lu et. al., Elsanadedy et. al., Zhao models accurately estimated the ultimate load of RC beams with shorter CFRP sheets length, with difference ratio don't exceed (5) %.

Notation

Many symbols are used in this article, included:

ϵ_{cu} , ϵ_{fu} , ϵ_{su} are ultimate strain of concrete, FRP, and steel bars respectively,
 ϵ_{fd} is FRP de-bonding strain,
 f_c' and f_{ct} are compressive strength and tensile strength of concrete, respectively,
 F_y is yield stress of steel rebars,
 ρ_s is main reinforcement ratio,
 n is number of FRP layers,
 E_c , E_f and E_s are modulus elasticity of concrete, FRP, and steel, respectively,
 A_s , A_f and A_s' are tensile steel, compression steel, and FRP sheets area, respectively,
 c is the distance between the neutral axis and beam compression fiber,
 d is the distance from compression fiber and centroid of tensile steel bars,
 h and b are height and width of beam cross-section, respectively,
 d_f refers to the effective depth of FRP sheets, and,
 b_f and t_f are width and thickness of FRP sheet, respectively.

References

- [1] MIAKHIL, S. U. - Singh, G.: Retrofitting of reinforced concrete beams using cfrp sheets. Journal of Green Engineering, vol. 10, no. 11, 2020, pp. 10438–10448.
- [2] HASHEMI, S.: Strengthening of concrete structures using carbon fibre reinforced polymers and cement-based adhesives. no. November, 2011, p. 246.
- [3] OBAIDAT, Y. T. - HEYDEN, S. - DAHLBLOM, O. - ABU-FARSAKH, G. - ABDEL-JAWAD, Y.:

- Retrofitting of reinforced concrete beams using composite laminates. *Construction and Building Materials*, vol. 25, no. 2, 2011, pp. 591–597, doi: 10.1016/j.conbuildmat.2010.06.082.
- [4] DIAS, S. J. E. - BARROS, J. A. O.: Shear strengthening of RC T-section beams with low strength concrete using NSM CFRP laminates. *Cem. Concr. Compos.*, vol. 33, no. 2, 2011, pp. 334–345, doi: 10.1016/j.cemconcomp.2010.10.002.
- [5] ABDALLAH, M.: Flexural strengthening of RC continuous beams with FRP reinforcements according to the NSM and EB techniques : experimental, analytical and numerical (FE) study. 2021, p. 232.
- [6] OEHLERS, D. J. - VISINTIN, P. - LUCAS, W.: Flexural Strength and Ductility of FRP-Plated RC Beams: Fundamental Mechanics Incorporating Local and Global IC Debonding. *J. Compos. Constr.*, 2016, p. 53, doi: 10.1061/(asce)cc.1943-5614.0000610.
- [7] HOLLAWAY, L. C. - TENG, J. G.: Strengthening and rehabilitation of civil infrastructures using fibre-reinforced polymer (FRP) composites. 2008. doi: 10.1533/9781845694890.
- [8] BUYUKOZTURK, O. - GUNES, O. - KARACA, E.: Progress on understanding debonding problems in reinforced concrete and steel members strengthened using FRP composites. *Construction and Building Materials*. 2004. doi: 10.1016/S0950-0618(03)00094-1.
- [9] CHEN, J. F. - TENG, J. G.: Anchorage Strength Models for FRP and Steel Plates Bonded to Concrete. *J. Struct. Eng.*, 2001, doi: 10.1061/(asce)0733-9445(2001)127:7(784).
- [10] TENG, J. G. - CHEN, J. F.: Mechanics of debonding in FRP-plated RC beams. *Proc. Inst. Civ. Eng. Struct. Build.*, 2009, doi: 10.1680/stbu.2009.162.5.335.
- [11] FU, B. - CHEN, G. M. - TENG, J. G.: Mitigation of intermediate crack debonding in FRP-plated RC beams using FRP U-jackets. *Compos. Struct.*, 2017, doi: 10.1016/j.compstruct.2017.05.049.
- [12] MOSTOFINEJAD, D. - MAHMOUDABADI, E.: Grooving as Alternative Method of Surface Preparation to Postpone Debonding of FRP Laminates in Concrete Beams. *J. Compos. Constr.*, 2010, doi: 10.1061/(asce)cc.1943-5614.0000117.
- [13] MOSHIRI, N. et al.: Flexural strengthening of RC slabs with nonprestressed and prestressed CFRP strips using EBROG method. *Compos. Part B Eng.*, vol. 201, p. 108359, 2020, doi: 10.1016/j.compositesb.2020.108359.
- [14] MOSHIRI, N. - TAJMIR-RIAHI, A. - MOSTOFINEJAD, D. - CZADERSKI, C. - MOTAVALLI, M.: Experimental and analytical study on CFRP strips-to-concrete bonded joints using EBROG method. *Compos. Part B Eng.*, vol. 158, 2019, pp. 437–447, doi: 10.1016/j.compositesb.2018.09.046.
- [15] TAJMIR-RIAHI, A. - MOSHIRI, N. - CZADERSKI, C. - MOSTOFINEJAD, D.: Effect of the EBROG method on strip-to-concrete bond behavior. *Constr. Build. Mater.*, vol. 220, 2019, pp. 701–711, doi: 10.1016/j.conbuildmat.2019.06.065.
- [16] ALI, A.: Experimental and numerical study of continuous reinforced concrete beams strengthened or retrofitted by bonding composite materials. 2017, p.206.
- [17] OBAIDAT, Y. T.: Structural Retrofitting of Concrete Beams Using FRP -Debonding Issues. 2011, p.185.
- [18] BARBATO, M.: Efficient finite element modelling of reinforced concrete beams retrofitted with fibre reinforced polymers. *Comput. Struct.*, 2009, doi: 10.1016/j.compstruc.2008.11.006.
- [19] FANNING, P. J. - KELLY, O.: Ultimate Response of RC Beams Strengthened with CFRP Plates. *J. Compos. Constr.*, 2001, doi: 10.1061/(asce)1090-0268(2001)5:2(122).
- [20] SPADEA, G. - SWAMY, R. N. - BENCARDINO, F.: Strength and Ductility of RC Beams Repaired with Bonded CFRP Laminates. *J. Bridg. Eng.*, 2001, doi: 10.1061/(asce)1084-0702(2001)6:5(349).
- [21] RAHIMI, H. - HUTCHINSON, A.: Concrete Beams Strengthened with Externally Bonded FRP Plates. *J. Compos. Constr.*, 2001, doi: 10.1061/(asce)1090-0268(2001)5:1(44).
- [22] WHITE, T. W. - SOUDKI, K. A. - ERKI, M.-A.: Response of RC Beams Strengthened with CFRP Laminates and Subjected to a High Rate of Loading. *J. Compos. Constr.*, 2001, doi: 10.1061/(asce)1090-0268(2001)5:3(153).
- [23] ELSANADEDY, H. M. - ABBAS, H. - AL-SALLOUM, Y. A. - ALMUSALLAM, T. H.: Prediction of Intermediate Crack Debonding Strain of Externally Bonded FRP Laminates in RC Beams and One-Way Slabs. *J. Compos. Constr.*, 2014, doi: 10.1061/(asce)cc.1943-5614.0000462.
- [24] CORONADO, C. A. - LOPEZ, M. M.: Sensitivity analysis of reinforced concrete beams strengthened with FRP laminates. *Cem. Concr. Compos.*, 2006, doi: 10.1016/j.cemconcomp.2005.07.005.
- [25] Chinese Code CECS, "Technical specification for strengthening concrete structure with carbon fiber reinforced polymer laminate." 2010, p. 237.
- [26] JSCE Recommendations, "Recommendations for Upgrading of Concrete Structures With Use of," Japan Soc. Civ. Eng., 2001.
- [27] 440.2R-17: Guide for the Design and Construction of Externally Bonded FRP Systems for

- Strengthening Concrete Structures. 2017. doi: 10.14359/51700867.
- [28] LU, X. Z. - TENG, J. G. - YE, L. P. - JIANG, J. J.: Intermediate Crack Debonding in FRP-Strengthened RC Beams: FE Analysis and Strength Model. *J. Compos. Constr.*, 2007, doi: 10.1061/(asce)1090-0268(2007)11:2(161).
- [29] LÓPEZ-GONZÁLEZ, J. C. - FERNÁNDEZ-GÓMEZ, J. - DÍAZ-HEREDIA, E. - LÓPEZ-AGÜÍ, J. C. - VILLANUEVA-LLAURADÓ, P.: IC debonding failure in RC beams strengthened with FRP: Strain-based versus stress increment-based models. *Eng. Struct.*, 2016, doi: 10.1016/j.engstruct.2016.03.024.
- [30] ABED, R. J. - MASHREI, M. A. - SULTAN, A. A.: Evaluating Flexural Strength of RC Beams Strengthened by CFRP using Different Analytical Models. *Civ. Environ. Eng.*, vol. 17, no. 2, 2021, pp. 465–475, doi: 10.2478/cee-2021-0049.
- [31] SAID, H. - WU, Z.: Evaluating and Proposing Models of Predicting IC Debonding Failure,” *J. Compos. Constr.*, 2008, doi: 10.1061/(asce)1090-0268(2008)12:3(284).
- [32] ARDUINI, M. - DI TOMMASO, A. - NANNI, A.: Brittle failure in FRP plate and sheet bonded beams. *ACI Struct. J.*, 1997, doi: 10.14359/487.
- [33] BUYUKOZTURK, O. - HEARING, B.: Failure Behavior of Precracked Concrete Beams Retrofitted with FRP,” *J. Compos. Constr.*, 1998, doi: 10.1061/(asce)1090-0268(1998)2:3(138).
- [34] MEIER, U.: Strengthening of structures using carbon fibre/epoxy composites. *Constr. Build. Mater.*, 1995, doi: 10.1016/0950-0618(95)00071-2.
- [35] SMITH S. T. - TENG, J. G.: FRP-strengthened RC beams. I: Review of debonding strength models. *Eng. Struct.*, 2002, doi: 10.1016/S0141-0296(01)00105-5.
- [36] KARBHARI, V. M. - NIU, H. - SIKORSKY, C.: Review and comparison of fracture mechanics-based bond strength models for FRP-strengthened structures. *J. Reinf. Plast. Compos.*, 2006, doi: 10.1177/0731684406074475.
- [37] TOUTANJI, H. - SAXENA, P. - ZHAO, L. - OOI, T.: Prediction of Interfacial Bond Failure of FRP–Concrete Surface. *J. Compos. Constr.*, 2007, doi: 10.1061/(asce)1090-0268(2007)11:4(427).
- [38] ASHOUR, A. F. - EL-REFAIE, S. A. - GARRITY, S. W.: Flexural strengthening of RC continuous beams using CFRP laminates. *Cem. Concr. Compos.*, 2004, doi: 10.1016/j.cemconcomp.2003.07.002.
- [39] TOUTANJI, H. - ZHAO, L. - ZHANG, Y.: Flexural behavior of reinforced concrete beams externally strengthened with CFRP sheets bonded with an inorganic matrix. *Eng. Struct.*, 2006, doi: 10.1016/j.engstruct.2005.09.011.
- [40] ZHAO, L.: Characterizations of rc beams strengthened with carbon fiber sheets. 2005, p. 221.
- [41] TENG, J. G. - SMITH, S. T. - YAO, J. - CHEN, J. F.: Intermediate crack-induced debonding in RC beams and slabs. *Construction and Building Materials*, 2003. doi: 10.1016/S0950-0618(03)00043-6.
- [42] LI, X.-H. - WU, G.: Finite-Element Analysis and Strength Model for IC Debonding in FRP-Strengthened RC Beams. *J. Compos. Constr.*, 2018, doi: 10.1061/(asce)cc.1943-5614.0000863.
- [43] ACI Committee 318, Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary on Building Code Requirements for Structural Concrete (ACI 318R-19). 2019.