International Journal of Civil Engineering and Technology (IJCIET)
Volume 10, Issue 02, February 2019, pp. 1949-1966. Article ID: IJCIET_10_02_193
Available online at http://www.iaeme.com/ijciet/issues.asp?JType=IJCIET&VType=10&IType=02
ISSN Print: 0976-6308 and ISSN Online: 0976-6316

REPAIRING AND STRENGTHENING OF RC BEAMS USING THIN LOWER CONCRETE LAYER REINFORCED BY FRP BARS

Ahmed H. Abdel-kareem, Ahmed S. Debaiky, M. H. Makhlouf and M. Badwi
Department of Civil Engineering, Benha Faculty of Engineering, Benha University, Egypt

ABSTRACT

This paper presents the test results of an experimental study that investigates the behavior of reinforced concrete (RC) beams strengthened or repaired in flexure by adding thin lower concrete layer reinforced mainly by Fiber Reinforced polymers (FRP) bars. A total of seventeen RC beams were constructed and tested under four-point loading. One of these beams was un-strengthened and considered as a reference beam. Eight beams were strengthened in flexure, and the other eight beams were loading up to 70% from the ultimate load of reference beam and then repaired using the same methods provided to the strengthened beams. Five test parameters were considered in this research; status of beam (strengthened or repaired), type of reinforcement used (glass FPR, carbon FPR or steel), amount of reinforcing FRP bars used (2 bars or 4 bars), type of the strengthening technique (reinforcing bars installed in the adding concrete layer or FRP sheets externally bonded to the soffit of the adding concrete layer) and type of connection between the adding lower concrete layer and the original beam (installing dowels bars or not). The test results included ultimate load, cracking load, the corresponding deflection, the failure modes and calculated relative ductility and flexure stiffness at un-cracked and cracked stages. The percentage enhancement in the flexural capacity of the tested beams ranged from 32% to 106% compared with the reference beam. Using FRP bars showed greater ultimate load and more ductile behavior than using externally FRP sheets. Many failure modes were observed during testing; FRP rupture, FRP debonding or partial debonding between the adding concrete layer and the original beam depending on the method of strengthening or repairing had been applied to the tested beams. The experimental ultimate strength for all strengthened and repaired beams were compared with the design provisions provided by ACI 440-2R-08, which showed reasonable and lightly conservative predictions for all strengthened and repaired beams

Keywords: Adding lower concrete layer; Fiber reinforced polymer; reinforced concrete; beam; repairing; strengthening; flexure.

Cite this Article: Ahmed H. Abdel-kareem, Ahmed S. Debaiky, M. H. Makhlouf and M. Badwi, Repairing and Strengthening of Rc Beams using thin Lower Concrete Layer Reinforced by FRP Bars, *International Journal of Civil Engineering and Technology*, 10(2), 2019, pp. 1949-1966.

http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=10&IType=02

1. INTRODUCTION

Several RC structural members all over the world required repairing and strengthening, due to expose to harsh environmental conditions, change in use or in code of practice or excessive loading. Various repairing and strengthening techniques for RC structural elements are available. However, the selection of the suitable technique depends on many factors, such as the conditions of which the element is exposed, the cost of the proposed technique and the applicability of the selected technique [1].

The FRP from carbon fibers (CFRP) or glass fibers (GFRP) as repairing and strengthening material become the excellent choice for its advantages such as high strength, corrosion resisting, light weight and durability [2-9]. At data, using FRP material as externally bonded reinforcement or near surface mounted (NSM) for repairing and strengthening RC elements are the recent and promising techniques [10-19]. The FRP externally bonded system consists of one or more strengthening sheets or strips bonded to the tension side of RC elements using suitable bonding material. The disadvantages of this technique are the FRP exposed to severe environmental conditions; damage and it often suffer from premature debonding. The NSM strengthening technique can be summarized as cutting longitudinal grooves in the concrete cover of the structural elements, and then the reinforcing bars are inserted into the grooves which filled with suitable bonding adhesive [10]. The NSM technique overcomes many disadvantages of externally bonded technique. The reinforcing bars used in NSM technique have less prone to premature debonding failure and are protected by concrete cover from mechanical damage and fire [11].

Many researchers investigated RC beams flexural strengthened with NSM and externally bonded technique using FRP bars and sheets [12-18]. All test results showed enhancement with different ratios in the flexural capacity of the strengthened beams, according to the parameters considered in the study, compared with the beam kept un-strengthened as a control beam. The tested beams failed with different failure modes. Jung el al. [12] studied the flexural performance of beams strengthened with NSM CFRP bars and externally bonded with CFRP sheets and compared between the two strengthening techniques. All beams failed by debonding. Tang et al. [13] investigated the NSM GERP strengthened beams where the concrete type, normal or lightweight, and the type of bonding material were variables. The failure modes were debonding or rupture of NSM GFRP bars. Al-Mahmoud et al. [14] evaluated the flexural responses of NSM CFRP strengthened RC beams. The groove filler and concrete strength enhanced the flexural strength of tested beams, and the failure mode was debonding. Tarek et al. [15] investigated the flexural strengthening of RC beams using NSM steel or GFRP bars. No debonding failure was observed and this was due to the sufficient end anchorage of the used bars and the good bonding of used epoxy adhesive. The beams failed by steel yielding or rupture of GFRP bars followed by concrete crushing. Sharaky et al. [16] evaluated the flexural behavior of RC beams strengthened using NSM bars from CFRP and GFRP, the beams failed by debonding. For beams with double grooves, it was observed concrete cover separation for CFRP strengthened beams and concrete splitting for GFRP strengthened beams. Bilotta et al. [17] investigated the efficiency of CFRP NSM strips and externally bonded plates strengthened RC beams. The beams failed by debonding, critical diagonal cracking debonding and separation of concrete cover. Gamal et al. [18] investigated the flexural strengthening RC beams with different reinforcement ratios using NSM or hybrid from NSM bars and externally bonded FRP sheets. The strengthening for beams with lower steel reinforcement was more efficient. Compared to MSM technique, the hybrid technique did not show an advantage. The beams failed by debonding.

However, using the NSM technique in strengthening RC beams has some limitations. The beam width must be sufficient for clear spacing between the NSM grooves and necessary edge clearance. In many cases, the strengthened beams needs more reinforcing bars to meet the design requirements, cutting two or more grooves in a beam of limited width increase the probability of debonding failure due to stress overlap [19,20]. Moreover, the strengthened beams with double grooves [16], the debonding failure was associated with separation of concrete cover or concrete spilling. To overcome the restrictions of NSM technique, the present research introduce technique of installing the reinforcing bars in a thin concrete layer bonded to the tension side of the beam. The study explores the flexural behavior of RC beams repaired and strengthened by adding thin lower concrete layer reinforced mainly by CFRP bars or GFRP bars. A total of seventeen beams were tested under four-point loading condition till failure. The studies parameters included material type of the reinforcing bars used and the amount of FRP, the type of connection between the adding concrete layer and the original beams and the strengthening technique either FRP bars installed in the concrete layer or FRP sheets externally bonded to the soffit of the concrete layer. The ultimate capacity of the tested beams was predicted using ACI 440-2R-08 [21].

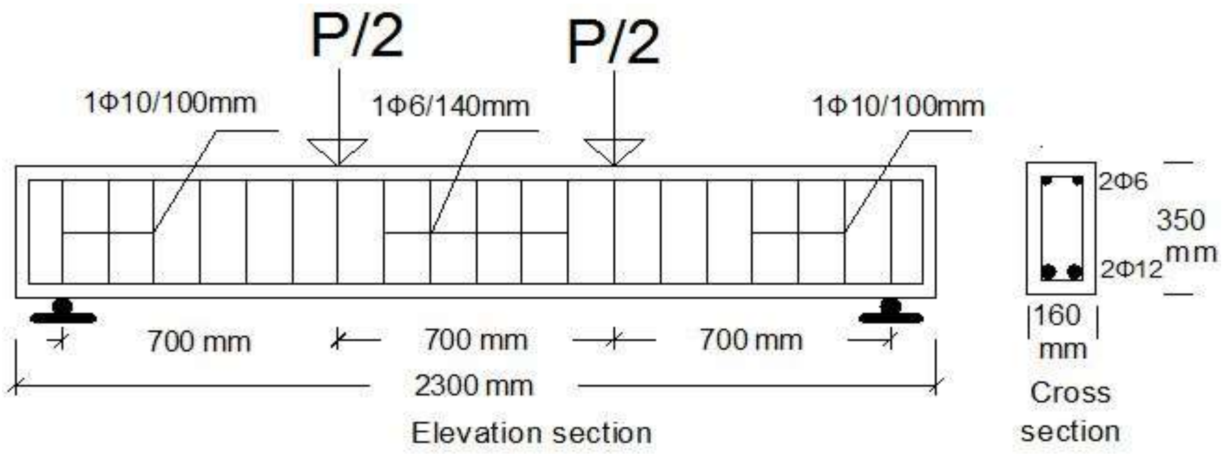
2. EXPERIMENTAL PROGRAM

2.1. Specimens and text matrix

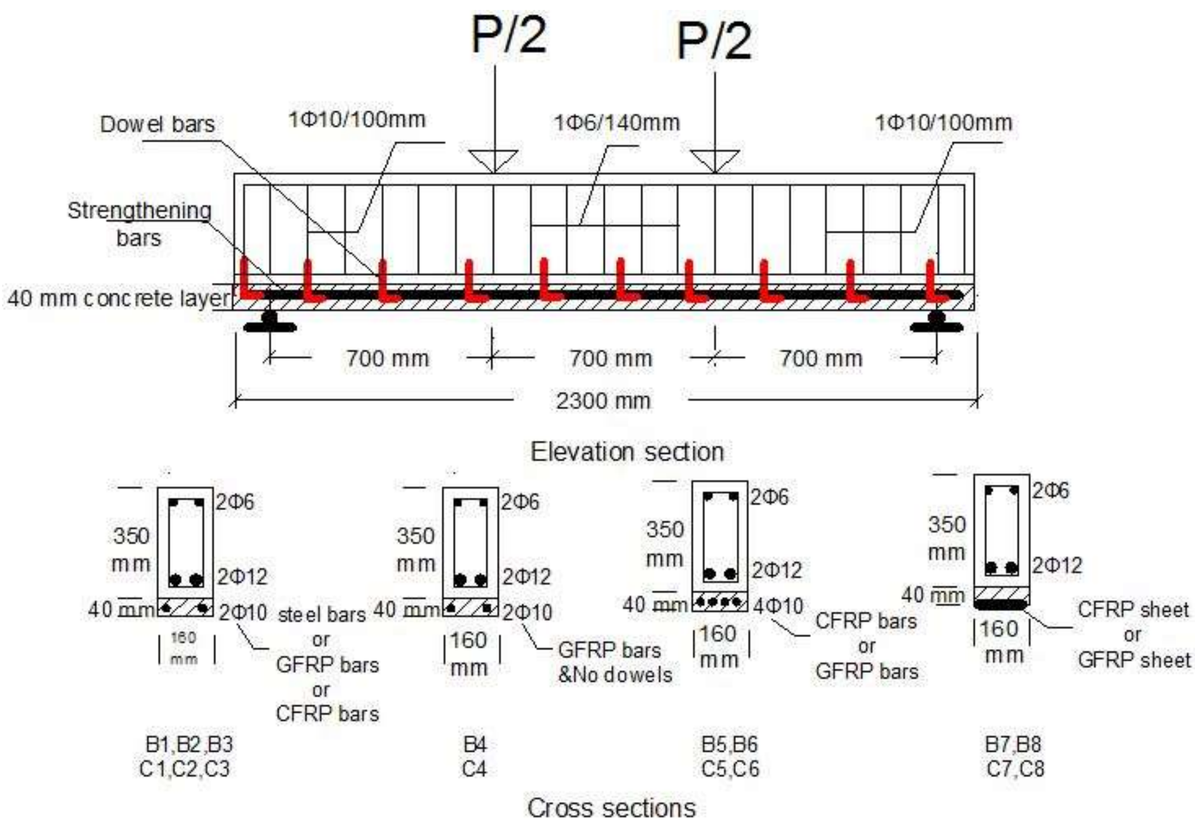
Seventeen beams were casted and tested to investigate the flexural behavior of RC beams strengthened or repaired at tension side by adding thin concrete layer reinforced mainly by FRP bars. The test beams divided to three groups. First group (A) contain one beam which was kept un-strengthened as a reference beam (REF). For reminder sixteen beams, 40 mm thick concrete layer was added to the tension side of the beams. They were divided to two groups (B) and (C) contained eight beams each. All beams in group two (B) were strengthened with different types and amounts of reinforcement bars, strengthening techniques and types of connection between the adding concrete layer and the original beam. The beams in group three (C) were repaired, where the beams were loaded up to 70% from the failure load of the reference beam and then repaired by the same methods used in the strengthened beams

All tested beams had cross section (160 x 350 mm) and 2300 mm long with an effective span 2100 mm. The beams were reinforced with 2ϕ12 in the tension side, 2ϕ6 in the compression side just for holding the stirrups in position during concreting, and stirrups ϕ10@ 100 mm spacing in the zones between the supports and the concentrated loads to avoid shear failure during testing and ϕ 6@ 140 mm spacing in the zone between the two concentrated loads.

All beams in groups (B) and (C) Except (B4, C4) with dowels bars installed between the adding concrete layer and the original beam. Three beams in each group (B) and (C) reinforced with 2ϕ10 mm steel, CFRP or GFRP bars in the adding lower concrete layer. Two beams in each group (B) and (C) reinforced with 4ϕ10 mm CFRP or GFRP bars. All type of used bars had the same tensile force. Finally, two beams in each group (B) and (C) reinforced externally with CFRP or GFRP sheets, having the same tensile force of two FRP bars, bonded to the soffit of the adding concrete layer. All beam sections for strengthened and repaired beams were design to be under-reinforcement to ensure tension failure during testing. The dimensions and reinforcement details of test beams are shown in Fig.1 Test matrix is summarized in Table 1.



a) Reference beam



b) Strengthened and repaired beams

Figure 1 Dimensions and reinforcement details for tested beams

Table 1 Test matrix

Case of beams	**Group**	**Beam** No.	**Beam** code	**Strengthening material type**	**Strengthening** material area
Reference	A	A1	REF	----------	-----------
Strengthened	B	B1	SS-2b-A	Steel bars	2ϕ10
		B2	SC-2b-A	Carbon bars	2ϕ10
		B3	SG-2b-A	Glass bars	2ϕ10
		B4	SG-2b-B	Glass bars	2ϕ10
		B5	SC-4b-A	Carbon bars	4ϕ10
		B6	SG-4b-A	Glass bars	4ϕ10
		B7	SC-sh-A	Carbon sheet	147 mm wide
		B8	SG-sh-A	Glass sheet	193 mm wide
Repaired	C	C1	RS-2b-A	Steel bars	2ϕ10
		C2	RC-2b-A	Carbon bars	2ϕ10
		C3	RG-2b-A	Glass bars	2ϕ10
		C4	RG-2b-B	Glass bars	2ϕ10
		C5	RC-4b-A	Carbon bars	4ϕ10
		C6	RG-4b-A	Glass bars	4ϕ10
		C7	RC-sh-A	Carbon sheet	147 mm wide
		C8	RG-sh-A	Glass sheet	193 mm wide

(Where S: Strengthening, R: repairing, S: steel, C: Carbon, G: Glass, b: bar, sh: sheet, A: installing dowel bars and B: without dowel bars).

2.2. Materials Properties

2.2.1. Concrete

The same concrete mix was used for the beams and the concrete layer added to the soffit of strengthened and repaired beams. The materials used in concrete mixture were Ordinary Portland Cement (OPC- 42.5 grade), natural sand with 2.70 fineness moduli and crushed dolomite with maximum aggregate size 16 mm. The mix design was carried out for 28-day concrete compressive strength (fcu) = 35 MPa.

2.2.2. Steel bars

6 mm diameter of normal mild steel were used for all beams as top reinforcement and stirrups, 10 mm diameter of high grade steel used as reinforcement for the adding lower concrete layer and stirrups and 12 mm diameter of high grade steel used for all beams as main tension reinforcement. The measured yield strength of the 6, 10 and 12 mm diameter were 330, 530 and 650 MPa, respectively. The modulus of elasticity for all steel bars was 200 GPa.

2.2.3. FRP bars

CFRP and GFRP bars were locally fabricated using the puitrusion process, and then surfaces were coated by sand layer to improve its bond. The bars are made of carbon or glass fibers with resin from polyester polymer. The fiber area on the bar was determined to give tensile force of the FRP bar equal to that of used steel bar 10 mm diameter. The mechanical properties of CFRP and GFRP rods were obtained by testing specimen. Table 2 shows the mechanical properties of the FRP bars used in this study.

2.2.4. FRP sheets

CFRP and GFRP sheets are, also, locally fabricated. The mechanical properties of FRP sheets used in this study, according to manufacture, are given in table 2. According to the fiber thickness for one layer, the width of FRP sheet was determined to give the same tension force of two FRP bars. When the width of GFRP sheet exceeded the beam width, the sheet bonded to the surface in two layers, where the first layer covered the entire width of the strengthened or repaired beam.

Table 2 Dimensions and characteristic properties of FRP:

a) FRP bars		
property	CFRP	GFRP
Diameter of bars (mm)	10	10
Area of bars (mm^2)	78.5	78.5
Area of fibers (mm^2)	29.3	30.1
Fiber ratio by area	37%	38%
Tensile strength (N/mm^2)	1420	1380
Elasticity modulus (N/mm^2)	216000	66000
Strain at failure	6600x10^{-6}	21000x10^{-6}
b) FRP sheets		
Property	CFRP	GFRP
Fabric design thickness (mm)	0.128	0.168
Fabric width (mm)	147	193
Tensile strength (N/mm^2)	4300	2500
Elasticity modulus (N/mm^2)	234000	72000
Strain at failure	1.84%	3.47%

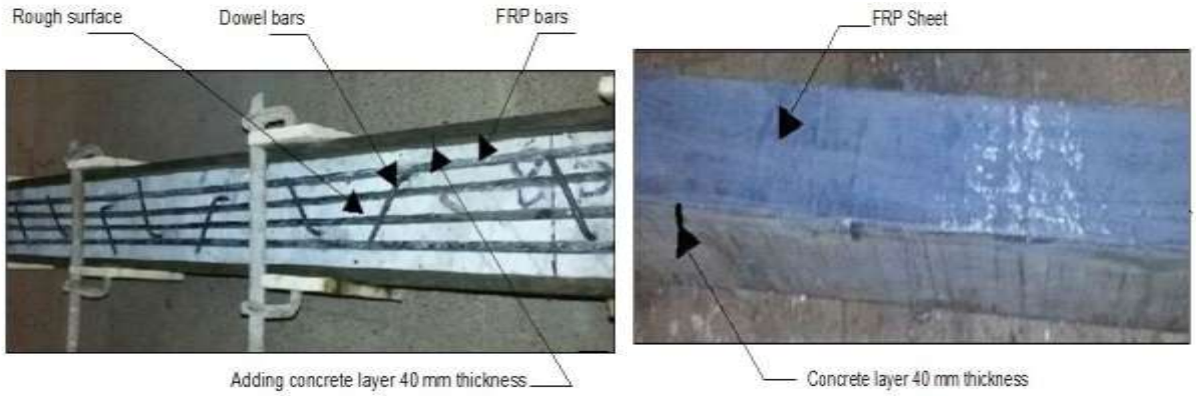
2.3. Strengthening and Repairing Procedures

The procedures for strengthening or repairing the tested beams by adding concrete layer reinforced by bars can be summarized as follows:

1. The beam was flipped upside down to apply the strengthening layer.
2. Beam surface was notched using an angle grinder to achieve rough surface.
3. 10 mm diameter staggered holes were drilled at the arranged positions of dowels bars spaced 250 mm.
4. Dowel bars 8 mm diameters were fixed in holes using bonding agent.
5. Surface of beams was cleaned with a wire brush and a high-pressure air jet.
6. Reinforcing bars were installed to the beam.
7. Surface of beams was brushed by bonding agent to improve bond between the original beam surface and the strengthening layer.
8. Concrete layer 40 mm thickness was casted and left for curing.

For beams without dowels bars installed between the adding concrete layer and the original beams, all strengthening procedures repeated except steps (3) and (4).

For beams strengthened or repaired by externally FRP sheets, the adding concrete layer not reinforced by FRP bars. Where, an epoxy resin was applied to the concrete surface at the area where FRP sheets were installed by using especial roller. Fig.2 shows beams strengthened using FRP bars or externally FRP sheets.



a) Using FRP bars   b) Using externally bonded FRP sheets

Figure 2 strengthened beams

2.4. Test Setup and Instrumentation

The beams were tested under four- point bending until failure. The details of test set-up are shown in Fig. 3. The beams were placed in a rigid reaction frame, 1000 KN capacity, and the load was applied using a 1000 KN capacity hydraulic jack connected to electrical pump. Each beam was installed with three linear variable differential transducers (LVDT) placed at the mid-span and directly under the loading point to monitor the displacement. Two strain gauges were attached to the middle of the bottom bars to measure the strain in reinforcement; one on a steel bar of the original beam and the second on a bar reinforced the adding lower Concrete layer during testing, the crack propagation was monitored with applied load increasing till failure. All test data were recorded using data acquisition system and a computer at intervals of two seconds.

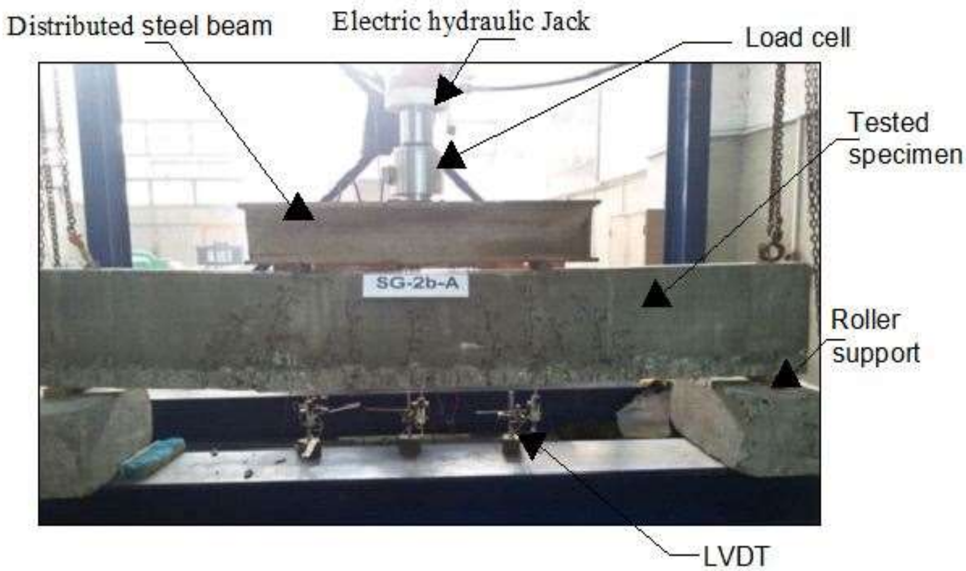


Figure 3 Test setup of tested beams

3. EXPERIMENTAL RESULTS AND DISCUSSION

Table 3 summarized the test results. Applied load verses mid-span deflection curves were plotted for all tested beams. The effect of parameters considered on this study on the tested beams will be discussed in the following items:

3.1. Load-deflection Relationships

All the strengthened and repaired beams in this study showed a significant enhancement in the strength and the rigidity compared with the reference beam. At the same loading level, the deflection values for strengthened and repaired beams were less than that recorded for the reference beam, as shown in Fig. 4 – 7.

3.1.1. Effect of strengthening material type

The effect of the three strengthened materials, steel bars, CFRP bars and GFRP bars, on the flexural behavior of tested beams could be observed in specimens SS-2b-A, SC-2b-A and SG-2b-A for the strengthened beams; and specimens RS-2b-A, RC-2b-A and RG-2b-A for the repairing beams, as shown in Fig. 4. It shows increasing in the ultimate load and decreasing in the deflection at the same load for all reinforcing bars used compared with the reference beam. The beams reinforced by CFRP bars gave the greatest ultimate load (68-79% increase) then that reinforced by GFRP bars (57-68% increase) and finally the beams reinforced by steel bars (44-53% increase). The reductions of the deflection at ultimate load of the reference beam were by 60-69%, 50-53% and 60-61% for beams strengthened or repaired by CFRP, GFRP and steel bars respectively.

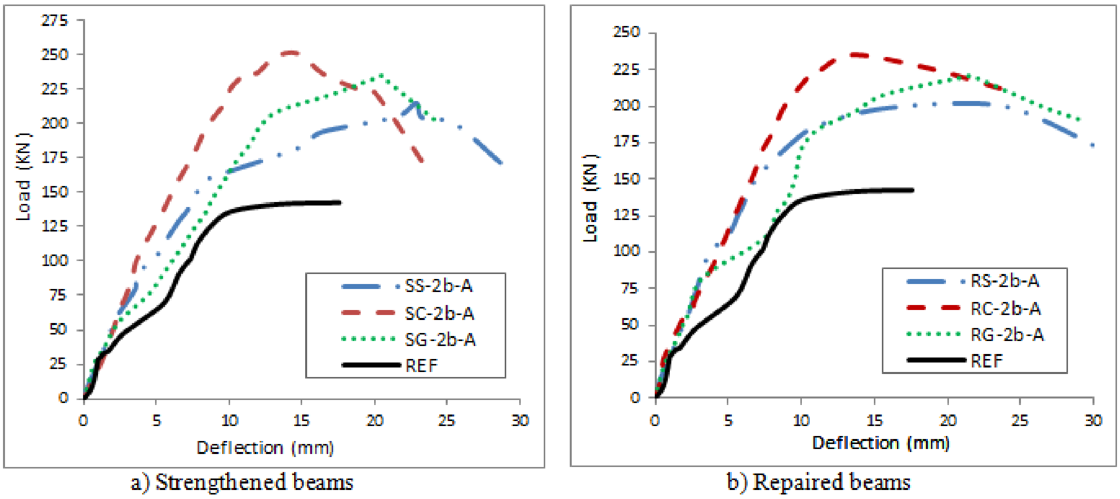


Figure 4 Load- deflection curves for beams reinforced by bars with different material type

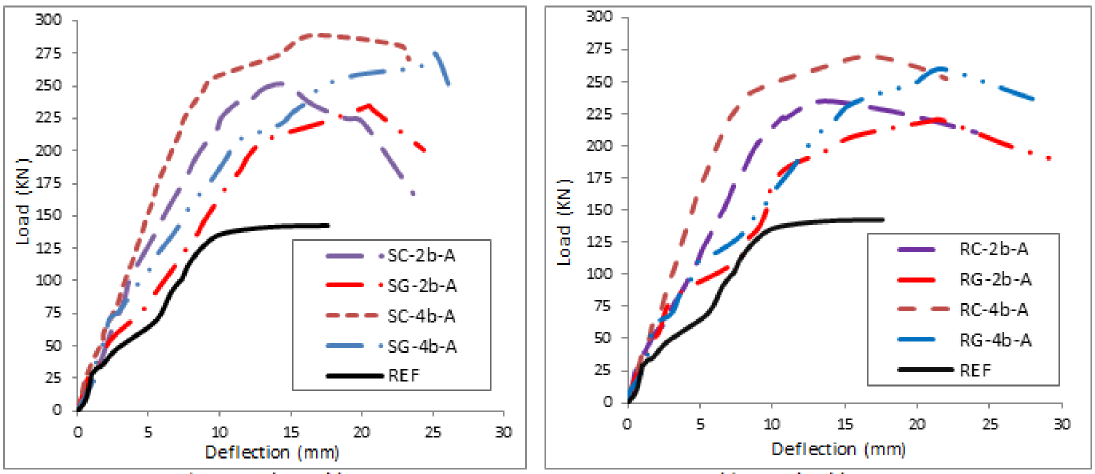
3.1.2. Effect of the amount of reinforcing FRP bars

The flexural behavior of beams reinforced by two or four FRP bars in the adding concrete layer could be detected by comparing the behavior of the specimens SC-2b-A, SG-2b-A, SC-4b-A and SG-4b-A for the strengthened beams; and the specimens RC-2b-A, RG-2b-A, RC-4b-A and RG-4b-A for the repairing beams with the reference beam, as shown in Fig. 5. Doubling the numbers of FRP bars increased the ultimate load but the increasing rate was not proportional to that in the cross sectional area of reinforcing bars. The ultimate load was higher than that of reference beam by 86 - 106% and by 57 - 79% for beams reinforced by four FRP and two FRP bars respectively, also the deflection at ultimate load of reference beam was reduce by 55 - 75% and 5o - 69%, for beams reinforced by four FRP and two FRP bars respectively in compared with reference beam.

Table 3 Summary of experimental results

Beam code	1st cracking		Ultimate		$P_u/P_{u,R}$	Ductility	Un-cracked stiffness (Ki)	Ultimate stiffness (Ku)	P calc. (KN)	$P_u/P_{calc.}$	Failure Mode
	Load (P_{cr}) (KN)	Cracking Δ_{cr} (mm)	Load (P_u) (KN)	Cracking Δ_u (mm)		Δ_u/Δ_{cr}	P_{cr}/Δ_{cr} (KN/mm)	$(P_u-P_{cr})/(\Delta_u-\Delta_{cr})$ (KN/mm)			
REF	35.2	1.75	140.1	18.46	1.00	10.55	20.1	6.28	125	1.12	Steel yielding
SS-2b-A	90.18	2.64	215.02	22.85	1.53	8.65	34.15	6.17	195	1.10	Steel yielding
SC-2b-A	70.1	2.71	251.13	14.72	1.79	5.43	25.87	15.07	209	1.20	Rupture of CFRP bars
SG-2b-A	55.49	2.39	235.22	20.52	1.68	8.59	23.22	9.91	200	1.18	Rupture of GFRP bars
SG-2b-B	50.39	2.41	205.11	16.87	1.46	6.99	20.87	10.70	188	1.09	Debonding of concrete layer
SC-4b-A	61.32	1.87	289.15	16.58	2.06	8.87	32.81	15.49	240	1.20	Debonding of CFRP bars
SG-4b-A	70.19	2.22	275.14	25.14	1.96	11.32	31.6	8.94	230	1.20	Debonding of GFRP bars
SC-sh-A	73.45	4.8	215.07	17.18	1.54	3.58	15.31	11.44	190	1.13	Debonding of CFRP sheets
SG-sh-A	50.12	4.25	200.17	18.18	1.43	4.28	11.79	10.77	186	1.08	Debonding of GFRP sheets
RS-2b-A	81.2	2.04	202.04	21.02	1.44	10.3	39.8	6.39	200	1.01	Steel yielding
RC-2b-A	60.2	1.95	235.05	14.1	1.68	7.22	30.87	14.38	210	1.12	Rupture of CFRP bars
RG-2b-A	55.14	2.17	220.17	21.75	1.57	10.01	25.36	8.43	198	1.11	Rupture of GFRP bars
RG-2b-B	50.15	2.23	191.1	17.1	1.36	7.66	22.46	9.48	188	1.02	Debonding of concrete layer
RC-4b-A	60.27	1.71	270.07	16.43	1.93	9.6	35.19	14.25	240	1.13	Debonding of CFRP bars
RG-4b-A	60.04	1.8	260.13	21.85	1.86	12.16	33.41	9.98	220	1.18	Debonding of GFRP bars
RC-sh-A	60.21	3.65	195.05	16.45	1.39	4.5	16.48	10.53	189	1.03	Debonding of CFRP sheets
RG-sh-A	50.38	3.34	185.16	15.89	1.32	4.76	15.08	10.74	166	1.12	Debonding of GFRP sheets
									Mean= 1.12		

$P_{u,R}$: ultimate load for reference beam.



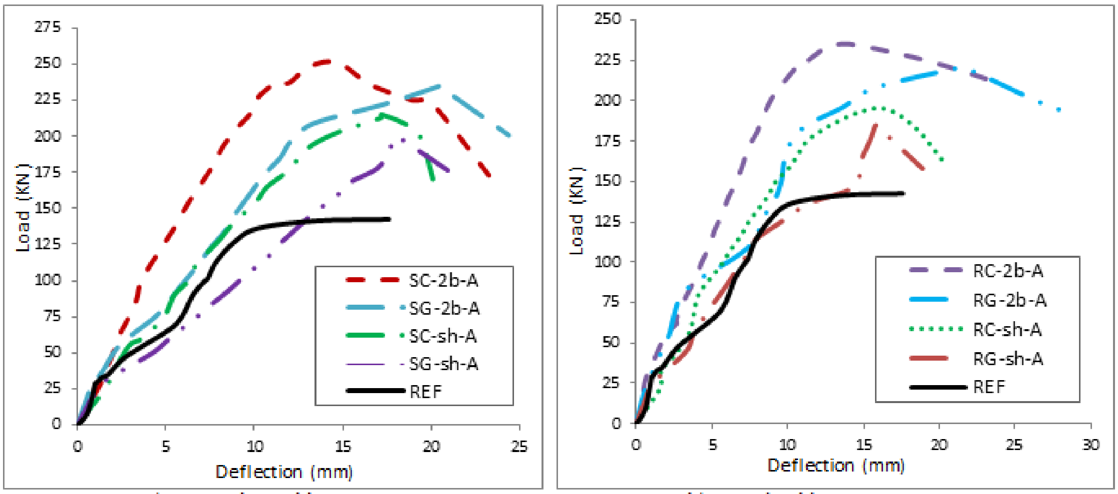
a) Strengthened beams b) Repaired beams

Figure 5 Load- deflection curves for beams reinforced with different amount of FRP bars

3.1.3. Effect of strengthening technique

The effect of reinforcing the adding concrete layer by FRP bars installed before concreting layer or by FRP sheets externally bonded after concrete layer on the flexural behavior of tested beams could be observed by studying the behavior of the specimens SC-2b-A, SG-2b-A, SC-sh-A and SG-sh-A for the strengthened beams and the specimens RC-2b-A, RG-2b-A, RC-sh-A and RG-sh-A for the repairing beams, as shown in Fig. 6. Using externally bonded

FRP sheets led to increase in the ultimate load by 32 - 54% compared with reference beam, which less than that achieved by using FRP bars (57 -79%), and reduce the deflection recorded at ultimate load of reference beam by 29-53%, which consider the lowest reduction in the deflection.

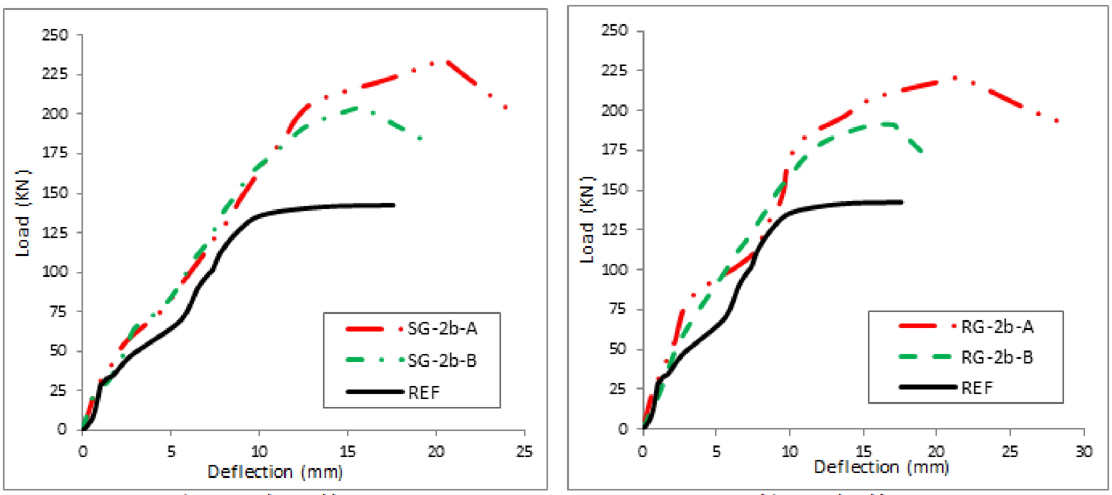


a) Strengthened beams b) Repaired beams

Figure 6 Load- deflection curves for beams with different strengthening techniques

3.1.4. Effect of connection between the adding concrete layer and the original beams

The effect of installing dowel bars or not between the thin concrete layer added to the soffit of the beams and the original beam could be observed by comparing the flexural behavior of the specimens SG-2b-A and SG-2b-B for the strengthened beams and the specimens RG-2b-A and RG-2b-B for the repairing beams with the reference beam, as shown in Fig. 7. This parameter had pronounced effect on the ultimate load of beams. Comparing with reference beam, the increasing in the ultimate load for the beams with installed dowel bars was 57 - 68% and for the beams without dowel bars was 36 - 46%. The reduction of the deflection at ultimate load of the reference beam was by 50 - 53%, and 53 - 56% for the beams with installed dowel bar and without dowel bar respectively.



a) Strengthened beams b) Repaired beams

Figure 7 Load- deflection curves for beams with different connection between the adding concrete layer and the original beam

3.2. Load carrying capacity

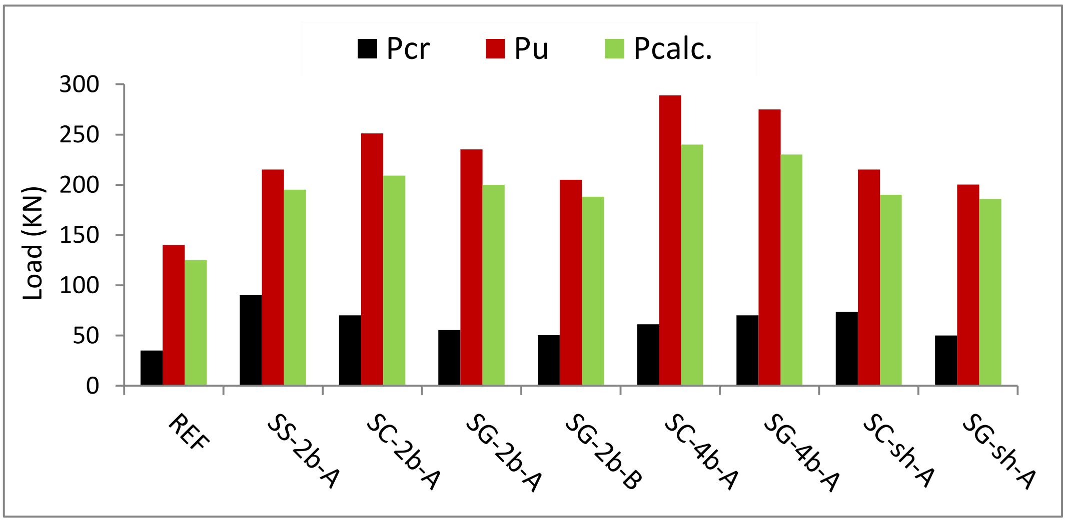
Fig. 8 demonstrated the load carrying capacities representing the first cracking and ultimate loads. The first cracking load *(P_{cr})* showed a notable increase for the strengthened and repaired beams by using steel bars (131-156%) compared by using FRP bars (42-100%) reinforced the adding lower concrete layer. The load carrying capacity (P_u) of the strengthened and repaired beams effectively enhanced. The average gain in P_u for the strengthened beams were 53-106% and for the repaired beams were 44-93%, which demonstrated a successful implementation of thin lower concrete layer reinforced with FRP or steel bars as strengthening system for RC beams.

With regard to the material types of reinforcing bars, which had the same tensile load, the CFRP bars showed higher enhancement in P_u than GFRP bars and steel bars. For beams strengthened with two CFRP bars gave higher capacity by 7% than beams strengthened by two GFRP bars and 17% than beams strengthened by two steel bars.

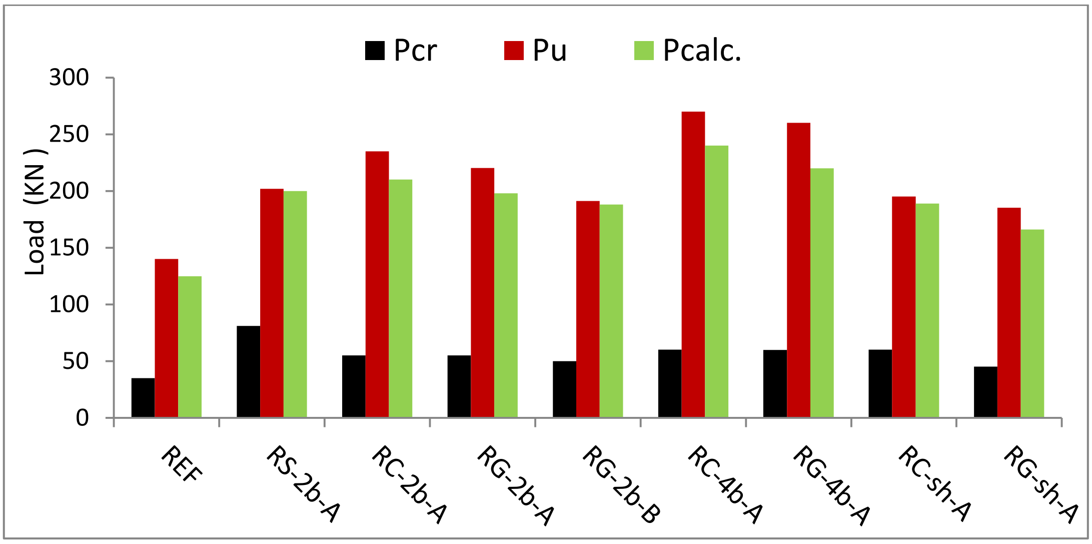
With regards to the amount of FRP bars, installing four FPR bars in the lower concrete layer instead of two FRP bars increased P_u by 15-18%. The gain in P_u was not proportional to the increasing in number of FRP bars. This disproportionality was due to the beams reinforced with two bars failed by rupture of FRP bars, which meaning the bars reached to its maximum tension capacity, but the beams reinforced with four bars failed by debonding of FRP bars.

As for the strengthening technique, replacing the two FPR bars reinforced the adding concrete layer by externally FRP sheets, having the same tensile force of the two FRP bars, bonded to the soffit of the concrete layer lowered the gain P_u. For beams externally strengthened by FRP sheets, the loss in P_u was 17-20 % compared with beams reinforced with two FRP bars. This is because of the external FRP sheets failed by debonding from concrete surface but for the bars installed in the concrete layer there was friction between the bars and the surrounding concrete.

Also, the type of connection between the adding concrete layer and the original beam had effect on the enhancement gain in P_u for strengthened and repaired beams. For beams without dowel bars installed between the adding concrete layer and the original beam, the gain in P_u lowered about 15% compared with the similar beams with installed dowel bars.



a) Strengthened beams



b) Repaired beams

Figure 8 Comparison between cracking load, experimental ultimate load and calculated ultimate load for all tested beams

3.3. Failure modes

All tested beams failed in flexure. The first crack formed at mid span, and spread towards the neutral axis of each beam. As the external applied load was increased, additional cracks developed. Many failure modes were observed during testing beams according to the type and the amount of reinforcing bars installed in the adding lower concrete layer and the strengthening technique used. Whatever, the failure modes, the tension steel reinforcement of the original beams was first yielded followed by the final failure mode. For beams reinforced with two bars of CFRP, GFRP or steel in the adding lower concrete layer, the final failure was due to rupture of FRP bars or steel yielding. Doubling amount of the FPR bars to be four CFRP bars or GFRP bars reinforced the lower concrete layer, changed the mode of failure to be debonding of the FRP bars. For beams externally strengthened with FRP sheets failed due to debonding of the strengthened sheets. Adding the lower concrete layer without installing dowel bars between it and the original beam led to the final failure mode was partial debonding between the concrete layer and the original beam. Typical failure modes of the tested beams are shown in Fig. 9.

3.4. Ductility

Ductility means the capability of a member to undergo inelastic deformation beyond the yield deformation without substantial loss of strength capability, and it provides warning of impending failure. The ductility is expressed in this study as the ratio of the deflection at the ultimate load to the deflection at the first crack load, as shown in Table 3. The ductility of beams strengthened by adding lower concrete layer reinforced by CFRP bars was the lowest comparing with the other used strengthened material due to highest modulus of elasticity of CFRP. The beams with four FRP bars as strengthening reinforcement had higher ductility by 32- 64% than the beams reinforced with two FRP bars only. This was due to the beams with two FRP bars failed by FRP rupture at a lower deflection value than the beams with four bar which failed by debonding FRP bars. The ductility of beams without dowel bars installed between the adding lower concrete layer and the original was less 23-31% than the beams with installed dowel bars due to the partial debonding of the concrete layer with strengthening reinforcement from the original beams. The beams externally bonded with FRP sheets was the lowest ductility from all strengthened and repaired beams due to the high ability of sheets to be deboned from concrete surface.

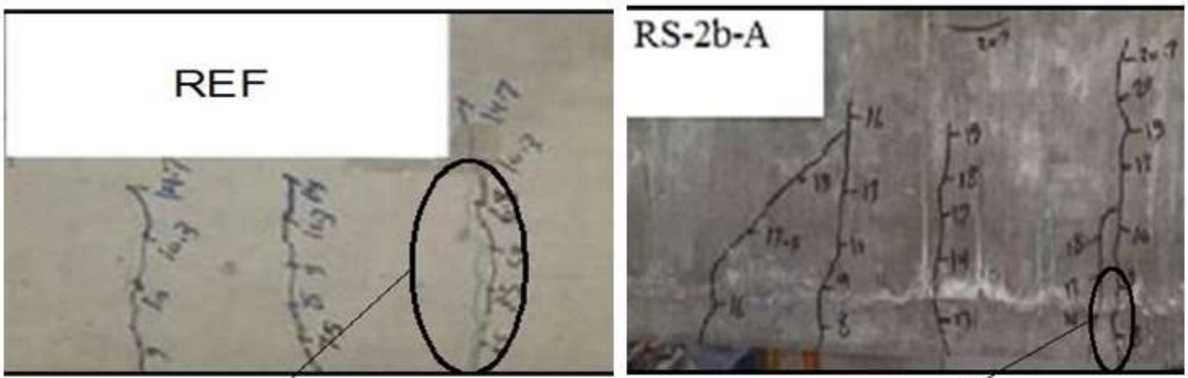
3.5. Stiffness

The un-cracked stiffness (Ki) and the ultimate stiffness (Ku) were calculated for the strengthened and repaired beams from the load and deflection values at cracking and ultimate loads as presented in Table 3. It shows Ki and Ku are affected by the type of the bars reinforced the adding lower concrete layer. Where, the Ki for beams reinforced with steel bars were higher by 28-56% than that reinforced with CFRP bars or GFRP bars. On the other hand, the Ku for beams reinforced with CFRP bars were higher by 52-70% than beams reinforced with GFRP bars and higher by 125-144% than beams reinforced with steel bars. This is because of the beams reinforced with steel bars had the highest first cracking load and the beams reinforced with CFRP bars had the highest ultimate load. The Ki of the beams reinforced with four FRP bars greater than the beams reinforced with two FRP bars by 24-36%. Externally strengthened beams by FRP sheets reduced Ki by 40-50% compared with the beams reinforced with two FRP bars in the adding concrete layer. Moreover, the Ku for the beams externally strengthened were less by 9-40% than the beams reinforced by two FRP bars. The amount of FRP bars reinforced the adding lower concrete layer and the type of connection between the adding lower concrete layer and original beam had slightly effect on Ku.

4. ANALYTICAL MODEL

The flexural capacity of tested beams was determined based on limit state principles, where the strain compatibility and the internal forces equilibrium have to be satisfied along the cross section. The FRP either bars or sheets treated as additional reinforcement with different material properties, with considering the assumptions that linear-elastic stress-strain of FRP until failure and no relative slip between FRP and concrete.

The ACI 440-2R-08 [21] was used to calculate the ultimate load of the strengthened and repaired beams to be compared to the ultimate load recorded during testing. All equations used and calculation steps are presented below:



Steel yielding of main reinforcement
a) Beam REF

Steel yielding of bars reinforced the adding concrete layer
b) Beam RS-2b-A

Figure 9 Typical failure modes for tested beams

Step 1: Computing the strain on the soffit of the original beam (ε_{bi})

For strengthening beams, the self–weight of the beam was small and the strain on the soffit was neglected. For the repairing beams, the strain on the soffit due to the pre-load applied to the beams before starting repairing was calculated using Eq. (1).

$$\varepsilon_{bi} = \frac{M_{bi}(d-k\,d)}{I_{cr}\,E_c} \tag{1}$$

Step 2: Assuming the depth of the neutral axis (C)

Assuming C = 0.15 from the effective depth of main reinforcing bars of the original beam (d) as an initial estimate value (C=0.15d). This value is adjusted after checking the internal force equilibrium.

Step 3: Calculating the strains in the concrete and the reinforcement of adding concrete layer using Eqs. (2) and (3)

$$\varepsilon_c = (\varepsilon_{fe} + \varepsilon_{bi})\left(\frac{c}{d_b - c}\right) \tag{2}$$

$$\varepsilon_{fe} = 0.003\left(\frac{d_b - c}{c}\right) - \varepsilon_{bi} \tag{3}$$

The maximum ε_c equal to 0.003 according to ACI 318-05 [22].The values of ε_{fe} depend on the failure modes of the strengthened and repaired beams. For beams failed by debonding of the FRP reinforcement, the ultimate value of ε_{fe} is obtained by multiplying the design rupture strain of FRP reinforcement (ε_{fu}) by the bond –depend coefficient of the FRP system. It is to be taken from the manufacturer and was considered as 0.7 in this study. For beams failed by rupture of the FRP bars, the value of $\varepsilon_{fe}$was taken equal to ε_{fu}. it was obtained from the FPR bars testing, as shown in Table 2.

The stain in the main steel reinforcement of the original beam determined based on the stain ε_{fe} using Eq. (4)

$$\varepsilon_s = (\varepsilon_{fe} + \varepsilon_{bi})(\frac{d-c}{d_f-c}) \tag{4}$$

Step 4: computing the stress level in the main steel reinforcement and the reinforcement of adding concrete layer using Eqs. (5) and (6)

$$f_s = E_s\ \varepsilon_s \ \leq f_y \tag{5}$$

$$f_{fe} = E_f\ \varepsilon_{fe} \tag{6}$$

Step 5: Calculate the internal force resultant and check equilibrium using Eq. (7)

$$C = \frac{A_s\ f_s + A_f\ f_b}{\alpha_1\ f_c'\ \beta_1\ b} \tag{7}$$

For the final failure due to FRP rupture or FRP debonding, the terms α_1 and β_1 in Eq. (8) have to be estimated from the parabolic stress –strain relationship for concrete and are expressed as in Eqs. (8) and (9).

$$\alpha_1 = \frac{3\ \varepsilon_c'\ \varepsilon_c - \varepsilon_c^2}{3\ \beta_1\ \varepsilon_c'^2} \tag{8}$$

$$\beta_1 = \frac{4\varepsilon_c' - \varepsilon_c}{6\ \varepsilon_c' - 2\ \varepsilon_c} \tag{9}$$

Where $$\varepsilon_c' = \frac{1.7\ f_c'}{E_c} \tag{10}$$

Step 6: The C value revised and the procedure repeated if the internal force resultants did not equilibrate.

Step 7: Calculating the ultimate flexural capacity using Eqs. (11) - (13).

$$M_{ns} = A_s\ f_s\ (\ d - \frac{\beta_1\ C}{2}) \tag{11}$$

$$M_{nf} = A_f\ f_{fe}\ (\ d_b - \frac{\beta_1\ C}{2}) \tag{12}$$

$$M_{total} = M_{ns} + \varphi_f\ M_{nf} \tag{13}$$

The calculated values of ultimate load against the measured one for all tested beams are given in Table 3 and Fig 9. The ACI 440 slightly underestimates the flexural capacity. It was for all strengthened and repaired beams with an average difference of 12% compared to the experimental results.

5. LIST OF NOTATIONS

$\boldsymbol{A_f}$:area of reinforcing bars or FRP sheets (mm^2)

$\boldsymbol{A_s}$:area of main steel reinforcement (mm^2)

$\boldsymbol{C}$:distance from extreme compression fiber to the neutral axis(mm)

$\boldsymbol{d}$:distance from extreme compression fiber to centroid of main steel reinforcement (mm)

$\boldsymbol{d_b}$: effective depth of reinforcing bars or FRP sheets (mm)

$\boldsymbol{E_c}$: modulus of elasticity of concrete (N/mm^2)

$\boldsymbol{E_f}$:tensile modulus of elasticity of FRP bars or FRP sheets (N/mm^2)

$\boldsymbol{E_s}$: modulus of elasticity of steel (N/mm^2)

$\boldsymbol{f_c'}$: specified compressive strength of concrete (N/mm^2)

$\boldsymbol{f_{fe}}$:effective stress in reinforcing bars or FRP sheets at failure (N/mm^2).

$\boldsymbol{f_{fu}}$: design ultimate tensile strength of reinforcing bars or FRP sheets (N/mm^2)

$\boldsymbol{f_s}$: stress in steel reinforcement (N/mm^2)

$\boldsymbol{f_y}$: yield stress of steel reinforcement (N/mm^2)

$\boldsymbol{I_{cr}}$: moment of inertia of cracked section (mm^4)

$\boldsymbol{K}$: ratio of depth of neutral axis to reinforcement depth measured from extreme compression fiber

$\boldsymbol{M_{bi}}$: moment due to pre-load applied to the repaired beams (N.mm)

$\boldsymbol{\alpha_1}$:multiplier on f_c' to determine intensity of an equivalent rectangular stress distribution for concrete

$\boldsymbol{\beta_1}$: ratio of depth of equivalent rectangular stress block to depth of the neutral axis

$\boldsymbol{\varepsilon_{bi}}$: strain level in concrete substrate at time of installation reinforcing bars

$\boldsymbol{\varepsilon_c}$: strain level in concrete.

$\boldsymbol{\varepsilon_c'}$: maximum strain of unconfined concrete corresponding to f_c'

$\boldsymbol{\varepsilon_{fe}}$: effective strain level in reinforcing bars or FRP sheets attained at failure

$\boldsymbol{\varepsilon_{fu}}$: design rupture strain of FRP bars or FRP sheets

$\boldsymbol{\varphi_f}$: FRP strength reduction factor = 1 for flexure

6. CONCLUSIONS

Seventeen RC beams strengthened and repaired at tension side by adding thin concrete layer reinforced with different types of reinforcing bars (CFRP, GFRP and steel). The test parameters included the type of strengthening material, the amount of FRP bars, the strengthening technique and the type of connection between the adding concrete layer and the original beam. Based on the analysis and comparison of mode of failure, load carrying capacity, load-deflection behavior, ductility and stiffness of the tested beams, the following conclusion can be drawn:

The strengthening and repairing system by adding thin concrete layer reinforced with FPR or steel bars and installing dowel bars between the concrete layer and the soffit of the original beams was significantly enhanced the flexural behavior of tested beams. The initial cracking load and the ultimate load increased by 57- 156% and 44% -106% respectively compared with the reference beam. Also, the deflections were notably reduced by a 50 % - 75%, compared to the reference beam at its ultimate load.

For all tested beams, the failure began firstly by steel yielding of main reinforcement of the original beam followed by the final failure which was different modes. For the beams reinforced with lower bars in the adding concrete layer, failed by rupture of FPR bars or yielding of steel bars. Increasing the amount reinforcing FPR bars, changed the final failure to be debonding of FPR bars. The failure of beams externally strengthened by FRP sheets was the classic FRP sheet debonding. Partial deboning between the added concrete layer and the soffit of original beam was the final failure for beams without installed dowel bars between the two contact concrete surfaces.

The strengthened and repaired beams reinforced with CFRP bars gave the greatest ultimate capacity, then that reinforced with GFRP bars, and finally beams reinforced with steel bars. However, the beams reinforced with CFRP showed the lowest ductility.

The increase in the ultimate capacity for strengthened and repaired beams reinforced with four FRP bars was 15-18% more than that for beams reinforced with two FRP bars. This indicates that doubling the amount of FRP bars had not the same impact on the ultimate capacity. Moreover, the beams reinforced with four bars had higher ductility than that reinforced with two bars by 21-64%. This is because the failure was due to FRP debonding for beams reinforced with four FPR bars.

Installing dowel bars between the adding lower concrete layer and the original beams had remarkable effect on improving the ultimate capacity and ductility of strengthened and repaired beams. For beams without installing dowel bars, the ultimate capacity and ductility reduced by 14% and 19-24%, respectively compared with that having installed dowel bars.

The beams strengthened and repaired by externally bonded FRP sheets had the lowest ultimate capacity and ductility due to the prone of FRP sheets to premature deboned from concrete surface.

The un-cracked stiffness improved for all strengthened and repaired beams , except the beams externally bonded with FRP sheets which had un-cracked stiffness lower than the reference beam. Also, the ultimate stiffness significantly enhanced especially with using CFRP bars as reinforcement for the adding concrete layer.

The predicated of ultimate flexural capacity of the strengthened and repaired beams using ACI 440 equations were very reasonable and conservative with an average of 12% compared to experimental results.

REFERENCES

[1] Al-Salloum, Y. A., El-Gamal, S., Almusallam, T. H., Alsayed, S. H., and Aqel, M., “Effect of harsh environmental conditions on the tensile properties of GFRP bars”, J. of Composites. B, V. 45, No. 1, 2013, pp. 835-844.

[2] T. Norris, H. Saadatmanesh, M.R. Ehsani, "Shear and flexural strengthening of R/C beams with carbon fiber sheets", J. Struct. Eng., V.123, No.7, 1997, pp.903–911.

[3] P.A. Ritchie, D.A. Thomas, L.W. Lu, G.M. Conelly, "External reinforcement of concrete beams using fiber reinforced plastics", ACI Struct. J., V. 88, No.4, 1991.

[4] T.C. Triantafillou, N. Plevris, "Strengthening of RC beams with epoxy-bonded fiber-composite materials", Mater. Struct., V. 25, No.4, 1992, pp. 201–211.

[5] H. Akbarzadeh, A.A. Maghsoudi, "Experimental and analytical investigation of reinforced high strength concrete continuous beams strengthened with fiber reinforced polymer", Mater. Des., V.31, No. 3, 2010, pp. 1130–1147.

[6] N. Attari, S. Amziane, M. Chemrouk, "Flexural strengthening of concrete beams using CFRP, GFRP and hybrid FRP sheets", Constr. Build. Mater., V. 37, 2012, pp.746–757.

[7] Y. Zhou, M. Gou, F. Zhang, S. Zhang, D. Wang, "Reinforced concrete beams strengthened with carbon fiber reinforced polymer by friction hybrid bond technique: experimental investigation", Mater. Des., V. 50, 2013, pp. 130–139.

[8] I.A. Sharaky, L. Torres, M. Baena, I. Vilanova, "Effect of different material and construction details on the bond behaviour of NSM FRP bars in concrete", Constr. Build. Mater., V. 38, 2013, pp. 890–902.

[9] I.M. Qeshta, P. Shafigh, M.Z. Jumaat, A.I. Abdulla, Z. Ibrahim, U.J. Alengaram, "The use of wire mesh–epoxy composite for enhancing the flexural performance of concrete beams", Mater. Des., V. 60, 2014, pp.250–259.

[10] L. De Lorenzis, Strengthening of RC structures with near surface mounted FRP rods, PhD Thesis, University of Lecce, Italy, 2002.

[11] De Lorenzis, L., Rizzo, A., and La Tegola, A., “A modified pull-out test for bond of near-surface mounted FRP rods in concrete”, J. of Composites. B, V. 33, No. 8, July. 2002, pp. 589-603.

[12] W.T. Jung, Y.H. Park, J.S. Park, J.Y. Kang, Y.J. You, "Experimental Investigation on Flexural Behavior of RC Beams Strengthened by NSM CFRP Reinforcements", ACI Special Publication, V.230, 2005, pp.795-806.

[13] W.C. Tang, R.V. Balendran, A. Nadeem, H.Y. Leung, "Flexural strengthening of reinforced lightweight polystyrene aggregate concrete beams with near surface mounted GFRP bars", Build. Environ, V.41, No. 10, 2006, pp.1381–1393.

[14] F. Al-Mahmoud, A. Castel, R. François, C. Tourneur, "Strengthening of RC members with near-surface mounted CFRP rods", Compos. Struct., V. 91, No.2, 2009, pp. 138–147.

[15] Almusallam, T. H., Elsanadedy, H. M., Al-Salloum, Y. A., and Alsayed, S. H., “Experimental and numerical investigation for the flexural strengthening of RC beams using near-surface mounted steel or GFRP bars”, J. of Construction and Building Materials, V. 40, 2013, pp. 145-161.

[16] I.A. Sharaky, L. Torres, J. Comas, C. Barris, "Flexural response of reinforced concrete (RC) beams strengthened with near surface mounted (NSM) fiber reinforced polymer (FRP) bars", Compos. Struct., V.109 , 2014, pp. 8–22.

[17] A. Bilotta, F. Ceroni, E. Nigro, M. Pecce, "Efficiency of CFRP NSM strips and EBR plates for flexural strengthening of RC beams and loading pattern influence", Compos. Struct., V.124, 2015, pp. 163-175.

[18] El-Gamal, S. E., Al-Nuaimi, A., Al-Saidy, A., & Al-Lawati, A., "Efficiency of near surface mounted technique using fiber reinforced polymers for the flexural strengthening of RC beams", Construction and Building Materials, V.118, 2016, pp.52-62.

[19] L. De Lorenzis, J.G. Teng, "Near-surface mounted FRP reinforcement: an emerging technique for strengthening structures", Compos. B Eng., V. 38, No.2, 2007, pp. 119–143.

[20] Hosen, M. A., Jumaat, M. Z., & Islam, A. S., "Side near Surface Mounted (SNSM) technique for flexural enhancement of RC beams", Materials & Design, V. 83, 2015, pp.587-597.

[21] ACI 440.2R-08, Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, American Concrete Institute, Farmington Hills, Mich, USA, 2008.

[22] ACI Committee 318, Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary (318R-05), American Concrete Institute, Farmington Hills, MI, 2005. 430 pp.