Improving the Flexural Performance of Reinforced Concrete One-Way Slabs

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Abstract

This research presents an experimental study on flexural strengthening of reinforced concrete one-way slabs with two different systems. The first system is the conventional concrete overly and the second system is the Carbon Fiber Reinforced Polymer (CFRP) strengthening. The suggested combination between the two systems is also studied. The experimental investigation was conducted using six small size one-way slab specimens. All slabs were tested to failure under simply supported conditions. The both strengthening systems increased the flexural strength and reduced the deflections and crack widths of the strengthened slabs. Two modes of failure were observed, debonding and rupture of the CFRP reinforcement. Significant increase in ultimate flexural capacity ranging from 13% to 139% was registered in all the strengthening slabs, as compared to the control slab. The slab which was strengthened with suggested combination strengthening system exhibited the highest efficiency.

الخلاصة

قدم هذا البحث دراسة مختبرية لنظامين مختلفين في تقوية الانحناء في السقوف الخرسانية الأحادية الاتجاه, النظام الأول هو الطريقة التقليدية في إضافة طبقة خرسا نية أما النظام الثاني فيتضمن استخدام البوليمرات المقواة بألياف الكاربون, كما تم دراسة النظام المركب. الدراسة المختبرية تمت باستخدام ستة نماذج مصغرة من السقوف أحادية الاتجاه, والتي تم فحصها لحد الفشل تحت تأثير شروط الإسناد البسيط. لقد وجد إن كلا الطريقتين في التقوية زادت من مقدار مقاومة الانحناء القصوى مع تقليل مقدار الهطول وعرض التشققات . وعند المقارنة مع نموذج السيطرة للسقوف تراوح مقدار الزيادة في مقاومة الانحناء القصوى من13% إلى 139% للسقوف الخرسانية المقواة كما وجد إن السقف المقوى بالطريقة المركبة التي تم اقتراحها في هذه الدراسة قد أعطى أعلى كفاءة.

1. Introduction

The need for strengthening reinforced concrete structures to the original or higher performance level due to mechanical damage, mistakes in design and/or construction works, functional changes or reinforcement corrosion has become common and necessary for economic reasons. It may also be necessary to strengthen old reinforced concrete structures as a result of damage in the structure due to environmental stresses or military operations.

In the past, reinforced concrete slabs were strengthened by conventional methods such as concrete overlay, span shortening and externally bonded steel reinforcement. Today there are several types of CFRP strengthening systems and techniques available to strengthen reinforced concrete slabs. The suitability of each system depends on the type of structure that shall be strengthened. Therefore, it is essential for engineers to understand the consequences of the design choice in terms of efficiency and failure mechanism for different systems before further attempts are carried out (Tan 2003).

Concrete overlay is a conventional strengthening technique. The additional concrete overlay increases the lever arm of the moment resisting of the concrete section (Aprile et al., 2007). Detachment between the bare concrete and the new concrete overlay was observed during the tests, see Figure (1-a).

Many researchers conducted experimental and analytical studies on concrete slabs strengthened in flexure using FRP strengthening system (for example; Alkhrdaji et al. 1999, Tan 2003, and Costeira et al. 2007). The results have shown that externally bonded FRP sheets may be used to rehabilitate the entire behavior of slabs.

However, one limitation in strengthening slabs is that the failure behavior at the ultimate load may become non-ductile, see Figure (1-b).

The main objective of this research is to study and compare the efficiencies of the conventional concrete overlay and relatively new CFRP strengthening system. The suggestion of combined system from these two systems is become necessary.

(a): Detachment of concrete overlay (Aprile et al., 2007)

(b): CFRP debonding (Tan, 2002)

Figure (1): Failure mode of strengthened RC one-way slab

2. Experimental program

This experimental study consisted of casting six reinforced concrete one-way slabs. Each slab had a 300 mm× 60 mm cross section. The flexural reinforcement of these slabs consisted of 5-Ø6 mm in the main direction and Ø6 mm @ 100 mm in the transverse direction. The flexural reinforcement ratio is 0.84% and it is below the maximum reinforcement ratio allowed under the current ACI 318-05 code (2005). Figure (2) shows the cross section and the reinforcement details for the bare slab specimens.

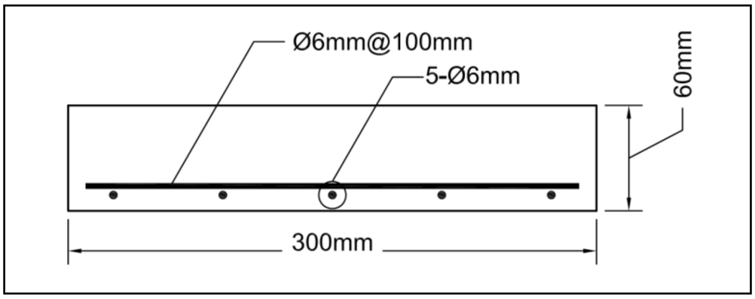


Figure (2): Cross-section of bare concrete slab

2.1 Concrete materials

2.1.1 Cement

Ordinary Portland cement of Tasluja-Bazian mark was used in casting all the specimens. The cement was stored in air-tight plastic containers to avoid undue exposure to the atmosphere Physical and chemical composition and properties for the used cement are given in Tables (1) and (2), respectively. The properties are conformed to the Iraqi Specifications Limits (I.Q.S. 5/1984).

Table (1): Physical properties for cement

Property		Result	Iraqi specification limits (I.Q.S. 5/1984)
Fineness by air permeability method (Blaine)		348 m^2/kg	Not less than 230 m^2/kg
Initial setting		125 min.	Not less than 45 min.
Final setting		230 min.	Not more than 600 min.
Soundness (Autoclave Method)		0.28%	Not more than 0.8%
Compressive strength	3-day age	22.8 MPa	Not less than 15 MPa
	7-day age	31.5 MPa	Not less than 23 MPa

Table (2): Chemical analysis and compound composition for cement

Oxides	Content,%	Iraqi specification limits (I.Q.S. 5/1984)
CaO	62.31	----
SiO_2	21.28	----
MgO	2.77	----
Fe_2O_3	3.60	----
Al_2O_3	5.31	----
SO_3	2.45	Not more than 2.8% if C_3A more than 5%
Free Lime	1.06	----
L.O.I	1.73	Not more than 4%
I.R	0.85	Not more than 1.5%
L.S.F	0.87	0.66%-1.02%
Compound composition		
C_3S	39.61	----
C_2S	31.13	----
C_3A	8.52	----
C_4AF	10.95	----

2.1.2 Fine aggregate

Al-Akhaider natural sand was used as fine aggregate. The sand was sieved at sieve size 4.75mm to get rid of coarse aggregate. The sand was then washed and cleaned with water several times, later it was spread out and left to dry in air, after which it was ready for use. The grading of the sand was conformed to the requirements of Iraqi Specifications Limits (I.Q.S. 45/1984) as shown in Table (3). Also, physical properties of fine aggregate are shown in Table (4).

Table (3): Grading of fine aggregate

Sieve size (mm)	Passing (%)	Iraqi specification limits (I.Q.S. 45/1984)
10	100	100
4.75	99	90-100
2.36	85	75-100
1.18	68	55-90
0.60	46	35-59
0.30	14	8-30
0.15	2	0-10

Table (4): Physical properties of fine aggregate

Properties	Test results	Iraqi specification limits (I.Q.S. 45/1984)
Grading Zone	Second	----
Fineness Modulus	2.80	----
Sulfate content (SO_3)	0.38%	Not greater than 0.5%
Materials finer than sieve No. 200,%	2%	Not greater than 5%

2.1.3 Coarse aggregate

Crushed gravel from Al-Nibaey region was used throughout this work with a maximum size of 14mm to account for concrete cover. The gravel was washed and cleaned with water several times and left to dry in air. Table (5) shows the grading of aggregate and the limits specified by Iraqi Specifications (I.Q.S. 45/1984). Physical properties of the coarse aggregate are shown in Table (6).

Table (5): Grading of coarse aggregate

Sieve size (mm)	Passing (%)	Iraqi specification limits (I.Q.S. 45/1984)
20	100	100
14	99	90-100
10	85	50-85
5	68	0-10

Table (6): Physical properties of coarse aggregate

Properties	Test results	Iraqi specification limits (I.Q.S. 45/1984)
Specific gravity	2.60	----
Bulk density	1650 kg/m^3	----
Sulfate content (SO_3)	0.09%	Not greater than 0.1%
Materials finer than sieve No. 200,%	3%	Not greater than 3%

2.1.4 Mixing water

Ordinary tap water was used for casting and curing all the specimens.

2.1.5 Concrete mix design

During the design phase of the experimental program, (20-30) MPa concrete compressive strength was chosen for the bare slab to mimic an older reinforced concrete one-way slab that would be subject to strengthening. High strength concrete (greater than 42 MPa) may be used for concrete overlay strengthening. Two different concrete strengths are obtained by using different cement content and water to cement ratios. The proportion of the two mixtures is presented in Table (7).

Table (7): Concrete mix proportions

Concrete type	Cement (kg/m^3)	Water (kg/m^3)	w/c ratio	Super plasticizer (%)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)
Bare slab (20-30) MPa	350	210	0.60	----	1000	750
Overlay (≥ 42) MPa	450	185	0.41	1.0	1050	750

2.1.6 Concrete cylinders

To obtain a measure of the compressive strength of concrete, five cylinders (200×100) mm were cast from the concrete of each slab specimens. Three cylinders were tested in uniaxial compression with each slab specimens at the same time to obtain the compressive strength using ELE Testing Machine (Capacity 200 Ton) in accordance with ASTM C39/C39M-05 (2005). The remained two cylinders were tested for indirect tension by applying a line load along the 200 mm long side to obtain the splitting tensile strength in accordance with ASTM C496/C496M-04 (2005). The cylinder test results are summarized in Table (8).

Table (8): Tests results for concrete cylinders

Specimen	Bare slab		Overlay	
	Compressive strength (MPa)	Tensile strength (MPa)	Compressive strength (MPa)	Tensile strength (MPa)
UP-0	31.8	2.5	----	----
UP-1	31.5	2.5	----	----
RP-0	32.3	2.3	40.4	2.6
RP-1	31.1	2.4	43.0	2.8
RP-2	32.5	2.4	43.5	2.8
RN-2	31.8	2.3	48.9	2.9

2.2 Steel reinforcing bars

For all slab specimens, two sizes of steel reinforcing bars were used. Values for yield and ultimate strength are given in Table (9).

Table (9): Reinforcing steel properties

Diameter	Yield strength (MPa)	Yield strain	Ultimate strength (MPa)	Ultimate strain
6mm	708	0.0034	740	0.051
4mm	715	0.0032	750	0.054

2.3 Concrete overlay process

Concrete overlay is a conventional strengthening technique. The additional concrete overlay increases the lever arm of the moment resisting of the concrete section. Here, 30 mm thick concrete layer were used as concrete overlay. The minimum steel reinforcement was used (Ø4 mm @ 100 mm) for each direction. To prevent shear failure at the interface between the old concrete (bare RC slab) and the concrete overlay, Quickmast®-108 (epoxy bonding agent) was applied after superficial cleaning and concrete dust suction. Figures (3) and (4) show the concrete overlay details.

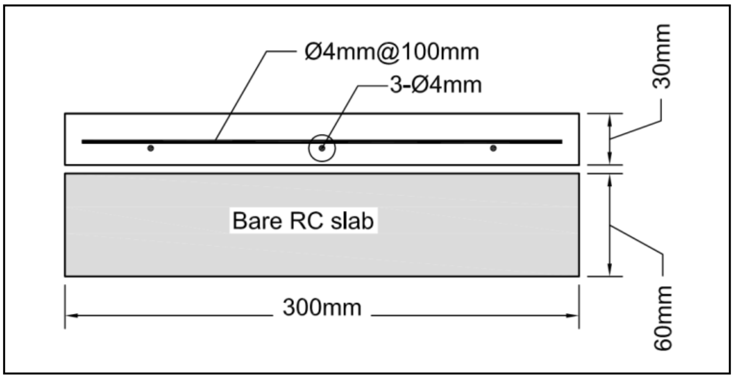
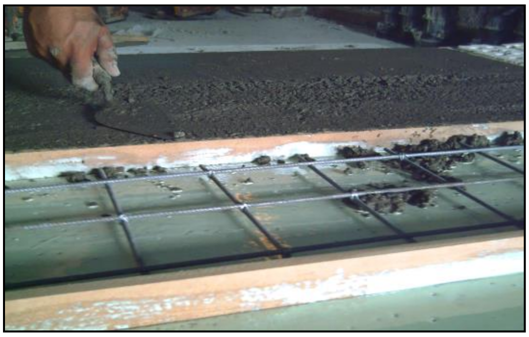


Figure (3): Reinforcement details of the concrete overlay

(a): Application of Quickmast®-108



(b): Casting of concrete overlay

Figure (4): Concrete overlay process

2.4 CFRP strengthening process

When loaded in tension, CFRP fibers do not exhibit any plastic behavior before rupture. SikaWarp®Hex-230C carbon fibers were used as flexural strengthening. The most crucial part of any strengthening application is the bond between the FRP and the surface to which the FRP is bonded. Proper bond ensures that the force carried by the structural member is transferred effectively to the FRP (Al-Mahaidi, 2003). Before the CFRP was applied to the soffit of the slabs, the surface of the concrete is grinded using an electrical hand grinder to expose the aggregate and to obtain a clean sound surface, free of all contaminants such as cement laitance and dirt, see Figure (5). Then, Sikadur®-330 (two-part epoxy impregnation resin) was used in this work for the bonding of CFRP sheet. The impregnation resin was mixed in 1:4 ratio by volume until it was uniform and spread to areas where the CFRP sheet has contact.

A two-part adhesive (black and white) was mixed in required proportion, until the color was a uniform grey, and then applied with a special tool to the concrete surface to a thickness of 1.5 mm. The adhesive was also applied to the CFRP sheet to the same thickness. The CFRP sheet was then placed on the concrete ,epoxy to epoxy ,and a rubber roller was used to properly seat the CFRP sheet by exerting enough pressure so the epoxy was forced out on both sides of the CFRP sheet and the adhesive line did not exceed 2 mm in thickness.

The mechanical properties of carbon fibers and impregnation resin are taken from manufacturing specifications (Sika, 2005) and as shown in Table (10) and (11), respectively.

Table (10): Technical properties of CFRP sheets (from manufacturer)

Properties	SikaWarp® Hex-230C
Tensile strength (MPa)	>3500
E-modulus (GPa)	230
Elongation at break (%)	>1.5
Width (mm)	50
Thickness (mm)	0.13

Table (11): Technical properties of impregnation resin (from manufacturer)

Properties	Sikadur®-330
Tensile strength , MPa	> 30
Bond strength , MPa	Concrete fracture
E-modulus , GPa	4.5
Open time , min.	30 (at +35°C)
Full cure , days	7(at +35°C)
Mixing ratio	1:4

(a): Grinding for concrete surface **(b): Final setting of CFRP**

Figure (5): CFRP strengthening process

2.5 Specimen Identification and Strengthening Schemes:

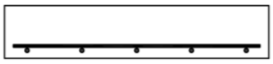
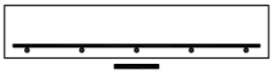
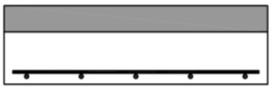
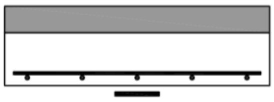
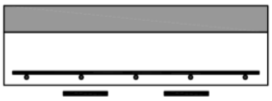
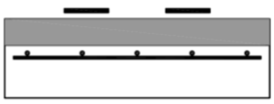
In order to identify the test specimens with different strengthening schemes, the following designation system is used:

- Concrete overlay: (R) for specimen with concrete overlay and (U) for specimen without concrete overlay.
- Loading type: (P) for positive moment and (N) for negative moment.
- Number of CFRP strengthening layer strips: (1) or (2).

Table (12) illustrates the specimen identification system used based on the specimen identification pattern described above.

As seen in Table (12) slab specimen UP-0 is not strengthened and directly subjected to the test loading to assess the structural performance of the control specimen. All of the remaining specimens are strengthened with concrete overlay and/or CFRP strengthening in order to evaluate the structural performances of the upgraded systems. Slab specimens UP-1 and RP-0 provided a comparison between the CFRP strengthening and concrete overlay techniques. The remaining two slab specimens (RP-1 and RP-2) are used to assess the effect of the amount of CFRP reinforcement. Finally, slab specimen RN-2 was tested with the restored concrete surface downside, in order to simulate the behavior of concrete slab sections at the supports and subjected to negative bending.

Table (12): Slab specimens characteristics

Specimen	Specimen cross section	Notes
UP-0		No concrete overlay No CFRP strengthening
UP-1		No concrete overlay 1-CFRP sheet strengthening applied to the bare concrete
RP-0		Concrete overlay No CFRP strengthening
RP-1		Concrete overlay 1-CFRP sheet strengthening applied to the bare concrete
RP-2		Concrete overlay 2-CFRP sheet strengthening applied to the bare concrete
RN-2		Concrete overlay 2-CFRP sheet strengthening applied to the concrete overlay

2.6 Test setup

All of the slab specimens were finally subjected to three-point tests up to failure. The load was applied making use of 200 Ton capacity Universal Testing Machine. The distance between the specimen supports was 800mm, see Figure (6). Deflection of the slab specimens was measured at mid-span using a dial gage with travel distance of 50 mm and accuracy of 0.01 mm. To observe crack development, beam specimens were painted white with emulsion paint before testing. Cracks were traced by pencil.

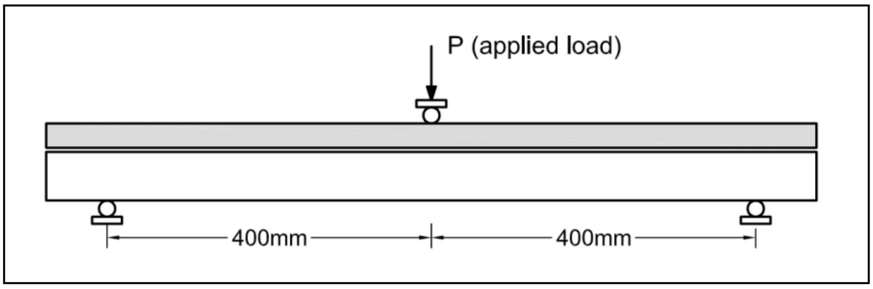


Figure (6): Test setup for slab specimens

3. Experimental results

The main objective of the current research work is to investigate the two different strengthening systems on the flexural behavior of reinforced concrete one-way slabs. Test results were analyzed based on load-deflection curves, first cracking load, cracking behavior, ultimate load, failure modes and ductility.

3.1 Load-deflection curves

The load vs. deflection curves for all the slab specimens are shown in Figure (7). Generally, it can be observed that the load versus mid-span deflection response can be divided into three stages of behavior. The first stage was characterized by an approximately linear relationship between the load and the mid-span deflection. During this stage of behavior, the section was uncracked and both the concrete and steel, in addition to the CFRP sheet, behave essentially elastic.

The second stage represents the behavior beyond the initial cracking of the composite section where the stiffness of the slab was decreased as indicated by the reduced slope of the load versus mid-span deflection curve. The end of this stage was distinguished when the main steel reinforcement start to exhibit inelastic behavior.

The third stage was characterized by a decreasing slope of the curve, where the tension steel reinforcement reaches the strain hardening stage.

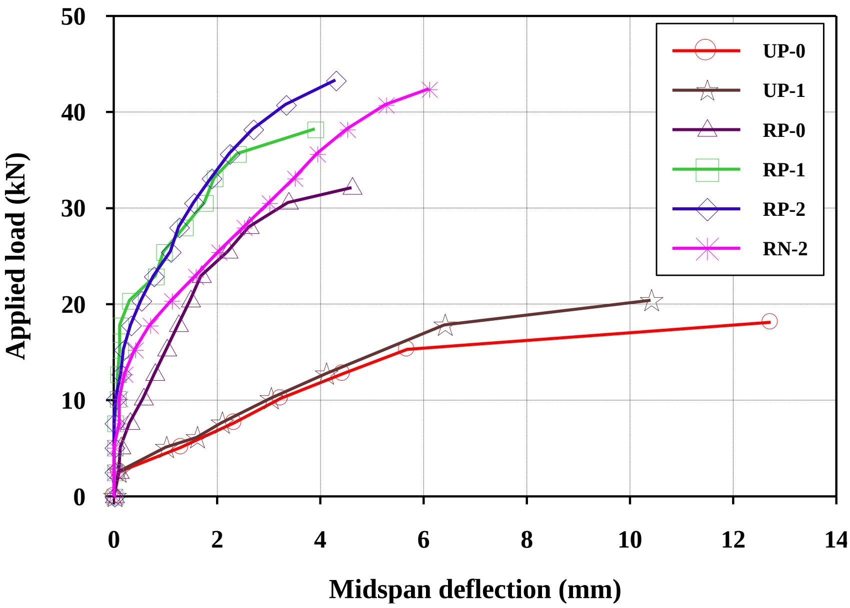


Figure (7): Load vs. Mid-span deflection curves

The first crack was observed in control slab specimen UP-0 immediately after applying the load at 2.6 kN and yielded after load of 15.3 kN was placed. The control slab continued to deform thereafter. The same behavior was observed for slab specimen UP-1. The maximum deflection prior to failure for these specimens was 12.7 mm and 10.4 mm, respectively.

The influence of concrete overlay on the stiffness of the slab was clearly observed in slab RP-0. Slab RP-0 showed higher stiffness than control slab until it reached 22.9 kN, at which point the internal steel reinforcement started to yield. It is exhibited a lower deflection as compared to control slab at the same load level. The maximum deflection prior to failure was 4.6 mm.

Slab RP-1 and slab RP-2 behaved similarly, with roughly linear response and stiffness greater than the control slab. They started to crack at 17.8 kN and yielded after load of 35.7 was placed. Slab specimens RP-1 and RP-2 showed an increase in first cracking load of 6.8 times, when compared with the control slab specimen UP-0. The maximum deflections for these slabs prior to failure were 3.9 mm and 4.3 mm, respectively. Finally, slab RN-2 started to crack at 12.7 kN. After that, it is exhibited a lower stiffness as compared to Slabs RP-1 and RP-2. The maximum deflection prior to failure was 6.1 mm.

Comparison between slab specimens at different loading stages can be presented in Figure (8). It is observed that the slab which was strengthened with suggested combined (concrete overlay plus CFRP composites) strengthening systems (i.e. slab specimens RP-2 and RN-2) exhibited the highest efficiency.

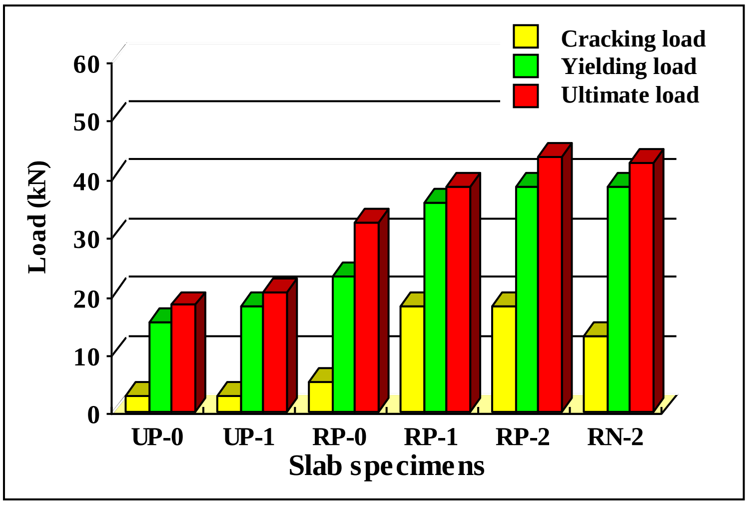


Figure (8): Comparison between slab specimens at different loading stages

3.2 Ultimate load and mode of failure

A measure of the efficiency of different systems can be obtained by considering the mode of failure and the failure loads of the slabs. Results are presented in Table (13) and Figure (9). The control slab specimen UP-0 behaved in expected fashion under flexural loading. As loads increased, flexural cracks increased in number, width and depth. Failure of the control slab was by yielding of steel followed by crushing of the concrete at the compression fiber, see Figure (9-a).

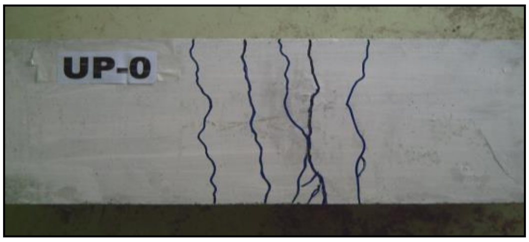
Slab specimen UP-1 showed an increase of only 13% in ultimate load capacity when compared to control slab specimen, and this limited increase in percentage gain in strength is due to the reduced amount of CFRP laminate used. Failure of this slab was by CFRP rupture in mid span occurred at 20.4 kN. Crack pattern after the failure of this slab is shown in Figure (9-b).

Slab specimen RP-0 showed a reduction of deflection compared to the control slab. No sing of detachment between the bare slab and the concrete overlay was observed. The failure load was 32.1 kN, which was 77% higher than that of the control slab. Failure of the test specimen was by yielding of steel followed by crushing of the concrete at the compression fiber in concrete overlay. Crack pattern after the failure of this slab is shown in Figure (9-c).

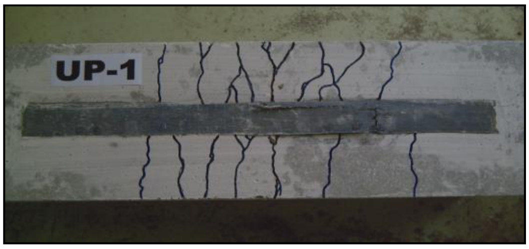
Slab specimen RP-1 failed in a sudden and brittle manner caused by rupture of CFRP at the mid span. The failure load was 38.2 kN, which was 111% higher than that of the control slab. The ruptured remains of carbon fiber sheet at both ends of the slab were still attached firmly to the concrete substrate. Figure (9-d) shows the cracks pattern after the failure of slab RP-1.

In slab specimen RP-2 the formation of flexural cracks that occurred as a result of the yielding of the steel reinforcement generated high stresses in the CFRP plate across the cracks. Since the concrete could not maintain the interface shear and normal stresses, the CFRP plates snapped from the concrete substrate. The failure load was 43.3 kN, which was 139% higher than that of the control slab. This relatively high percentage in ultimate load gain was due to the fact that slab specimen RP-2 was strengthened with the combined strengthening system. Crack pattern after the failure of this slab is shown in Figure (9-e).

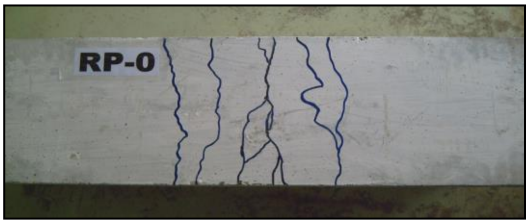
Slab specimen RN-2 results in 134% increase in its ultimate load capacity when compared with control slab specimen UP-0. Failure of the test specimen was by CFRP rupture at the mid span. Crack pattern after the failure of this slab is shown in Figure (9-f).



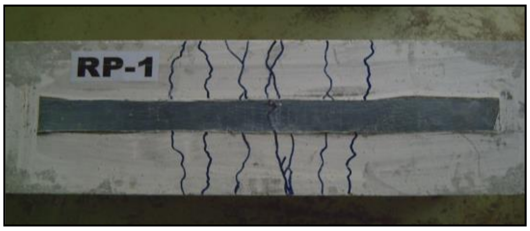
(a) Slab UP-0



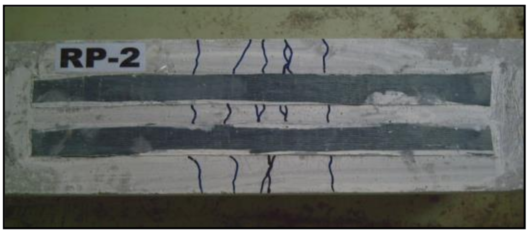
(b) Slab UP-1



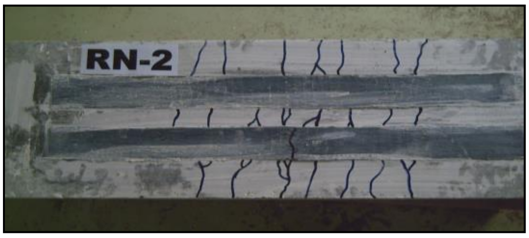
(c) Slab RP-0



(d) Slab RP-2



(e) Slab RP-2



(f) Slab RN-2

Figure (9): Crack patterns after failure for the slab specimens

Table (13): Ultimate load capacity and failure mode

Specimen	Ultimate load , kN	Increase in ultimate load,%	Failure mode
UP-0	18.1	N/A	Typical flexural failure
UP-1	20.4	13	CFRP rupture at mid-span
RP-0	32.1	77	Typical flexural failure
RP-1	38.2	111	CFRP rupture at mid-span
RP-2	43.3	139	CFRP debonding at mid-span
RN-2	42.4	134	CFRP rupture at mid-span

3.3 Ductility Ratios

The ductility of a flexural member can be defined as its ability to sustain inelastic deformation without loss in its load carrying capacity prior to failure and can be expressed as the ratio of ultimate deformation to deformation at yield. Here, deflection will be used as the primary measurement of ductility. The ductility ratio values for the slab specimens are presented in Figure (10) and it can be seen that the ductility ratio of the slab specimens decreases significantly.

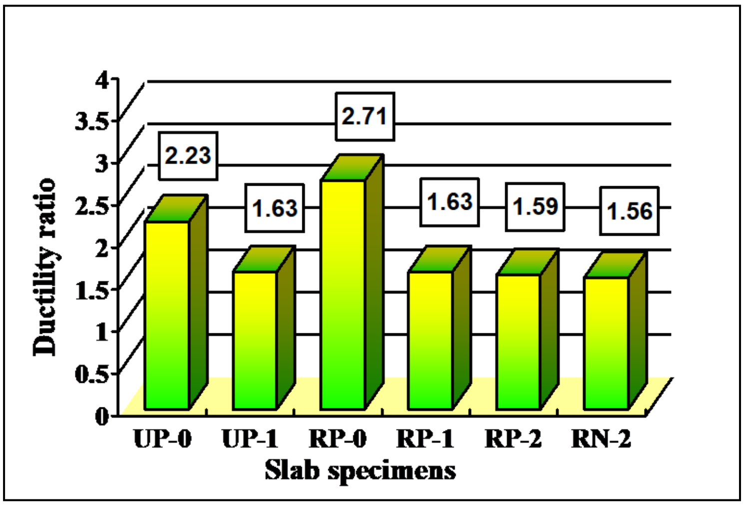


Figure (10): Ductility ratio for the tested slabs

4. Conclusions and recommendations

Based on the results obtained from the experimental work, the following conclusions are presented:

1. For the tested slab externally strengthened with CFRP strengthening system, the ultimate flexural load is increased by 13%. No increase in cracking load. The ductility ratio is decreased by 27% when compared with the control slab. These results may be attributing to the reduced amount of CFRP composites.
2. Concrete overlay strengthening system exhibited a significant increase in ultimate and cracking loads. These increases reached up to 77% and 100%, respectively. Also, the ductility ratio is increased by 22% when compared with the control slab.
3. Substantial increase in flexural efficiency was observed when the slabs strengthened with suggested combined strengthening system. The increase in ultimate load reaches up to 139% and 134% for RC one-way slabs strengthened in positive and negative flexural bending, respectively. These Slab specimens showed an increase in first cracking load of 7 and 5 times, respectively, when compared with the control slab specimen.
4. The recorded ductility ratios for slab specimen strengthened with combined strengthening system are 1.56-1.63. These values present reduction by 30%-27% when compared with the control slab.
5. Further studies should focus on expanding the experimental database of reinforced concrete slabs strengthened with CFRP composites and concrete overlay techniques through full scale experimental tests and on long-term performance.

5. References

المواصفات العراقية رقم (5) "الأسمنت البورتلاندي" الجهاز المركزي للتقييس والسيطرة النوعية, بغداد, 1984.
(I.Q.S. 5/1984) .

المواصفات العراقية رقم (45) "ركام المصادر الطبيعية المستعمل في الخرسانة والبناء" الجهاز المركزي للتقييس والسيطرة النوعية, بغداد, 1984. (I.Q.S. 45/1984)

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

Alkhrdaji, T., Nanni, A., Chen, G. and Barker, M. (1999). “Upgrading the transportation infrastructure: solid RC decks strengthened with FRP” Concrete International: Design and Construction, Vol. 21, No. 10, pp. 37-41.

Al-Mahaidi, R. (2003), "Use of FRP Composites for Strengthening of Concrete Buildings and Bridges" Monash University, Melbourne, Australia.

American Concrete Institute, Committee 440 (2002), ACI 440.2R-02, "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures" 45 pp.

Aprile, A., Pela, L. and Benedetti, A., (2007),”Repair and Strengthening with FRP of Damaged Bridge R/C Slabs", University of Patras, Greece.

ASTM C 39/C39M-05(2005)," Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens", 2005 Annual Book of ASTM Standards, Vol.01.01, ASTM, Philadelphia, PA.

ASTM C 496/C496M-04(2005), "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens", 2005 Annual Book of ASTM Standards, Vol.01.01, ASTM, Philadelphia, PA.

Costeira, P., Juvandes, L. and Figueiras, J., (2007),”Behavior of RC Slabs Strengthened by Externally Bonded CFRP Systems", University of Patras, Greece.

Sika (2005), "Sikadur 330-Two Part Epoxy Impregnation Resin ", Technical Data Sheet, Edition 2, (web site: www.sika.co.id).

Sika (2005), "SikaWrap230C-Woven carbon fiber fabric for Structural Strengthening", Technical Data Sheet, Edition 2, (web site: www.sika.co.id).

Tan, K., Y., (2003),” Evaluation of Externally Bonded CFRP Systems for the Strengthening of RC Slabs” MSc. Thesis, University of Missouri-Rolla.