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# Loading effect on flexural strength of reinforced concrete beams before bonding externally with Carbon Fiber Reinforced Polymers (CFRP) Laminates

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# تأثير التحميل على مقاومة الإنحناء للكمرات الخرسانية المسلحة قبل تقويتها من الخارج بصفائح البولميرات المسلحة بالألياف الكربونية

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**Abstract:**
The main aim of this paper is to evaluate the behaviour of RC beams strengthened with CFRP after a specified loading period. 11 RC beams were tested. One is control beam and the rest of beams were loaded statically at site using two points loading with 0 %, 25 %, 37.5 %, and 50 % of the ultimate predicted failure load for a period of 60 days. No maintenance or repair was carried out on the beams during loading period. The main variables investigated were the internal steel reinforcement ratio, and CFRP external reinforcement ratio. The beams were provided with adequate shear reinforcement with high shear capacity resistance to avoid any failure due to shear. The beams were then strengthened externally with CFRP laminates, later on they were tested to failure in laboratory. The load and deflection at midspan were recorded up to complete failure. The flexural response of the strengthened beams was investigated based on the ultimate failure load of strengthened loaded beams compared to the ultimate failure load of strengthened unloaded beams. Results show that the sustained load levels before strengthening with CFRP have no significant effect on the ultimate load carrying capacity of strengthened beams.

**Keywords:** Carbon Fiber, Strengthening of concrete beams, loading before, strengthening, ultimate load carring capacity.

**الملخص:**
إن الهدف الرئيسي من هذا البحث هو تقييم سلوك الكمرات الخرسانية المسلحة و المقواة بصفائح البوليمرات المسلحة بألياف الكربون بعد فترة تحميل, 11 كمرة خرسانية مسلحة تم إختبارهن, واحدة مرجعية و البقية تم تحميلهن بحمل ساكن مركز في الموقع بنسب تحميل 0 % , 25 %, 37.5 % , 50 % من الحمل المتوقع للإنهيار و لمدة 60 يوماً, لم يتم إي صيانة أو معالجة للكمرات الخرسانة أثناء فترة التحميل, إن المتغيرات الرئيسية التي تم دراستها هي نسبة حديد التسليح الداخلية, و نسبة صفائح الكربون الخارجية, الكمرات الخرسانية تم تسليحها بحديد ذو مقاومة عالية للقص لتفادي أي إنهيار قد يحدث بسبب القص, و من ثم تم تقوية الكمرات الخرسانية من الخارج بصفائح البوليمرات المسلحة بالألياف الكربونية, و من ثم تم إختبارهن في المعمل حتى الإنهيار, تم قياس الحمل و الإنحراف في منتصف الفضاء للكمرات حتى الإنهيار, ثم تم حساب مقاومة الإنحناء للكمرات بناءً على أقصى حمل للإنهيار للكمرات المقواة المحملة قبل الفحص مقارنة مع أقصى حمل للإنهيار للكمرات المقواه و الغير محملة قبل الفحص, النتائج توضح أن التحميل قبل التقوية بصفائح البوليمرات المسلحة بألياف الكربون ليس له تأثير واضح على سعة التحميل القصوى للكمرات الخرسانية المقواة.

**الكلمات المفتاحية:** ألياف الكربون, تقوية الكمرات الخرسانية, التحميل قبل التقوية, أقصى سعة تحميل.

## Introduction

The flexural behaviour and mode of failure of RC beams externally strengthened with CFRP laminates can be characterized by initial flexural stiffness, flexural strength, displacement at yield and ultimate stage, and overall ductility. The characteristic values determining the

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flexural behaviour of strengthened RC beams are usually dependent on the properties and amount of constituent and strengthening material, method and type of strengthening and the magnitude of sustained loads at the time of strengthening.

When FRPs are used for flexural strengthening of concrete beams reinforced with conventional steel, the steel reinforcement may yield before the FRP contributes any additional capacity to the beam. Therefore, it could be difficult to obtain a significant increase in yield load or stiffness for a beam. When an increase in beam yield load or stiffness is required, larger cross sections of FRPs must be used (before the steel yields), which generally increase the cost of strengthening.

FRP strengthening system should be designed in accordance with ACI 318-19 strength and serviceability requirements, using the load factors stated in ACI 318-19. The strength reduction factor required by ACI 318-19 [1] should also be used. Additional reduction factors applied to the contribution of the FRP reinforcement are recommended to reflect lesser existing knowledge of FRP system according to ACI 440.13-24 [2].

($C_E$ =0.85, and $\psi_f$ =0.85).

The design flexural strength $\phi M_n$ (Eq (1) refers to the nominal strength of the member multiplied by a strength – reduction factor. The guide recommends the use of the strength reduction factors ϕ (Eq (2)) with an additional strength reduction factor of 0.85 applied to the flexural contribution of the FRP reinforcement alone ($\psi_f$ = 0.85).

$$\phi M_n = \phi\left[A_s f_s\left(d - \frac{\beta_1 \times c}{2}\right) + \psi_f \times A_f \times f_{fe}\left(h - \frac{\beta_1 \times c}{2}\right)\right] \ldots\ldots\ldots\ldots Eq(1)$$

Reduction factor ($\phi$) is 0.65 to brittle sections and 0.9 for ductile sections. Therefore strength reduction factor given by eq (2) should be used [1], where $\varepsilon_s$ is the strain in the steel at the ultimate- limit state.

$$\phi = \begin{cases} 0.9 & \text{For } \varepsilon_s \geq \varepsilon_{sy} + 0.003 \\ 0.65 + [0.25\,(\varepsilon_s - \varepsilon_{sy})/0.003] & \text{For } \varepsilon_{sy} < \varepsilon_s < \varepsilon_{sy} + 0.003 \\ 0.65 & \text{For } \varepsilon_s \leq \varepsilon_{sy} \end{cases} \ldots\ldots\ldots\ldots \textbf{Eq (2)}$$

The nominal strength of FRP- strengthened concrete member can be determined based on strain compatibility, internal force equilibrium, and the controlling mode of failure**.**

If the retrofitting of RC beam with CFRP laminates has been delayed, there will be more deterioration of the existing steel and concrete of the beam. So the nominal strength of reinforced concrete beams bonded with FRP may effected by loading of beams before strengthening. Loading before strengthening may reflect reality of the beam as much as the strengthening delays.

The main objective of this research is to evaluate the behavior of RC beams strengthened with CFRP after a specified period of preloading. Thus the flexural strength of reinforced concrete beams bonded with CFRP can be estimated based on an actual reality. The effect of loading and partially defected of reinforced concrete beams have to be evaluated in reference to safety levels for prediction of the nominal moment of resistance of RC beams strengthened with CFRP laminates.

A total of 11 RC beams with same length and same cross sectional dimensions, reinforced internally with different steel ratios, and same concrete compressive strength of 32 MPa. The beams were then loaded statically at site using two - point loading with 0%, 25 %, 37.5 %, and 50 % of the ultimate predicted failure load. The beams were then strengthened with CFRP laminates, using different ratios, and then tested in laboratory up to failure.

The flexural response of the strengthened beams was investigated based on the ultimate failure load in laboratory compared to the ultimate predicted failure load.

## Material and methods

The results reported in this paper were obtained from 11 reinforced concrete beams which were tested in laboratory up to failure, after loading at site with 25 %, 37.5 %, and 50 % of the ultimate predicted failure load, for 60 days period. One is control beam (unloaded unstrengthened), eight were loaded for 60 days, then they strengthened with CFRP sheets, two were unloaded but strengthened with CFRP sheets. No maintenance or repair was carried out on the beams during loading period. All beams were left exposed to the effect of natural elements in Awata village south of Tripoli about 70 Kilometers.

## Properties of materials

The mix proportions were 0.6 : 1 : 2.09 : 2.34 : 0.91 (water: cement: fine aggregate: coarse aggregate of 15 mm max size: coarse aggregate of 25 mm max size), all by mass. A set retarding concrete admixture (Sikament – R 2002) added to the mix as 0.6 % by the weight of the cement, to obtain good workability. Portland cement, sea sand, a combination of two sizes of coarse aggregates have been used in concrete mix which were of 15mm max size and 25mm max size, and the ratio of combination was 0.72, 0.28 respectively. The slump was 70 mm. The 7–days cubes compressive strength were 18.4 MPa, on 28-days were 25 MPa, and at the same date of beams crush were 32 MPa.

The physical properties of the steel reinforcement bars which were used as internal reinforcement in beams as shown in table (1) based on tensile test report

**Table 1**. Physical properties of steel bars.

| Property | Flexural steel bars | Shear steel bars |
|---|---|---|
| Diameter | 12 mm | 8 mm |
| Tensile yielding stress | 380 MPa | 500 MPa |
| Yielding strain | 0.0019 | 0.0025 |
| Modulus of elasticity | 200000 MPa | 200000 MPa |
| Tensile stress at break | 563 MPa | 573 MPa |
| Strain at break | 0.0402 | 0.01718 |

The laminates which have been used for strengthening produced in Sika Company. The type which has been used was of low modulus of elasticity (Sika Carbodur S512), and the physical properties are as shown in table (2) based on tensile test report.

**Table 2**. Physical properties of CFRP laminates.

| Property | Description |
|---|---|
| Width (wf) | 50 mm |
| Thickness (tf) | 1.2 mm |
| *Fiber volume content | > 68 % |
| Yielding tensile stress | 2822 MPa |
| Yielding strain | 4.35 % |
| Modulus of elasticity | 64874 MPa |

*** Fiber volume content: based on technical data sheet reported by producer.**

Sikadure-30 has been used as an adhesive mortar for bonding of CFRP laminates, it is produced as component A (Risen), and component B (hardener), the two components have been mixed with ratio 3**:**1 by the weight respectively. The epoxy has physical properties as shown in table (3) based on technical data sheet reported by producer [3].

**Table 3**. Physical properties of adhesive mortar.

| Property | Description |
|---|---|
| Tensile strength | 4 MPa |
| Compression strength | 100 MPa |
| Elastic Modulus in tension | 12800 MPa |
| Shrinkage | 0.04 % |

## Detail of tested beams

A total of 11 RC beams with same length and same cross sectional dimensions 150*300*3500 mm and reinforced internally with different steel ratios at an effective depth of 260 mm. Variables considered were steel reinforcement ratio, area of CFRP laminates, and loading ratio at site for 60 days period. Concrete compressive strength was considered the same, 32MPa (same concrete mix used for all beams). The beams were provided with adequate shear reinforcement with high shear capacity resistance to avoid any failure due to shear. The beams then were caste at site, figure (1) shows the details of fabricated beams. Full details of all beams are given in table (4).

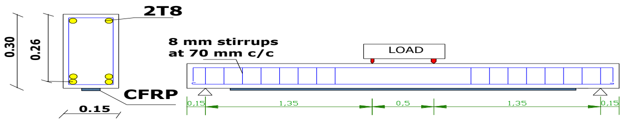


**Figure 1**. Beams detail (Reinforcing and strengthening are varies)

## Loading program

Different beams with different loading ratios as given in table (4) have been loaded at site for a period of 60 days. The load has been applied gradually. No maintenance or repair was carried out on the beams during loading period. All the beams were left exposed to the effect of natural elements. Two walls with appropriate dimensions and strength were parallel fabricated as supports for the beams during loading period, and two steel beams with an appropriate length and sufficient resistance were put on a couple of beams to simulate a concentrated load at site which also will be applied in the laboratory. Concrete blokes with known weight were then applied on the beams and hollow concrete bricks also with known weight have been used to adjust the required loading ratio. Figure (2) shows the beam's loading technique at site during the period of 60 days.

**Figure (2-a**). Beam’s loading technique

**Figure (2-b).** Beam’s loading technique.

After the end of the sustained loading period (60 days), all loads on the beams were removed, and then strengthening of beams done at site as shown in figure (3) without any repair because no cracks appeared during loading period. The concrete surface brushed up then the well-mixed adhesive material (Sikadure-30) pasted on clean surface of concrete beams for about 2mm thickness. Within the open time of the adhesive, the CFRP laminates pressed on the adhesive material using rubber roller until the material forced out. The lengths of laminates were 88% of length of beam to avoid premature failure, and then the surplus adhesive materials were removed. Then the beams were tested in the laboratory, they were loaded gradually at two point loads exactly at the same points loaded at site as shown in figure (4), and the load and deflection at midspan were recorded up to complete failure.

**Figure 3.** Beam’s strengthening

**Figure 4**. Beam's testing in laboratory

**Table 4**. Full details of beams

| Beam (Bs-f/L)* | *ρs* | *ρf* | Loading ratio % | applied load at site kN |
|---|---|---|---|---|
| **B4-0/U** | 0.0116 | 00 | 0 | Unloaded |
| **B4-1/U** | 0.0116 | 0.00154 | 0 | Unloaded |
| **B4-1/25** | 0.0116 | 0.00154 | 25 | 15.7 |
| **B4-1/37.5** | 0.0116 | 0.00154 | 37.5 | 23.5 |
| **B4-1/50** | 0.0116 | 0.00154 | 50 | 31.4 |
| **B4-2/U** | 0.0116 | 0.00308 | 0 | Unloaded |
| **B4-2/25** | 0.0116 | 0.00308 | 25 | 15.7 |
| **B4-2/37.5** | 0.0116 | 0.00308 | 37.5 | 23.5 |
| **B4-2/50** | 0.0116 | 0.00308 | 50 | 31.4 |
| **B3-1/50** | 0.0087 | 0.00154 | 50 | 24 |
| **B2-1/50** | 0.0058 | 0.00154 | 50 | 16 |

***: Bs-f/L**
**s** = Number of steel bars.
**f** = Number of CFRP sheets.
**L**= Applied loading ratio at site to the ultimate predicted Failure load of the beam (U= unloaded).

## Results and discussion
### Deflection Behavior
Increasing the sustained load before strengthening from 0 to 50 % increased the deflection by 30 to 78 % at the given load. However at ultimate load all specimens except the control beam reached approximately the same deflection. As the sustained load increased from 0 to 50 % it seems that the effects of moment of inertia which decreased with the increase of sustained load leading to higher deflection at higher load, this indicated by the slop of load deflection curve in the experimental data of figure (5). The figure also shows that the deflection .

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increases with the increase of level of sustained load at site before strengthening (50 % loading at site gives the highest deflection for beams strengthened with 1 sheet of CFRP).

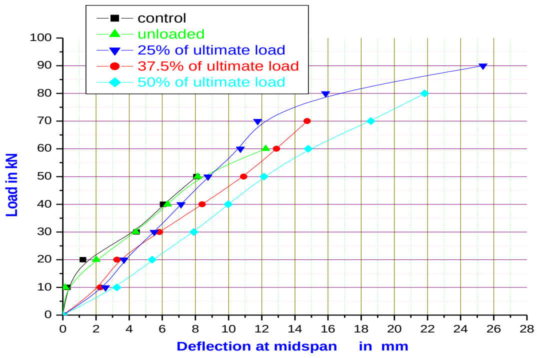


**Figure5**. Load deflection behavior of beams strengthened with 1 sheet of CFRP.

But for beams strengthened with 2 sheets of CFRP, the increase of sustained load before strengthening increased the deflection with about 23 % at the given load. At ultimate load also all beams except the control beam reached approximately the same ultimate load and approximately the same deflection too. And the deflection is higher at higher load as shown in figure (6).

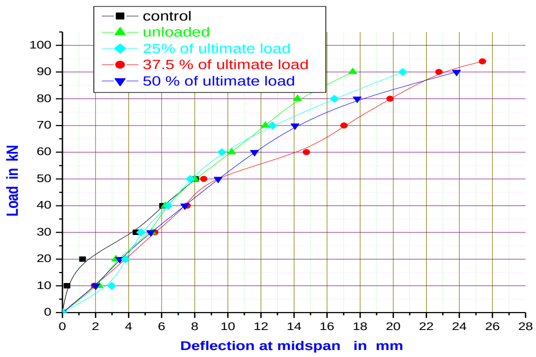


**Figure 6**. Load deflection behavior of beams strengthened with 2 sheet of CFRP.

From deflection point of view adding 1 more sheet of CFRP, the deflection of tested beams generally decreased at service load, the decrease was 50 % for beams loaded with 50 % before strengthening. However at ultimate stage the ultimate deflection was not affected due to cracked section. Moreover the ultimate moment capacity of all beams was not affected significantly by the presence of the additional sheet, therefore the significance of the additional sheet was in reducing the deflection of service load but had no significance effect on ultimate load.
For beams loaded with 50 % and strengthened with same area of CFRP laminates and reinforced internally with different steel reinforcement ratios. As the steel ratio increased from 20, 28 to 36 % in reference to the balanced steel ratio ( $\rho_b$ ), the deflection at the given load decreased by 19 to 22 % at service load. The percentage decrease in deflection was not high, but at ultimate load, it relatively high, about 33 to 80 % respectively. Regarding the ultimate moment capacity, the beam with lower percentage of steel (20 %) gave significantly higher deflection. This may interpreted that when steel yield the CFRP will be less contributed to

strength the beam, as shown in figure (7), which shows the load-deflection behavior of strengthened beams with different steel reference ratio.

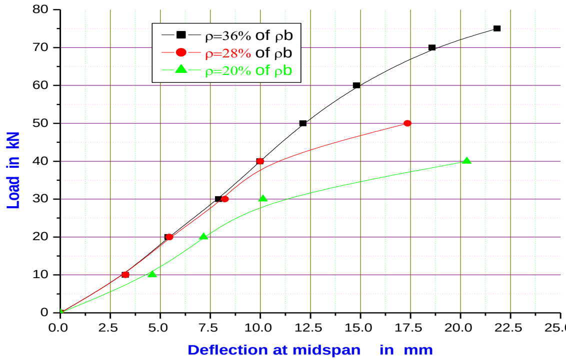


**Figure 7.** Load deflection behavior of beams strengthened with 1 sheet of CFRP and reinforced with different steel reinforcement ratios.

## Ultimate load carrying capacity

The preloading level of the beams at site for 60 days has no significant effect on the load-carrying capacity of the beams strengthened with 1 and 2 sheets of CFRP laminates. Figures (8) and (9) show the increase of the load - carrying capacity of beams strengthened with 1 and 2 sheets of CFRP laminates compared to control beam.

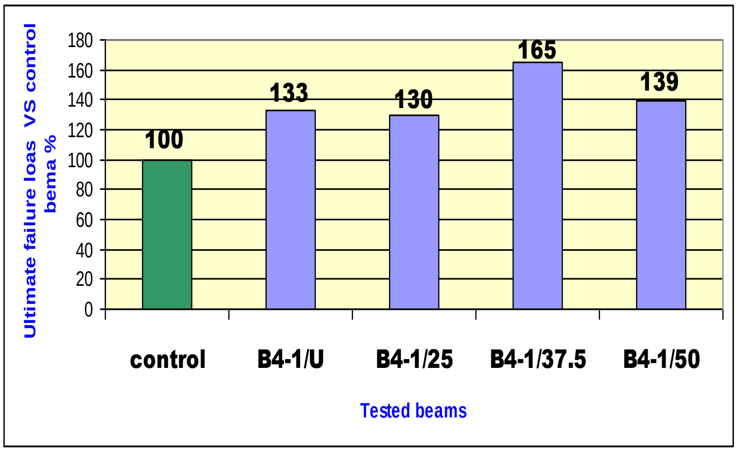


**Figure 8**. Increase of ultimate failure loads of beams strengthened With 1 sheet of CFRP compared to control beam.

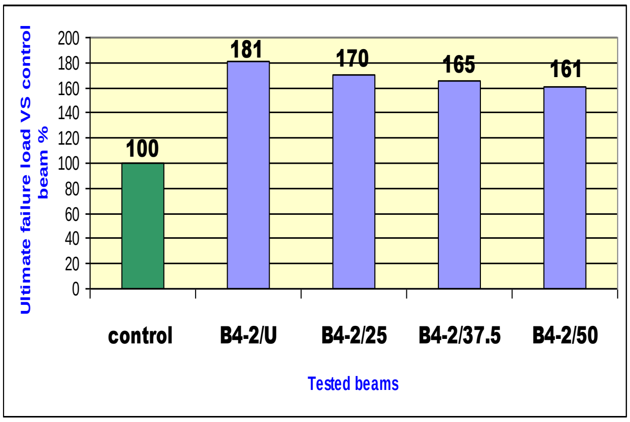


**Figure 9**. Increase of ultimate failure loads of beams strengthened With 2 sheet of CFRP compared to control beam.

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The ultimate failure load generally increases with the increase of applied number of CFRP sheets as shown in figure (10). (1 sheet increases the ultimate load 34%, and 2 sheets increase the ultimate load 70%).

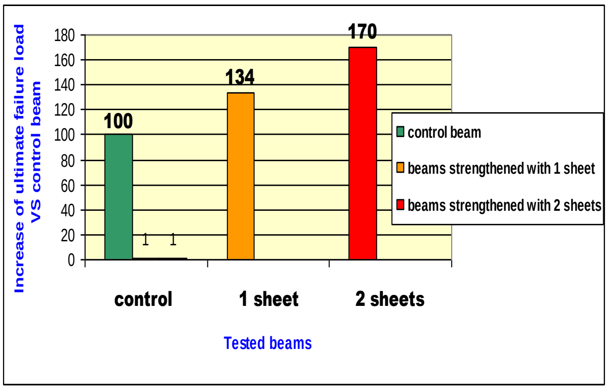


**Figure 10**. Increase of ultimate failure load of beams strengthened with 1 and 2 sheets of CFRP compared to control beam.

The comparison of ultimate failure loads (experimental failure loads in laboratory) with those of theoretical failure loads as calculated from equations according to ACI 440.13-24 (Calculate the design flexural strength of the section, but not including any ultimate or reduction factors) is shown in figures (11) to (13).

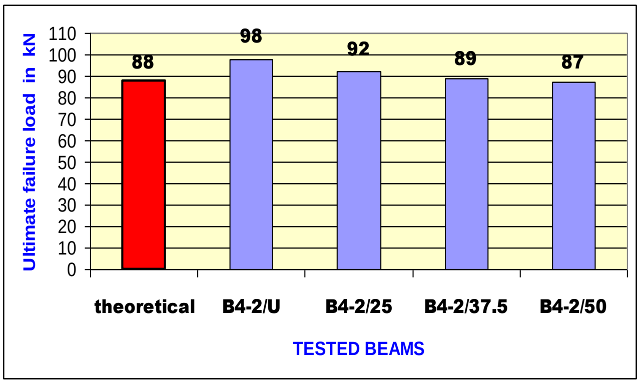


**Figure 11**. Ultimate failure load of beams strengthened with 2 sheets of CFRP compared to theoretical load.

From figure (11), the ultimate failure load of beams strengthened with 2 sheets of CFRP is higher than the theoretical failure load, so the beams could carry the load safely, but for beams strengthened with lesser area of CFRP (1 sheet), the ultimate failure load of beams is lower than the theoretical load (figure (12)), so the beams could not carry the load safely with the decrease of applied of CFRP sheets.

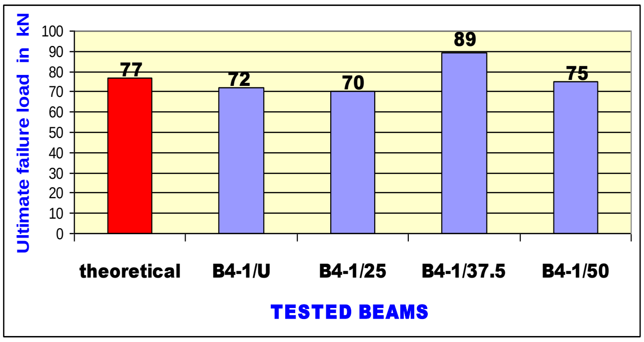


**Figure 12**. Ultimate failure load of beams strengthened with 1 sheet of CFRP compared to Theoretical load.

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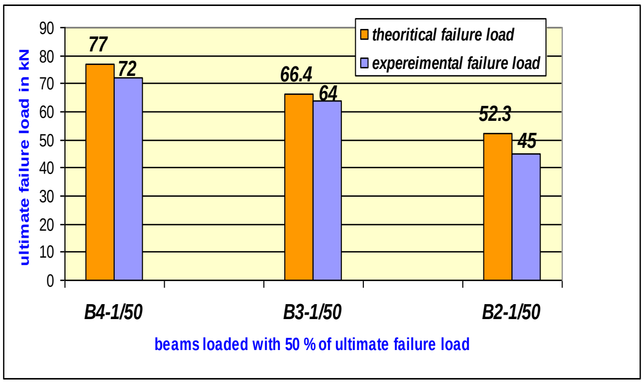


**Figure 13**. Ultimate failure load comparing to theoretical load of beams Loaded 50 % of Ultimate load before strengthening with 1 sheet of CFRP.

From figure (13) shown above the difference between ultimate failure load and theoretical load was higher when ( $\rho_s$ ) was lower. This may interpreted that when steel yield the CFRP will be less contributing to strength the beam, and the beams could not carry the loads safely.

**Based on** the experimental results of loaded beams with different levels of sustained load before or after strengthening with CFRP including an other studies (Soo, Yeong, 2003, Nabil Grace, 2004, and M. Werfally, 2005) [4,5,and 6] showed in figure (14) it can be said that the increase of ultimate failure load of strengthened loaded beams compared to unloaded strengthened beam squeezing the current study in other studies which have been done before. From the figure (14) it is observed that the repeated or sustained load have no significant effect on the ultimate load carrying- capacity of beams strengthened with CFRP.

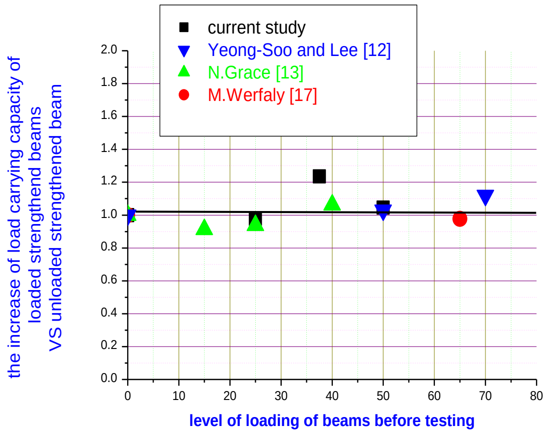


**Figure14**. ratio of ultimate failure load of loaded strengthened beams to ultimate failure load of unloaded strengthened beams including other studies.

## Flexural behavior

The calculation of nominal moment of strengthened beams with CFRP laminates will be according to equation (1) as discussed in introduction. The nominal flexural strength in equation (1) according to ACI 440.13-24 as follows:

($\psi_f$ = 0.85) is reduction factor of CFRP contribution. And the reduction factor ($\phi$ ) is indicated in equation (2).

The flexural resistance calculated according to ACI 440.13-24 is conservative as shown in table (5) which shows the difference between ACI level which is decreased with the decrease of number of CFRP applied sheets, and this different level is not effected with variability of internal steel reinforcement ratio. On the other hand it gives an adequate margin of safety against collapse of strengthened RC beams.

**Table 5.** Safety levels according to ACI 440.13-24

| Beam | $M_{ult}$ In laboratory | $\phi M_n$ According to ACI 440 , 2019 factor $\psi_f$ =0.85 | Safety level according to ACI 440, 2019 factor $\psi_f$ =0.85 |
|---|---|---|---|
| | kN.m | kN.m | % |
| B4-0/U | 37.75 | 37.00 | 02.03 |
| B4-2/U | 67.45 | 50.70 | 33.04 |
| B4-2/25 | 63.40 | 50.70 | 25.05 |
| B4-2/37.5 | 61.38 | 50.70 | 21.07 |
| B4-2/50 | 60.70 | 50.70 | 19.72 |
| B4-1/U | 49.90 | 45.20 | 10.40 |
| B4-1/25 | 48.55 | 45.20 | 07.41 |
| B4-1/37.5 | 61.38 | 45.20 | 35.80 |
| B4-1/50 | 51.93 | 45.20 | 14.89 |
| B3-1/50 | 44.50 | 38.40 | 15.89 |
| B2-1/50 | 31.68 | 32.76 | -03.30 |
| **Average of strengthened safely beams** | | | 20.36 |

## Conclusion

Based on the experimental results discussed in this research, several conclusions can be drawn as follow:

1- At service load levels, strengthening of a beam by CFRP increases the stiffness of such a beam by about 50 % of that unstrengthened control beam.

2- Deflection of strengthened beams increases as the ratio of ( $\frac{\rho_s}{\rho b}$ ) decreases for all tested beams.

3- The use of CFRP laminates in strengthening of RC beams increases the ultimate load carrying capacity of beams about 34 % and 70 %, depending on the strengthening ratio (0.00154, and 0.00308 respectively).

4- The sustained load applied on beams for 60 days have no significant effect on the ultimate load carrying capacity of beams strengthened with CFRP.

5- The flexural resistance of loaded and strengthened beams calculated according to ACI 440.13-24 is in good safety level comparing with experimental results. Therefore, $\psi_f$ =0.85 is recommended as conservative value.

## Compliance with ethical standards

*Disclosure of conflict of interest*

The authors declare that they have no conflict of interest.

## Notation

As = area of non-prestressed steel reinforcement in ( $mm^2$ ).
A$f$ = area of CFRP external reinforcement in ( $mm^2$ ).
c = distance from extreme compression fiber to the neutral axis of the beam in (mm).
CE = Environmental reduction factor.
d = effective depth of the beam in (mm).
$f_c^-$ = compression strength of concrete in (MPa).
f$fe$ = effective stress in FRP, stress level attained at section failure in (MPa).
$f$s = stress in non prestressed steel reinforcement in (MPa).
fy = specified tensile strength of non prestressed steel reinforcement in (MPa).
h = overall height of the beam in (mm).
Mn = nominal moment strength in (kN.m).
n = number of plies of FRP reinforcement.
t$f$ = nominal thickness of one ply of FRP reinforcement.
w$f$ = width of FRP reinforcement.
$\psi_f$ = flexural strength reduction factor of CFRP.
$\phi$ = strength reduction factor.
εs = strain level in non prestressed steel reinforcement.
ε$sy$ = strain corresponding to the yield strength of non prestressed steel reinforcement.
$\beta_1$ = ratio of the depth of the equivalent rectangular stress block to the depth of the neutral axis.
$\rho s$ = ratio of non prestressed steel reinforcement.
$\rho f$ = ratio of FRP reinforcement.
$\rho b$ = balanced reinforcement ratio (steel+FRP).

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