Flexural Strength and Ductility of CFRP Strengthened Reinforced Concrete Beams

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ABSTRACT
A total of fourteen beams, 100×150 mm in cross-section were tested in the laboratory over an effective span of 2000 mm. Two of them were used as reference beams. Twelve fiber reinforced concrete beams were provided with externally bonded CFRP laminates at the soffit of the beam. The variables considered included number of CFRP layers, yield strength of steel reinforcement (f_y) and steel reinforcement ratio (ρ). All the beams were tested until failure. The test results showed that the ultimate load carrying capacity increased by 56% as average by increasing of the ratio of steel reinforcement from (0.0127 to 0.0324). The deflection ductility index DDI values averaged (1.80) and (1.75) for one-layer strengthened beams and two-layer ones, respectively. The corresponding energy ductility index EDI values averaged (1.75) and (1.73), respectively. The DDI and EDI for the control beams were 4.61 and 6.24, respectively. With the exception of the control beams, all of the beams exhibited poor ductility. Failures in all strengthened beams were accompanied by the release of large amounts of energy (known as elastic energy) relative to inelastic energy. Therefore, a reasonable factor of safety should be used in the design of FRP strengthened reinforced concrete members.
Keywords: Ductility, CFRP laminate, strengthening

INTRODUCTION
There is a large need to strengthen concrete structures around the world and there can be many reasons for strengthening. Deficiencies are usually the results of deterioration caused by age and exposure to adverse environment, heavier traffic brought about by a growing society, or functional changes such as higher required permit load. As a result, a large number of concrete highway bridges are in need of rehabilitation or replacement.

The idea of strengthening concrete structures with externally bonded FRP systems were developed as alternatives to traditional external reinforcing techniques such as steel plate bonding and steel or concrete column jacketing [1]. FRP materials have high strength-to-weight ratio, high resistance to corrosion compared with steel plates, it is very easy and speed to transport, installation. The properties above consider advantages ofFRP composites, but it is high cost, and the risk of fire, vandalism or accidental damage, unless the strengthening is protected. CFRP is selected as a strengthening material because of its outstanding tensile strength and stiffness compared to other composite materials [2].

The addition of Carbon Fiber Reinforced Polymer (CFRP) composites, which is another form of tension reinforcement, affects the ductility of concrete beams strengthened with CFRP sheets, in spite of using tension reinforcing steel bars which plays a major role in determining the flexural

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ductility of reinforced concrete beams. Therefore; there is a need to investigate the effect of the CFRP laminates on the overall ductility of strengthened beams [3].

In (201٥), Sarsam et al. [4] had studied the behavior and shear strength characteristics of eight Steel Fiber Reinforced High Strength Concrete SFRHSC beams strengthened with CFRP strips subjected to combined bending and shear (in addition to a9th control beam without CFRP strengthening). The studied variables were shear span to effective depth ratio (a/d) and the deep beam effect, the effect of end anchorage of the CFRP strips with the beams, and effect of the amount of wrapping (width and spacing of the CFRP strips).Tests showed that the presence of end anchorage for the strips increases the shear capacity of the beams by 12%for beams with the same properties regardless to the compressive strength.

In (2015), Sarsam et al.[5] investigated seven singly Reactive Powder Concrete (RPC) beams strengthened by externally bonded CFRP in flexure, one was the control beam (no CFRP was applied) and six were externally strengthened by CFRP. The experimental variables considered in the test program included, number of CFRP strip layers (1 layer or 2 layers) and the width of CFRP strip, with and without using external anchorages. The experimental results showed that the ultimate loads are increased up to 64.29 % for the beams strengthened with bonded CFRP sheets and external anchorage with respect to the un strengthened reinforced concrete beam (control beam). Also, these strengthened beams showed an increase in the first cracking load up to 100 %. On the other hand, there is a lower deflection at corresponding loads than the un strengthened reinforced concrete beam.

Research Significance

Several researches have investigated the use of CFRP to increase the flexural strength of concrete beams. However, the flexural ductility of beams with respect to the amount and yield strength of existing ordinary steel bars has not been investigated in depth. This paper presents results of an experimental research that focuses on the ductility of CFRP strengthened concrete beams. The main variables are the amount of the existing reinforcing steel bars, yield strength of steel bars, and number of CFRP layers.

Experimental Program

The experimental program consists of casting and testing of fourteen reinforced concrete beams. Twelve beams were strengthened with CFRP laminates, the two beams were considered as control beams, and all beams have been tested under four-point loading to failure. In all beams, the cross section was 100mm wide and 150mm in depth, the overall length was 2200mm with clear span 2000mm. The beams were designed to have extra strength in shear to ensure flexural failure even after strengthening; therefore, the shear span was reinforced with ϕ 6mm @ 50mm as shear reinforcement in all beams as shown in **Fig. (1)** And Table **(1)**.The dimensions of the CFRP laminates were constant (100mm width and 2000mm length) and applied to the bottom of the strengthened beams only by one and two layers. The compression steel bars were 2ϕ8mm in all beams, and the concrete cover was 15mm for the four sides of the concrete beam section as shown in **Fig. (2)**.

The concrete mix was (1: 2.3: 2.56) with water to cement ratio 0.37 and super plasticizer to cement ratio (1%) using Glenium ACE 30 super plasticizer. The concrete compressive was 45 MPa with a 100 mm slump. Carbon Fiber Reinforced Polymer used in this study is known as SikaWrap-230 C/45 sheets. Dry fiber properties provided by the manufacturers guaranteed a tensile strength of 4.3 GPa, the modulus of elasticity was 234 GPa and the elongation at break was 1.8%.

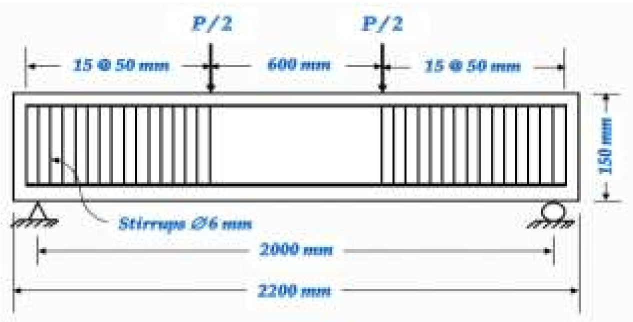


Figure. (1) Details of the reinforcement in the beam specimen

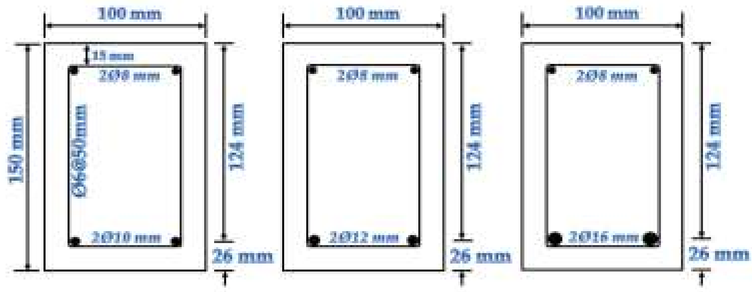
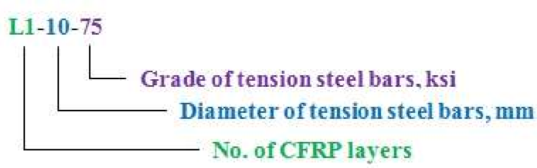


Figure. (2) Reinforcement details of the beam sections

Table (1) Details of the reinforcement and CFRP strips of beams

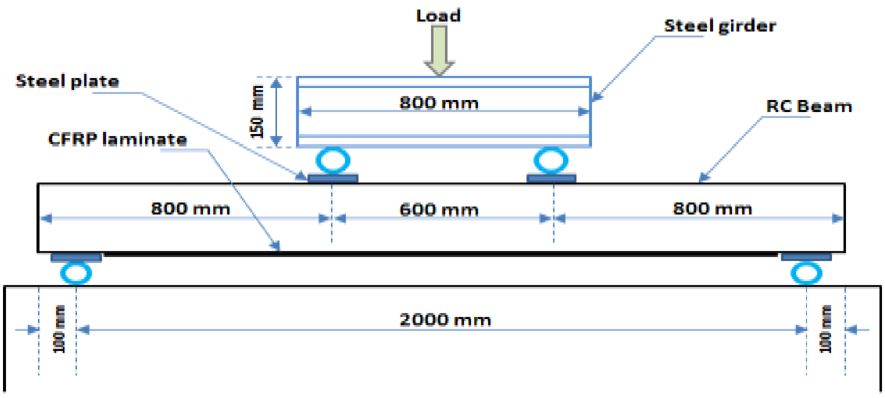
Beam symbol	Tension reinforcement	Yield Strength of tension bars(MPa)	No. of CFRP layers
L0-10-75	2 ϕ 10 mm	595	None
L1-10-75	2 ϕ 10 mm	595	1
L2-10-75	2 ϕ 10 mm	595	2
L1-12-75	2 ϕ 12 mm	593	1
L2-12-75	2 ϕ 12 mm	593	2
L1-16-75	2 ϕ 16 mm	535	1
L2-16-75	2 ϕ 16 mm	535	2
L0-10-60	2 ϕ 10 mm	460	None
L1-10-60	2 ϕ 10 mm	460	1
L2-10-60	2 ϕ 10 mm	460	2
L1-12-60	2 ϕ 12 mm	418	1
L2-12-60	2 ϕ 12 mm	418	2
L1-16-60	2 ϕ 16 mm	418	1
L2-16-60	2 ϕ 16 mm	418	2

Where:



The universal testing machine, which was used in this study, consists of a self-supporting steel frame with a hydraulic jack of 600 kN capacity and a computerized measuring unit connected to data logger to read load, deflection and strain as shown in Fig. (3).To generate four-point loading system, the load from the center of the universal testing machine must be transmitted to the beam deck in two point load. For this purpose, a steel girder of (150) mm depth and (0.8) m length was used.

To avoid local bearing failure during testing, steel plates (120 x 50 x 6 mm) at the point of load application and the reactions were used**.** After checking all the instruments, the vertical load was applied to the beam at two points using a steel girder which transmits the center load of the hydraulic jack to the beam deck at two points as shown in Fig. (3). For each load stage, the deflection and strains were recorded and the cracks were noticed. The total load on the test beam specimen was taken to be equal to the applied load from the universal test machine. The self-weight of the steel girder and the beam specimen itself were ignored. As the failure was reached, the failure load was recorded and the load was removed to allow taking photographs of the final cracked beam specimens.



(a) Test arrangement

(b) Beam specimen before load application

Figure. (3) Loading system shows specimen under flexure

Analysis of Results

Load-deflection curves

The load- deflection curves showed different deformations and behaviors under load for all beams. Table (2) provides a summary of the measured loads at first cracking and measured loads and deflections at first yielding of steel reinforcement and at ultimate level for all beam specimens.

In the elastic (pre-cracking) stage, the deflection increased linearly with applied load since the strains in the steel and concrete are relatively small and both materials steel and concrete are in the elastic portion of their respective responses. Initial cracking was observed at loads ranging from 13 % for (L1-16-75) to 22.8 % for (L0-10-60) of the beam ultimate load.

It can be shown that the behavior of the control beams (L0-10-60) and (L0-10-75) is typical of anunder-reinforced concrete beam specimen, showing linear behavior up to yielding of reinforcement (where deflections measured 13 mm and 11 mm, respectively), followed by a change in stiffness and increased deformation until failure (at 27.55 and 30.5 kN, with corresponding deflections of 62 mm and 50.5 mm, respectively), see Fig. (4).

Table (2) Summary of test results for all beam specimens

Beam symbol	*First cracking load (kN)*	*Yield load (kN)*	*Yield deflection (mm)*	*Ultimate load (kN)*	*Ultimate deflection (mm)*
L0-10-75	6.72	25.66	11.184	30.5	50.5
L1-10-75	8.288	36.73	16.320	47.04	35.2
L2-10-75	10.976	43.68	22.500	54.88	37.1
L1-12-75	8.736	45.92	20.462	49.952	28.6
L2-12-75	11.424	54.88	21.050	65.184	35.2
L1-16-75	9.408	5٧.٣٤	21.100	72.128	35.0
L2-16-75	11.872	63.62	23.088	79.744	34.7
L0-10-60	٦.٢٧٢	22.86	13.170	٢٧.٥٥٢	٦٢.١
L1-10-60	7.842	26.96	15.962	37.408	33.2
L2-10-60	8.736	32.15	15.615	43.456	33.0
L1-12-60	7.392	32.79	14.615	45.248	29.0
L2-12-60	9.184	40.85	20.965	52.64	37.1
L1-16-60	8.512	50.11	16.970	59.584	25.8
L2-16-60	11.2	62.94	20.200	74.816	36.4

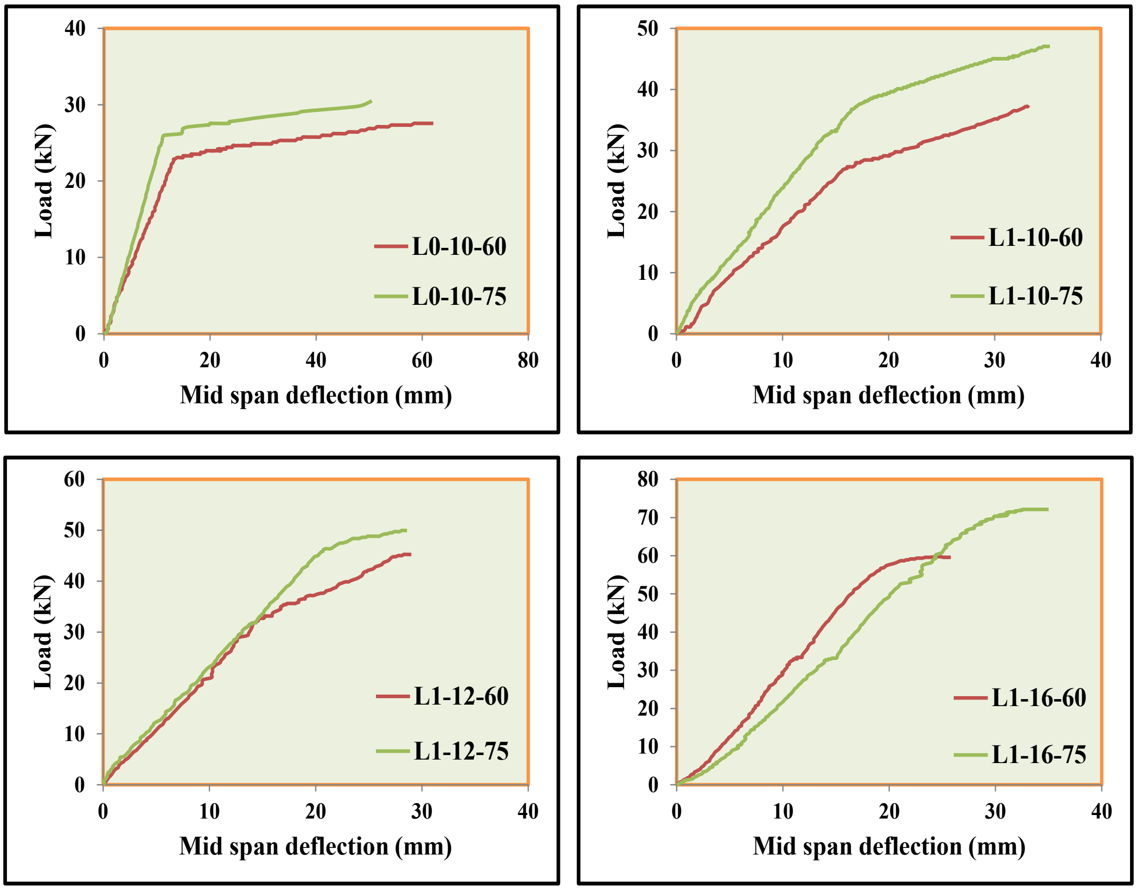
The cracking load was generally not apparent from the curves for strengthened specimens, although a slight change in the slope at roughly (8.288 kN) was noticed for L1-10-75 beam and (10.976 kN) for L2-10-75, for instance, which was higher than the cracking load observed in the control specimen (6.72 kN). The same is true for other specimens.

In the post-cracking (pre-yielding) stage, there is a change of slope in the load-deflection curve due to the cracking of concrete, which in turn results in reduction of the effective moment of inertia of the beam cross section. After cracking, deflection gain an increase almost linearly with load up to the point at which the tensile steel yields. Tensile steel yielding loads varied between 72.2% for (L1-10-60) to 90% for (L1-12-75) of the ultimate load.

Yielding of steel, which is characterized by the change of the post-crack slope, is clearly apparent in the strengthened specimens, though it is more evident in the control specimen. In the one-layer and two-layer strengthened specimens, yielding occurred at a higher applied load (for instance, beams L1-10-60 andL2-10-60: 27 kN and 32 kN) and with a higher mid span deflection (16mm and 17mm), respectively than in the control specimen (23 kN, 13mm), see Fig. (5). This is attributed to the retention of the composite action at the tension face, which lowered the neutral axis, giving a greater displacement at the yielding of steel.

In the post-yielding stage, the contribution of CFRP becomes very significant, since additional contribution of steel is zero in the yield plateau; post- yield part of the curve is flat for a reinforced concrete beam. The CFRP strengthened beams continue to provide strength increase because the CFRP force contribution continues at the same level.

At ultimate, the un strengthened specimen exhibited a higher mid span deflection compared with the strengthened specimens; however, the strengthened specimens achieved higher load capacities than the un strengthened specimens, the two-layer strengthened beams being the highest. The strengthened specimens also exhibited substantially large deflections beyond the yielding of steel. Given the applied load, they showed reduced deflections and thus, increased serviceability. All the strengthened specimens exhibited an approximately bilinear load deformation response characteristic with the change in the slope of each plot occurring at a point corresponding to the yield strain of the steel.



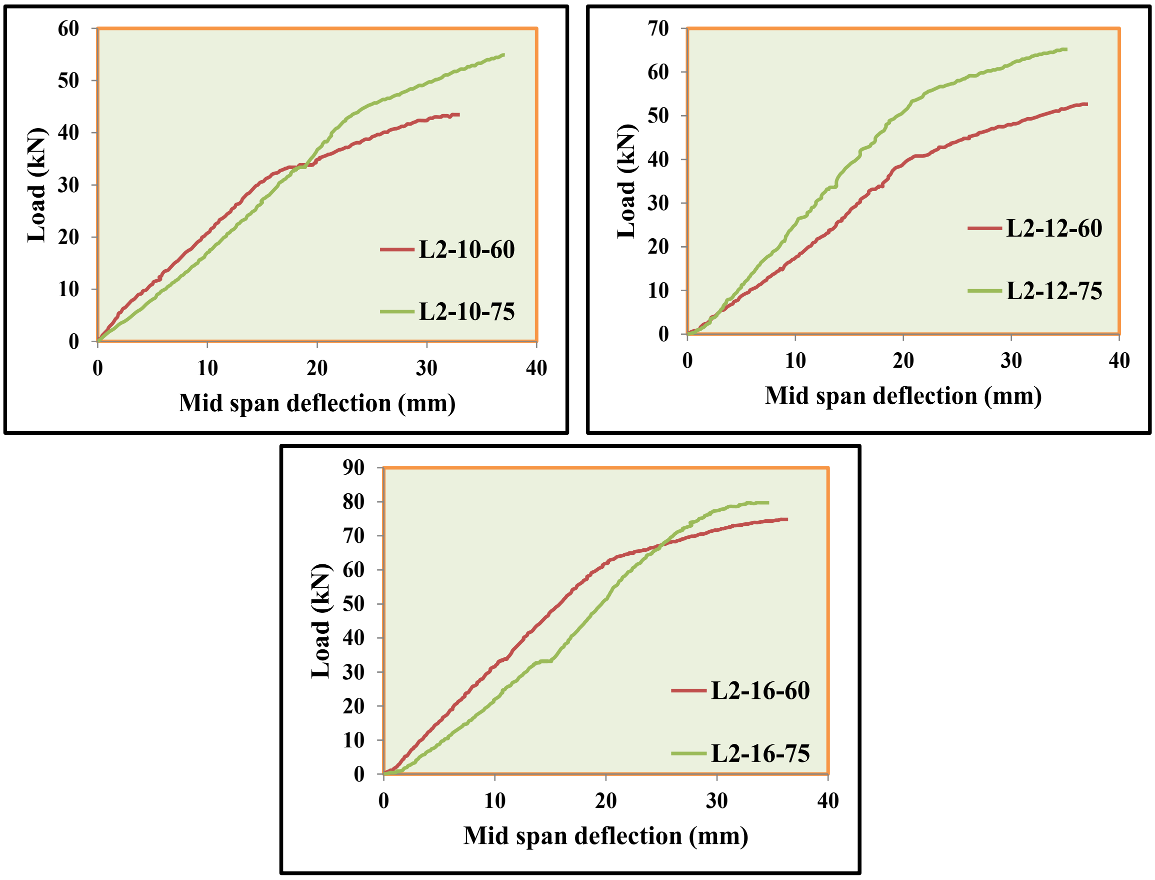
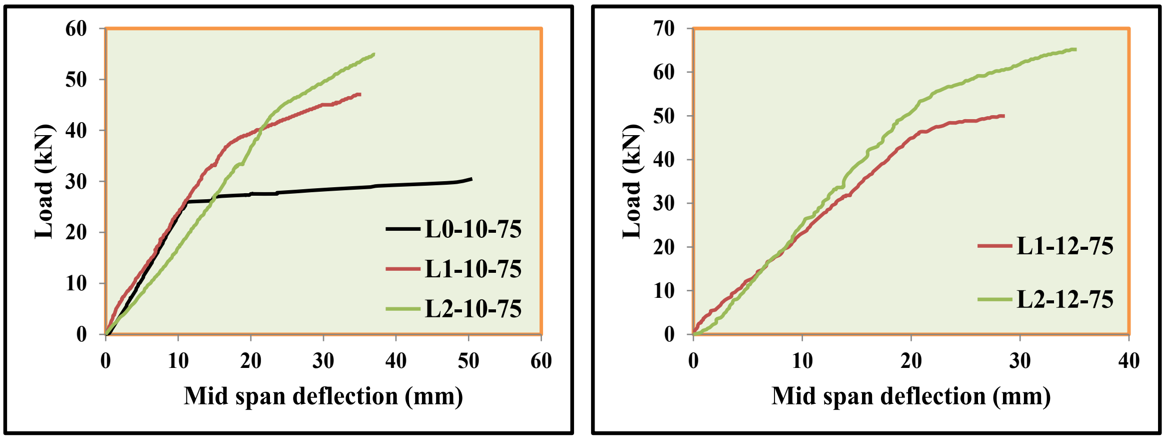


Figure. (4) Effect of tension steel bars yield strength on the load – deflection curves



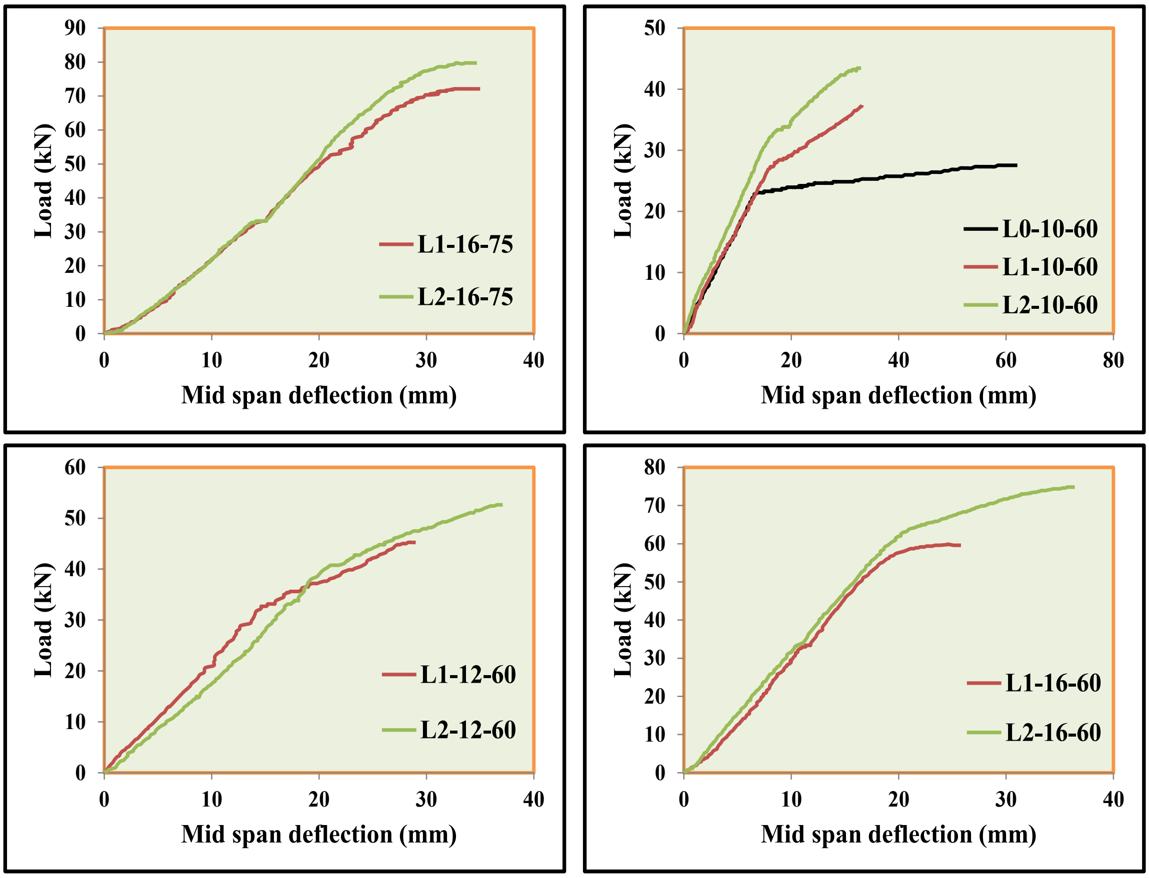
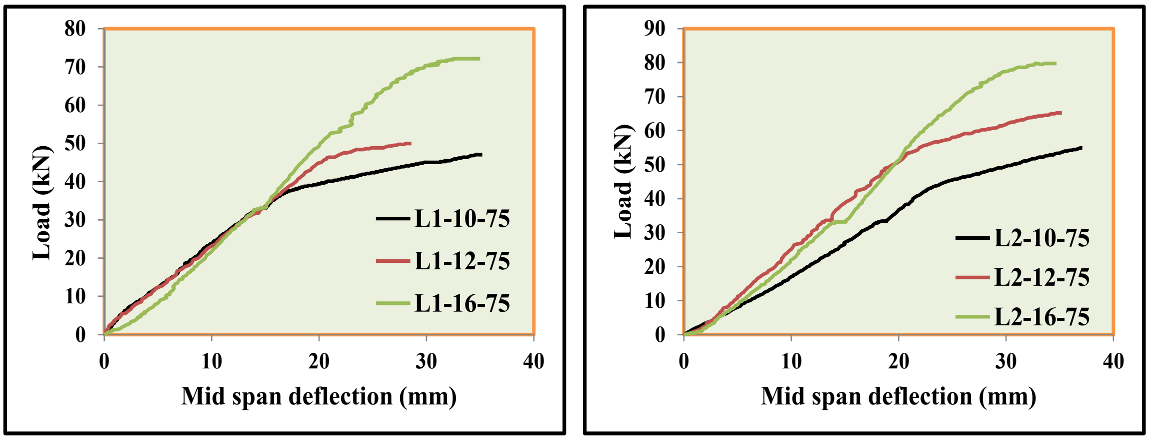


Figure. (5) Effect of CFRP layers on the load – deflection curves



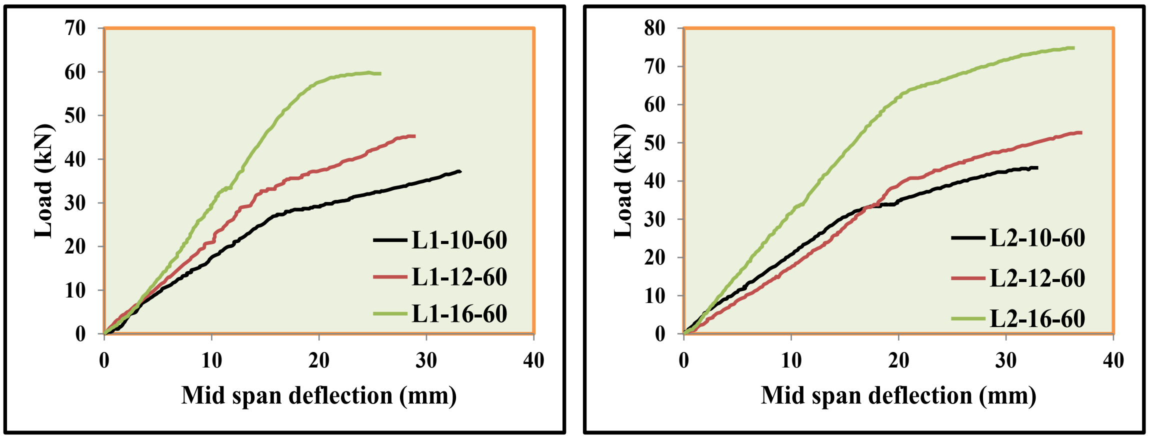


Figure. (6) Effect of tensile steel reinforcement ratio on the load – deflection curves

From the figures below, we observe that the increasing of CFRP layers resulted in substantial reduction in mid span deflection and this reduction may be attributed to the increase of beam stiffness, rigidity and moment of inertia of the beam section, the increasing of CFRP layers and the increasing of yield strength and ratio of tensile steel reinforcement resulted in substantial reduction in mid span deflection and this reduction may be attributed to the increase of beam stiffness and rigidity when increasing of (fy) and tensile steel ratio.

Failure Modes

As a result of experimental testing program, all the tested beams are designed to fail with flexure by increasing the shear strength of the beams. In all tested (reference and strengthened) beams, when the load is applied to the beam, the first crack appears in the bottom of the beam face at the center of beam between the two point load and after the gradual increment of the load the cracks propagated to the top of beam. At higher loads, the already formed cracks are widened while new cracks started to form.

Examination of failure modes suggests that all beams experienced flexural failure, and all beams except Beams L2-16-60 and L2-16-75 failed in tension. The tension failures were either by steel yielding or by debonding of the CFRP laminate from the concrete substrate. Following steel yielding, the CFRP sheets were either deboned or ruptured. No rupture of CFRP sheets occurred for the two-layer strengthened beams. See Fig. (7).

For the beams failing in compression, evidently, the fact that the beam was reinforced with highest reinforcement ratio and strengthened by the two CFRP layers may have affected the mode of failure.

Some peelings in the concrete substrates adjacent to the CFRP sheets were observed. The peelings indicate that the epoxy type, coupled with the CFRP plates, was stronger than the concrete.


L0-10-75
L1-10-75
L2-10-75
L1-12-75
L2-12-75
L1-16-75
L2-16-75
L0-10-60

Figure. (7) Mode of failure for all beams

Ductility

Ductility is described as the ability of a structural element to sustain in elastic deformation without significant loss in resistance [6]. A significant consideration that may have to be added to strength and serviceability is ductility. It is important to ensure that in the extreme event of a structure being loaded to failure, it will behave in a ductile manner. This means ensuring that the structure will not fail in a brittle fashion without warning but will be capable of large deformations at near maximum load carrying capacity [7].

Two methods of measuring the flexural ductility are discussed in this section. One is based on the ductility index commonly used, and the other is a ductility index based on past research.

Conventional Method

Ductility has generally been measured by a ratio called a ductility index or factor (μ). The ductility index is usually expressed as a ratio of rotation (θ), curvature (ϕ), or deflection (Δ) at failure to the corresponding property at yield. For this study, deflection will be used as the primary measurement of ductility.

Energy Method

The energy method that is used here to estimate ductility of CFRP strengthened RC beams was proposed by ***Oudah and El-Hacha (2012)***.They developed a new ductility model based on the response of a typical steel RC beam strengthened using FRP reinforcement (FRP SC) beam; however, it is also applicable for conventional concrete beams. The model was proposed for both fatigued and un fatigued beams, but we will explain the un fatigued beam ductility model only.

The tri-linear load–deflection response of a typical FRP SC beam is shown in **Fig. (8)**. First, the total energy, E_{tot} is calculated as the summation of the five areas under the load deflection curve as follows:

$$\boldsymbol{E_{tot} = I + II + III + IV + V} \qquad \text{——} \ (1)$$

After that they suggested the equation below to calculate the elastic energy E_{ela}:

$$\boldsymbol{E_{ela} = \frac{P_u^2}{2S}} \text{——} \ (2)$$

where P_u is the ultimate load, kN, and S is the Slope of the line separating the elastic energy from the inelastic energy.

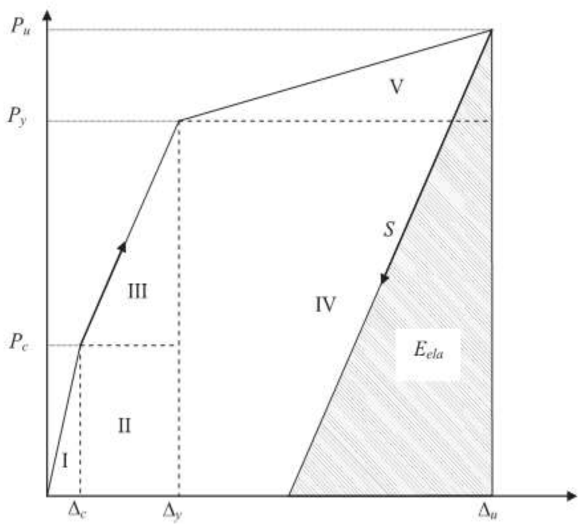


Figure. (8) Schematic representation of the load–deflection behavior of un-fatigued beams [8]

In addition, calculate the energy ratio E_{tot}/E_{ela}:

$$\mu_E = \frac{\boldsymbol{E_{tot}}}{\boldsymbol{E_{ela}}} = \frac{\boldsymbol{S[P_y(\Delta_u - \Delta_c) + P_u(\Delta_u - \Delta_y) + P_c\Delta_y]}}{\boldsymbol{P_u^2}} \text{——} \ (3)$$

where μ_E is energy ductility index, Δ_u is the ultimate deflection, mm, Δ_c the cracking deflection, mm, Δ_y is the yielding deflection, mm, P_c is the cracking load, kN, and P_y is the yielding load, kN.However, if no data is available, then S can be estimated by simply assuming that the slope of the unloading branch is similar to that of the curve connecting the crackingload to the yielding load. Thus, S can be expressed as follows:

$$S = \frac{P_y - P_c}{\Delta_y - \Delta_c} \quad (4)$$

Table (3) shows the results of ductility index for all tested beams by aforementioned two methods. Whether based on energy or on deflection, the calculated ductility values were close to each other. Due to the close values of ductility index for all strengthened beams, a comparison between the one layer CFRP beams or the two-layer ones is not possible.

Failures in all strengthened beams were accompanied by the release of large amounts of energy (known as elastic energy) relative to inelastic energy. Therefore, a reasonable factor of safety should be used in the design of FRP strengthened reinforced concrete members.

Table (3) Ductility indices by deflection and energy method

Beam symbol	*Conventional Method*			*Energy Method*		
	Yield deflection (mm)	*Ultimate deflection (mm)*	*Deflection Ductility Index (μ)*	*Total Energy (kN.mm)*	*Elastic Energy (kN.mm)*	*Energy Ductility Index (μ_E)*
L0-10-75	11.184	50.5	4.515	1247.484	202.825	6.151
L1-10-75	16.320	35.2	2.157	1116.888	505.210	2.211
L2-10-75	22.500	37.1	1.649	1169.983	730.178	1.602
L1-12-75	20.462	28.6	1.398	874.946	566.206	1.545
L2-12-75	21.050	35.2	1.672	1394.513	766.890	1.818
L1-16-75	21.100	35	1.659	1399.844	911.698	1.535
L2-16-75	23.088	34.7	1.503	1495.407	1092.254	1.369
L0-10-60	13.170	62.1	4.715	1383.863	218.625	6.330
L1-10-60	15.962	33.2	2.080	782.894	433.185	1.807
L2-10-60	15.615	33	2.113	921.306	487.794	1.889
L1-12-60	14.615	29	1.984	800.901	463.634	1.727
L2-12-60	20.965	37.1	1.770	1160.062	683.268	1.698
L1-16-60	16.970	25.8	1.520	926.365	546.207	1.696
L2-16-60	20.200	36.4	1.802	1781.869	875.347	2.036

CONCLUSIONS

Based on the experimental investigation described in this study, the following conclusions are drawn:

1. In the post-yielding stage, the contribution of CFRP becomes very significant. For instance, the ultimate load of beams reinforced with 2 No. 10 steel bars of Grade 520 MPa had increased from 30.5 kN to 47 kN (54%) when strengthened with one layer of CFRP, and to 54.9 kN (80%) when strengthened with two layers.
2. At ultimate, the un strengthened specimens exhibited a higher mid span deflection compared with the strengthened specimens; however, the strengthened specimens achieved higher load capacities than the un strengthened specimens, the two-layer strengthened beams being the highest.

3. For both the one-layer CFRP beams and the two-layer ones, the load-deflection curves were almost identical from beginning until the load reaches ultimate stages, where the two-layer CFRP beams showed higher strengths.
4. Examination of failure modes suggests that all beams experienced flexural failure, mostly failed in tension. The tension failures were either by steel yielding or by debonding of the CFRP laminate from the concrete substrate. No rupture of CFRP sheets was occurred for the two-layer strengthened beams.
5. Some peelings in the concrete substrates adjacent to the CFRP sheets were observed. It indicates that the epoxy type, coupled with the CFRP plates, was stronger than the concrete.
6. With the exception of the control beams, all of the beams exhibited poor ductility. The energy ductility index values ranged (1.535 - 2.211) and (1.369 - 2.036) for one-layer strengthened beams and two-layer ones, respectively.
7. Failures in all strengthened beams were accompanied by the release of large amounts of energy. Therefore, a reasonable factor of safety should be used in the design of FRP strengthened reinforced concrete members.

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