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Experimental study on long-term behaviour of CFRP strengthened RC beams under sustained load

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Abstract. The strengthening and rehabilitation of reinforced concrete structures with externally bonded carbon fibre reinforced polymer (FRP) laminates has shown excellent performance and, as a result, this technology is rapidly replacing steel plate bonding techniques. This paper addresses this issue, and presents results deals with the influence of external bonded CFRP-reinforcement on the time-dependent behavior of reinforced concrete beams. A total of eight reinforced concrete beams with cracked and un-cracked section, with and without externally bonded CFRP laminates, were investigated for their creep and shrinkage behavior. All the beams considered in this paper were simply supported and subjected to a uniform sustained loading for the period of six months. The main parameters of this study are two types of sustained load and different degrees of strengthening scheme for both cracked and un-cracked sections of beams. Both analytical and experimental work has been carried out on strengthened beams to investigate the cracking and deflection performance. The applied sustained load was 56% and 38% of the ultimate static capacities of the un-strengthened beams for cracked and un-cracked section respectively. The analytical values based on effective modulus method (EMM) are compared to the experimental results and it is found that the analytical values are in general give conservative estimates of the experimental results. It was concluded that the attachment of CFRP composite laminates has a positive influence on the long term performance of strengthened beams.

Keywords: long-term deflection; cracked beam; CFRP laminates; sustained loading; creep and shrinkage

1. Introduction

In recent years, the external bonding of high-strength Carbon Fiber Reinforced Polymer (CFRP) composites has widely gained popularity in the concrete construction industry, particularly in rehabilitation works to rectify inadequate design or structural damage. Comprehensive experimental investigations conducted in the past have shown that this strengthening method has several advantages over the traditional ones. CFRPs possess high stiffness-to-weight ratio, favourable corrosion resistance and low relaxation characteristics when compared to steel reinforcement, offering economically and structurally sound alternative in most applications. The need for rehabilitation or strengthening of bridges, building and other structural elements may arise due to

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one or a combination of several factors including construction or design defects, increased load carrying demands, change in use of structure, structural elements damage, seismic upgrade, or meeting new code requirements This implies that these factors are contributed to infrastructure becoming either structurally inefficient or functionally obsolete. Before the introduce of carbon fibre reinforced polymer (CFRP) strengthening technologies, one popular technique for upgrading reinforced concrete beams was the use of external epoxy-bonded steel plates (Swamy *et al.* 1987, Hamoush and Ahmed 1990, Sommerard 1977). However, this method suffers deterioration problem caused by the corrosion of the steel. There is currently a wide range of techniques available to repair or strengthen structurally deficient and functionally obsolete structures. The basic concepts in the use of FRPs for strengthening of concrete structures are covered in a review article (Triantafillou 1998). Previous researches have shown that CFRPs composites in strengthening RC members, in the form of sheets, have emerged as a viable, cost-effective minimally disruptive technique for improving structural performance (Saadatmanesh and Ehsani 1991, Meir and Kaiser 1991, Al-Mahaidi and Kalfat 2010).

Serviceability of concrete can be defined as satisfactory performance under service load conditions which in turn can be described in terms of two basic parameters namely cracking and deflection. Deflections constitute one of the important serviceability criteria in the design of reinforced concrete (RC) structures. Creep and shrinkage effect are the most dominating factors affecting time-dependent deformations of reinforced concrete beams. Due to these effects deformation of reinforced concrete beams increases with time a significant amount. In case of CFRP laminate strengthened beam, the creep of epoxy in between the sheet and concrete surface and also the relaxation of CFRP laminate can play roles in accelerating this time-dependent deformation. Cracking has been commonly observed for RC beams in service. The deflection due to the time dependent effect is more critical for cracked beams. In cases where deflection control is critical, it is important to accurately predict the long-term time dependent deflections.

A number of research works has been carried out on the instantaneous deflection of reinforced concrete (RC) beams externally bonded with different types FRP system (Alsaycd 1993, Chajes *et al.* 1994, Ross *et al.* 1999). It was observed from these studies that an increase in the flexural strength and stiffness of the beams results due to the strengthening effect of FRP laminates. Several researches (Plevris and Triantafillou 1984, Arockiasamya *et al.* 2000, Tan and Saha 2006, Gilbert 2006, Muller *et al.* 2007, Al Chami *et al.* 2009) have also been conducted on the long-term behaviour of FRP strengthened reinforced concrete beams and it's received a considerable attention from the research community. However, long-term deflection of RC beams with externally bonded FRP laminate induced by creep and shrinkage is still a major concern due to lack of large-scale experimental data.

Al Chami *et al.* (2009) conducted a series of experiment on the long-term performance of CFRP strengthened concrete beams. Different levels of sustained loads varied from 59% to 78% of the ultimate static capacities of the un-strengthened beams were applied. It was concluded that CFRP strengthening is effective for increasing the ultimate capacities of the beams; however, there is virtually no improvement in performance with regard to the long-term deflections. Paulson et al. (1991) showed that compression reinforcement has significant effect in reducing the long-term deflection and the efficiency of this reinforcement is more pronounced in normal strength concrete beams as compared to high strength beams.

Presently, along with ACI (American Concrete Institute) approach (ACI 435R 2003), some analytical methods (Ezeldin and Shiah 1995, Gilbert 2001, Ghali *et al.* 2002, Zou 2003, Saha and

Tan 2005) are available to compute the long-term deflections in RC members. These are mainly based on strain compatibility and equilibrium of forces with different models to account for the curvature due to creep and shrinkage. Once the curvature is known, deflections can be computed by double integration of the curvature or by using conjugate beam method.

In this study, experimental investigation on long-term deflections of reinforced concrete beams strengthened with externally bonded CFRP laminates induced by creep and shrinkage are carried out to provide necessary experimental data.

The ACI recommended analytical method is adopted to compute the long-term deflection of CFRP strengthened beams. Experimental values of ultimate creep coefficient and shrinkage strain are used in the ACI recommended creep and shrinkage model. The curvature due to shrinkage of concrete includes the effect of CFRP bonded laminates in evaluating shrinkage deformation. The experimental data is compared to the presented analytical approach. Finally, some critical issues related to the long-term serviceability performances of such structures are discussed.

2. Analytical consideration

This section describes the analytical approach to evaluate the instantaneous and long-term deflection of a reinforced concrete beams. The analysis is based on elastic beam theory considering time-dependent properties of concrete and CFRP laminates. Time-dependent deflections performance of beams subjected to sustained load can be predicted using effective modulus method (EMM) by incorporating ACI recommended (2003) creep and shrinkage models.

2.1 Instantaneous deflections

The equation of instantaneous deflection of a simply supported beam of spans length l, under the uniformly distributed loading w (refer to Fig. 1(a)) can be expressed as

$$\delta_{(t_o)} = \frac{5}{384}\frac{wl^4}{E_c I_e} \tag{1}$$

Where E_c is defined as modulus of elasticity of concrete and I_e is the effective moment of inertia.

For un-cracked members, gross section (refer to Fig. 1(b)) of the beam is effective and un-cracked transformed section analysis is used to calculate the I value whereas, for the cracked members I_e

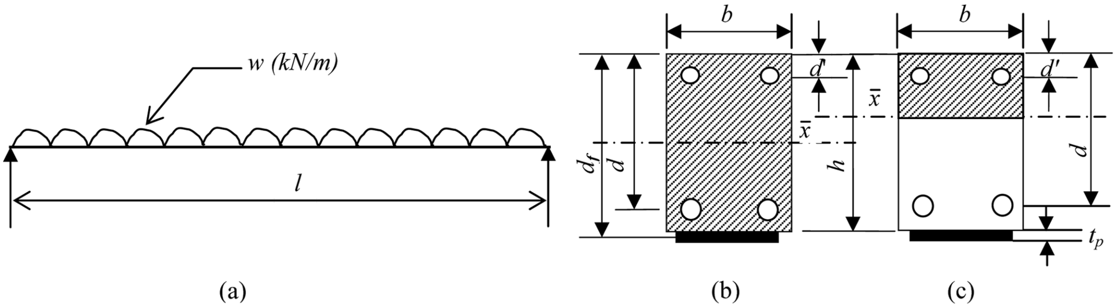

Fig. 1 (a) Uniformly distributed loaded (UDL) beam (b) un-cracked section and (c) cracked section details can be evaluated from the well-known Branson (1977) formula is given by

$$I_e = \left(\frac{M_{cr}}{M_a}\right)^3 I_g + \left[1 - \left(\frac{M_{cr}}{M_a}\right)^3\right] I_{cr} \le I_g \tag{2}$$

Where M_{cr} = cracking moment; M_a = maximum applied moment; and I_g and I_{cr} = moment of inertia of a gross and a cracked section respectively.

For an un-cracked FRP-bonded beam with a rectangular cross section, moment of inertia can be evaluated based on gross section (I_g) using transformed area for both steel and FRP reinforcement, that is (refer to Fig. 1(b))

$$I_g = \frac{bh^3}{12} + bh\left(\bar{x} - \frac{h}{2}\right)^2 + (n-1)A_s(d-\bar{x})^2 + (n-1)A_s'(\bar{x}-d')^2 + n_p b_p t_p (d_f - \bar{x})^2 \tag{3}$$

Where b = beam width; h = beam height; $\bar{x}$ = neutral axis depth for un-cracked section; the modular ratio of steel to concrete, $n = E_s/E_c$; modular ratio of CFRP composite laminate to concrete; $n_p = E_p/E_c$; A_s = total area of tensile steel reinforcement; d = distance from the top compressive face to the centroid of tensile steel reinforcement, d_f = distance from the top compressive face to the centroid of CFRP laminate, b_p = width of CFRP laminate and t_p = thickness of CFRP laminate.

For a cracked rectangular section, moment of inertia (I_{cr}) can be expressed as (refer to Fig. 1(c))

$$I_{cr} = \frac{bh^3}{3} + nA_s(d-\bar{x})^2 + (n-1)A_s'(\bar{x}-d')^2 + n_p b_p t_p (d_f - \bar{x})^2 \tag{4}$$

Where x = neutral axis depth for a cracked section; A_s' = total area of compressive steel reinforcement; and d' = distance form top compressive face to the centroid of compressive reinforcement.

2.2 Long-term analysis of cross section

The coefficient for creep at times t_d (days) after load application is given by the following expression recommended by ACI 435R (2003)

$$\phi_{c(t)} = \frac{t_d^{0.6}}{10 + t_d^{0.6}} \phi_{uc} \tag{5}$$

Where ϕ_{uc} is the ultimate creep coefficient and depends on conditions of concrete.

The age-adjusted modulus of elasticity is given by the following expression

$$\bar{E}_{c.t} = \frac{E_c(t_o)}{1 + \chi \phi_{c(t)}(t, t_o)} \tag{6}$$

Where χ is the aging coefficient of concrete and varies between the values of 0.7 to 0.9 with the average value of 0.8. Similarly, the age adjusted modulus of CFRP laminates can be expressed as (Tan and Saha 2006).

$$E_{FRP(t)} = \frac{E_{FRP}(t_o)}{1 + \phi_{FRP(t)}} \tag{7}$$

Where $\phi_{FRP(t)}$ is the creep coefficient and is given by

$$\phi_{FRP(t)} = \left(\frac{t_h}{t_{ho}}\right)^n - 1 \tag{8}$$

Here t is the time in hours and t_{ho} is 1 hour, n is the gradient of the curve which has to be determined from the experimental results.

Based on the age-adjusted modulli, the neutral axis depth can be found after any time period from the transformed section analysis. For the cracked section, by using the neutral axis depth the $I_{cr.t}$ (moment of inertia of a cracked section) and $I_{e.t}$ (effective moment of inertia) can be calculated after time t. Finally, the "instantaneous plus creep" deflection is obtained by substituting the age-adjusted modulus $E_{c.t}$, and $I_{e.t}$ in Eq. (1).

The curvature (φ_{sh}) due to shrinkage of concrete in an asymmetrically RC member can be found by the fictitious tensile force method (Branson 1977) as

$$\varphi_{sh} = \frac{Te}{E_e I_{cr,t}} \tag{9}$$

where T = fictitious compressive force induced in the steel reinforcement and CFRP composite laminate, considered in total; and e = eccentricity of the steel reinforcement and CFRP composite laminate measured from the centroid of the cracked transformed concrete section. For a CFRP-bonded section (Tan and Saha 2006)

$$Te = [A_s E_s(d-\bar{x}) - A_s' E_s(\bar{x}-d') + b_p t_p E_{FRP}(t)(h-\bar{x})]\varepsilon_{sh}(t,t') \tag{10}$$

where $\varepsilon_{sh}(t,t')$ = shrinkage strain at time t, with drying commencing at time t'.

The shrinkage strain at any time t (in days) can be expressed recommended by ACI 435R (2003)

$$\varepsilon_{sh}(t,t') = \frac{t}{\alpha+t}\varepsilon_{sh.u} \tag{11}$$

Where α is an experimental constant, $\varepsilon_{sh.u}$ = ultimate shrinkage strain.

Finally, the deflection due to shrinkage for a simply supported beam can be expressed as

$$\Delta_{sh} = \frac{1}{8}\varphi_{sh} l^2 \tag{12}$$

This shrinkage deformation will be added to the previously determined deflection considering creep effects to get the total deflection.

3. Experimental investigation

3.1 Test program

Table 1 shows the test program that was initiated to investigate the effect of CFRP laminates on the long-term performance of RC beams for cracked and un-cracked section and to verify the accuracy of the analytical methods. The main parameters investigated in this study are the two types of sustained load and different configurations of CFRP for both cracked and un-cracked sections of

Table 1 Test program for time-dependent test

Section type and sustained load	Beam designation	FRP ratio, ρ_{CFRP} (%)	Service load*	Time-dependent strengthening scheme
Un-cracked (15.31 kN)	CBU	0	0.38 P_0	Un-strengthened (control) beam
	FBU-1L	0.4	0.25 P_1	One layer of CFRP laminate bonded beam
	FBU-2L	0.8	0.22 P_2	Two layers of CFRP laminates bonded beam
	FBU-3L	1.2	0.21 P_3	Triple layers of CFRP laminates bonded beam
Cracked (22.56 kN)	CBC	0	0.56 P_0	Un-strengthened (control) beam
	FBC-1L	0.4	0.36 P_1	One layer of CFRP laminate bonded beam
	FBC-2L	0.8	0.33 P_2	Two layers of CFRP laminates bonded beam
	FBC-3L	1.2	0.30 P_3	Triple layers of CFRP laminates bonded beam

Note: *Sustained service load = 0.56 × Ultimate capacity of control beam (P_{uc})
Flexural capacity of un-strengthened (control) beam, P_0 = 40.3 kN
Flexural capacity of 1-layer CFRP strengthened concrete beam, P_1 = 62.0 kN
Flexural capacity of 2-layer CFRP strengthened concrete beam, P_2 = 69.75 kN
Flexural capacity of 3-layer CFRP strengthened concrete beam, P_3 = 74.4 kN

beams. A total of eight beams having different level of strengthening scheme and subjected to different sustained loads to ensure cracked and un-cracked section were tested in the laboratory. Two beams (designated as CBC and CBU) were not bonded with CFRP laminates, three beams (FBU-1L, FBU-2L and FBU-3L) for un-cracked section and the rest three beams (FBC-1L, FBC-2L and FBC-3L) for cracked section were bonded with 1, 2 and 3-layers of CFRP laminates. The CFRP ratio, ρ_{CFRP}, is the area of CFRP composite laminate divided by the gross concrete area. Different CFRP ratios were chosen such as to facilitate comparison among these beams with the same sustained loads. CFRP composites laminates were bonded on the tension face of the beams 1500 mm, 1300 mm and 1100 mm in length, along which 250 mm, 350 mm and 450 mm were un-bounded for 1, 2, 3-layers of CFRP laminates for un-cracked and cracked section respectively.

The flexural capacities of different layered CFRP-bonded beams have been investigated from the static test in the laboratory. In Table 1, the beam designation corresponding to the service load denotes the sustained load level as a percentage of the beam's calculated ultimate flexural strength. This percentage of the sustained load was then used for the long-term deflection testing.

3.2 Material properties

3.2.1 Concrete

To achieve a 28-day concrete cube compressive strength of 36.0 MPa, the mix proportion was set at 1:1.65:2.45:0.45 by weight of ordinary Portland cement, locally available natural sand, and crushed granite aggregate of 10 mm nominal size and water. Standard size specimens were tested in the laboratory to determine the cube's compressive strength, modulus of elasticity and modulus of rupture at 28 days. The characteristics concrete strengths as obtained from laboratory tests are shown in Table 2.

Table 2 Concrete properties

Properties	Values found in the laboratory
Concrete cube strength (MPa)	36.0
Modulus of elasticity (GPa)	28.6
Modulus of rupture (MPa)	3.7
Creep coefficient	1.3
Shrinkage strain (in/in)	0.000352

Compressive creep test

A total of six cylinders measuring 150 mm in diameter and 300 mm in height were cast in the laboratory and cured into the curing tank for 28 days. The test was conducted in compliance to the ASTM C512-87 ("Annual" 1990) standard test method for creep of concrete in compression. Three cylinders were tested to determine the ultimate compressive strength; three were stacked and loaded together 0.40 times the cylinder ultimate compressive strength on a creep rig. The creep strain was determined the average strain value of the three specimens. The creep coefficient is calculated by taking the ratio of creep strain of the concrete at the testing age to the instantaneous elastic strain of the concrete.

Fig. 2 shows the results of the concrete creep test over a period of six months. It was observed that the curve of the experimental result for concrete creep coefficient did not fully stabilize after six months period. Therefore, to carry out the theoretical calculation of this paper, the experimental value of creep coefficient is used instead of the ACI recommended creep model as mentioned earlier in section 2.

Drying shrinkage test

The drying shrinkage was performed on 100 mm × 100 mm × 285 mm prisms in accordance with the ASTM C157-92. Three specimens were casted in steel moulds. The shrinkage strain for each specimen was the average value of three specimens. Fig. 3 shows the experimental results for the shrinkage strain of concrete over a period of six months. Similar to the creep results, the shrinkage strain of concrete did not stabilize fully after the six months period. Again, instead of ACI recommended shrinkage model, the experimental result will be used to carry out the theoretical calculation to get better accuracy in the results.

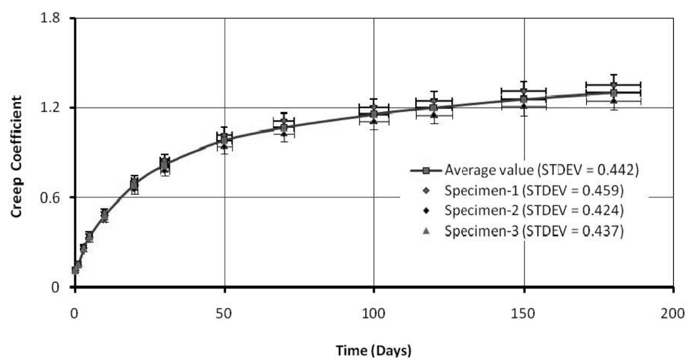

Fig. 2 Concrete creep coefficient versus time plot

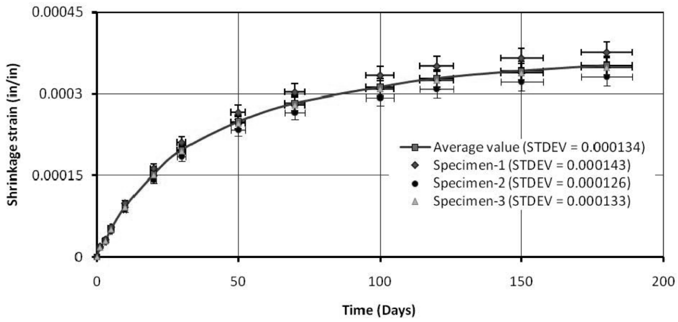

Fig. 3 Concrete shrinkage strain versus time plot

3.2.2 Steel reinforcement

High yield deformed bars of 6 mm and 10 mm (T6 and T10) were used as compression and tension reinforcement for the beam specimens. Plain round mild steel bar of 6 mm diameter (R6) is used at a constant spacing of 125 mm throughout the entire length of the beams so as to prevent the beams from failing in shear. Tensile tests were conducted in the laboratory to obtain the modulus of elasticity and yield strength values of steel reinforcing bars and these values were used for theoretical predictions. Table 3 shows the details of steel reinforcement properties.

3.2.3 CFRP laminates and epoxy adhesive

The carbon fiber reinforced polymer (CFRP) laminates are commercially available with unidirectional plain roving form. CFRP composites laminate of 1.2 mm thickness and 100 mm wide were used for the strengthening purposes of the beams and are cut from the Sika Carbodur S1012/

Table 3 Steel properties

Reinforcement type	Yield strength (MPa)	Modulus of elasticity (GPa)
Tension, T10	482	195
Compression, T6	470	186
Shear, R6	215	200

Table 4 CFRP laminates and epoxy adhesive properties

Materials	Property	Values
CFRP laminate	Sheet form	Uni-directional roving
	Yield strength (MPa)	1315
	Modulus of Elasticity (GPa)	165
	Elongation at ultimate (%)	2.15
	Tensile strength (MPa)	1685
	Density (g/cm^3)	1600
Epoxy adhesive	Modulus of Elasticity (GPa)	3
	Elongation at ultimate (%)	2.6
	Tensile strength (MPa)	55

160 (2008) roving laminate. The CFRP composite laminate was tested in the laboratory to get the tensile strength, yield strength, modulus of elasticity and the percentage of ultimate elongation until the failure. The creep strain of the CFRP composite laminate also needs to investigate. The study conducted by Plevris and Triantafillou (1984) showed that the carbon fibers laminates are practically creep free. Based on the outcome of that study, the creep coefficient of CFRP laminates is considered as zero for the long-term analysis of the section. The other properties of the carbon fibers and epoxy adhesive as supplied by the manufacturer are shown in Table 4.

3.3 Specimen fabrication

The specimen configuration is shown in Fig. 4. All the beam specimens are 150 × 200 mm in cross section and 1900 mm in span length on a simply supported span. The tensile reinforcements were placed at a depth of 168 mm while the compressive reinforcement depth was 30 mm. The

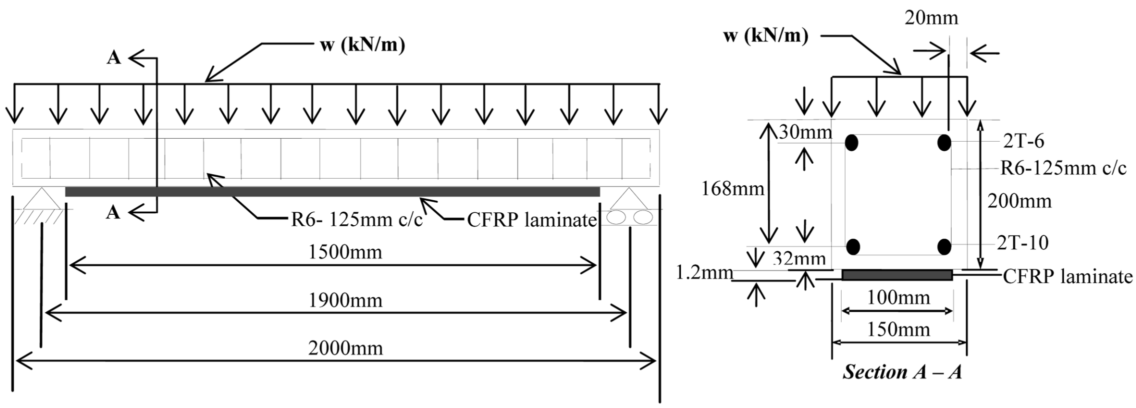

Fig. 4 Longitudinal and cross section detail of the experimental beams

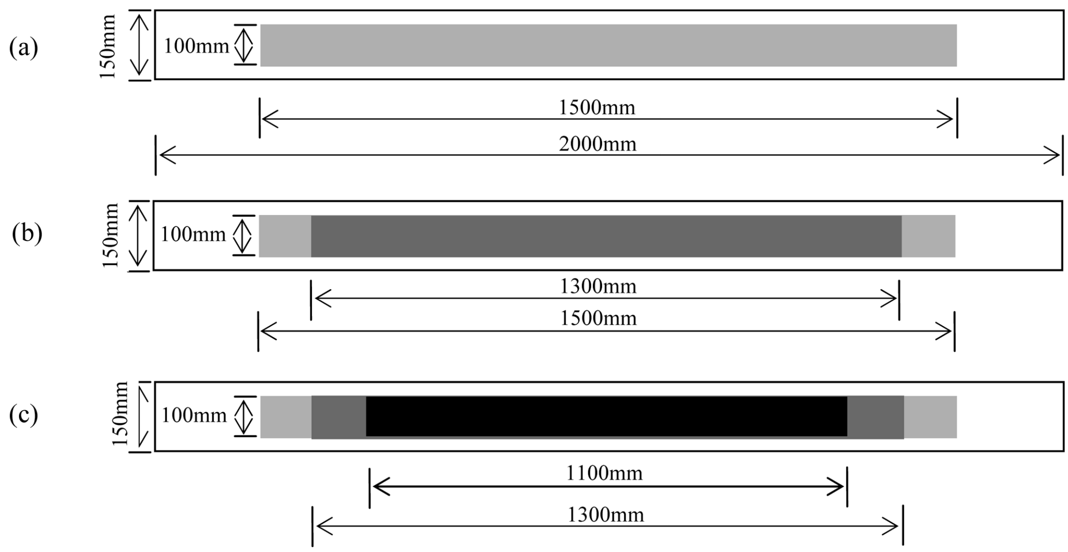

Fig. 5 Strengthening schemes of RC beams: CFRP laminates of (a) single, (b) double and (c) triple layers

control beam was designed to fail in flexure following the BS8110, Part 1 (1997). Figs. 5(a), 5(b) and 5(c) show the schematic diagram of single, double and triple layers CFRP strengthening scheme of reinforced concrete beams.

3.4 Surface preparation techniques

In the fabrication of beams, it is needed to prepare the substrate before composites sheets is bonded to the tensile face of the concrete. The surfaces were prepared as suggested by the manufacture instruction for proper bonding of the CFRP laminates into the concrete. Prior to the bonding of the CFRP laminates to the beams, the concrete substrate was mechanically abraded by using a grinding wheel, creating somewhat a rough surface to remove other dirt. Also, it was observed that no moisture was visible on the roughened surface. Sikadur-30 two-part (Part-A and Part-B) cold curing epoxy resin is used for the bonding of the CFRP laminates. The two-parts are mixed at a proportion of 1:3 in accordance with the manufacture's instruction and then applied on the prepared concrete surface. The CFRP laminates were cleaned properly using sika colma cleaner. A nominal thickness of the epoxy adhesive has been controlled for the attaching of epoxy on the CFRP surface. Sikadur-30 adhesive was applied on cleaned and prepared substrate components and then, the CFRP laminates were placed onto the prepared concrete surface. The CFRP composites laminates was attached starting at one end and applying enough pressure by rubber roller to press out any excess epoxy from the sides of the laminates. All the excess epoxy was removed from the sides of the CFRP laminates. To ensure a proper bonding, a minimum of 3 days curing of the externally applied adhesive is maintained for all the specimens.

3.5 Test set up and instrumentation

The beams were set up over the simply supports with a clear span 1900 mm to investigate the long-term performance of multi-layered CFRP strengthened cracked and un-cracked beams subjected to distributed sustained loads. Fig. 6 shows the loading and instrumentation detail of the typical test beam. In this situation, loads were applied using concrete blocks and steel beams along the length of the beam to simulate uniformly distributed loading. The mid span deflection of each beam including self-weight value was recorded instantaneously after the load application. During the testing, the deflections of all beams were measured at mid span and quarter span of the beams

Fig. 6 Long-term deflection test setup

using digital dial gauges. Also, two dial gauges were placed at mid-span at 20 mm from the front and back sides of the beam, to check for any unintentional rotation of the beams due to loading. The average of the two dial gauge readings was taken as the mid-span deflection. The quarter span dial gauges were used to check the symmetrical nature of the loaded beams. Readings were taken at regular interval starting 1, 3, 5, 7, 10, 14, 21 days, weekly up to 3 months and every 15 days thereafter for up to 6 months for the experimental beams. In long-term deflection test, the service load levels as mentioned in Table 1 that corresponds to the cracked and un-cracked sections are simulated.

4. Results and discussion

4.1 Effect of CFRP ratio under sustained loads

The long-term deflections of un-cracked and cracked beams with different CFRP ratios under the sustained loads are compared as shown in Figs. 7 and 8. All these beams are cast from the same concrete batch and reinforced with the same reinforcement. The level of the applied sustained load is presented in terms of ultimate capacity (P_{uc}) of un-strengthened (control) beam for un-cracked and cracked section. It is clear that the higher the CFRP ratio, the smaller is the instantaneous and time-dependent deflections for un-cracked and cracked section due to the corresponding sustained loads. Thus, the CFRP laminate seems to be effective in decreasing the instantaneous deflections and also its influence on the long-term deflections under sustained load. The time-dependent deflections of beams FBU-1L, FBU-2L and FBU-3L are 20, 28 and 35% less than the un-cracked control beam (CBU) under the service loads ($0.38P_0$) whereas for the cracked beams FBC-1L, FBC-2L and FBC-3L, it is 37, 46 and 56% less respectively, than the control beams (CBC) under the service loads ($0.56P_0$). It is also observed that the instantaneous deflections for un-cracked and cracked beams with different CFRP configurations are significantly lower than the comparable un-strengthened beams. The sustained load intensity of all un-cracked beams is smaller than that of cracked beams and hence un-cracked beams exhibits smaller long-term defections than those of cracked beams. In general, the higher the CFRP ratio, the lower is the long-term deflection of the CFRP strengthened beams. Hence, CFRP ratio is affecting the time-dependent performance of the strengthened beams.

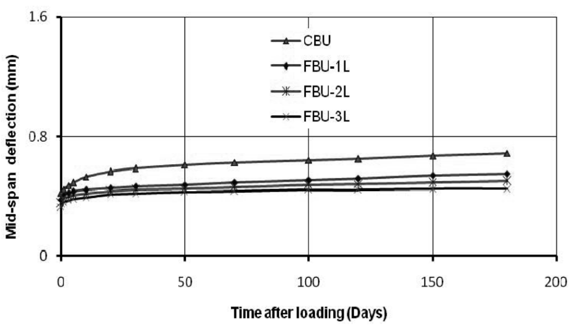

Fig. 7 Long-term deflection of RC beams Strengthened with CFRP (Un-cracked section)

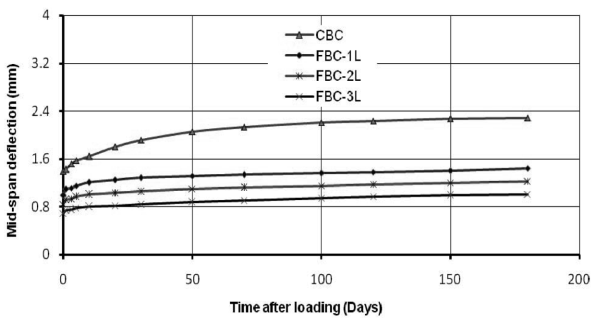

Fig. 8 Long-term deflection of RC beams Strengthened with CFRP (Cracked section)

Table 5 Deflection of RC beams strengthened with CFRP laminates

Beam	FRP ratio, ρ_{frp} (%)	Instantaneous deflection (mm)	Long-term deflection (mm)	Long-term/instantaneous deflection
CBU	0	0.42	0.69	1.642
FBU-1L	0.4	0.38	0.55	1.447
FBU-2L	0.8	0.35	0.5	1.428
FBU-3L	1.2	0.33	0.45	1.363
CBC	0	1.38	2.28	1.652
FBC-1L	0.4	0.99	1.44	1.454
FBC-2L	0.8	0.84	1.22	1.452
FBC-3L	1.2	0.69	1.00	1.449

4.2 Instantaneous and long-term deflections

The measured instantaneous and long-term deflections under sustained loads at the end of six months for un-cracked and cracked beams are summarized in Table 5. In all cases, the long-term defections are obtained by subtracting the instantaneous defection from the total defection. It is seen that the Instantaneous deflections for CFRP strengthened beams (FBU-1L, FBU-2L, FBU-3L, FBC-1L, FBC-2L and FBC-3L) are significantly lower than the comparable un-strengthened (control) beams. From the experimental investigation, it is identified that the long-term deflections for CFRP strengthened beams after a period of 180 days were about 1.45, 1.43, 1.36 and 1.45, 1.45, 1.44 times the instantaneous deflection due to sustained loads for 1, 2 and 3-layers CFRP strengthened beams for un-cracked and cracked section respectively. This is significantly lower than the un-strengthened reinforced concrete beams under sustained service loads in which the deflection of control beams at the same period had been measured to be about 1.64 and 1.65 times the instantaneous deflection for un-cracked and cracked section respectively. The reduction of time-dependent deflection is less for un-cracked section as compared to that of cracked sections. Long-term deflections of CFRP strengthened beams are occurred on average 72% and 73% within 70 days for un-cracked and cracked section from the time when the sustained load was applied, while it is occurred about 76% and 83% over a period 70 days for un-strengthened beams. Thus, it is concluded that attachment of CFRP laminates not only reduces the Instantaneous deflection but it is also more effective in controlling the long-term deflection under sustained load.

4.3 Comparison of test results with analytical predictions

Effective modulus approach based on the recommendation of ACI committee 435R-95 (2003) was used to compute the instantaneous and long-term deflections of CFRP strengthened reinforced concrete beams. The instantaneous and long-term deflections were predicted based on the applied sustained loads by including the beam self-weight using this method. ACI recommended creep and shrinkage model are adopted in this study in evaluating time dependent deformation. The experimental defections at the mid-span are compared with the analytically predicted behavior. In the analysis for the predictions long-term deflections, the creep coefficient obtained earlier from the compressive tests and the shrinkage strains measured from the drying shrinkage tests were used to

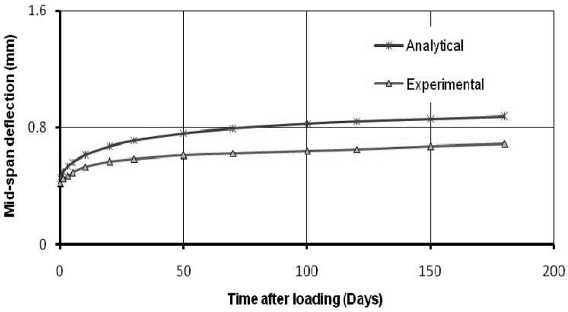

Fig. 9 Long-term deflection of un-strengthened un-cracked beam (CBU)

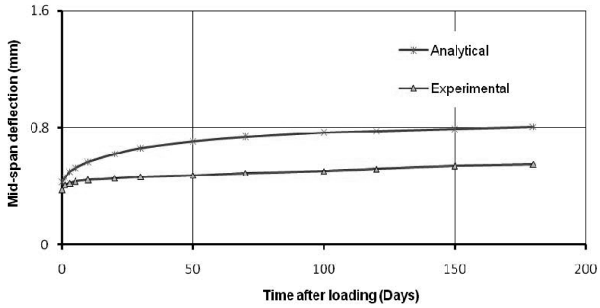

Fig. 10 Long-term deflection of 1-layer strengthened un-cracked beam (FBU-1L)

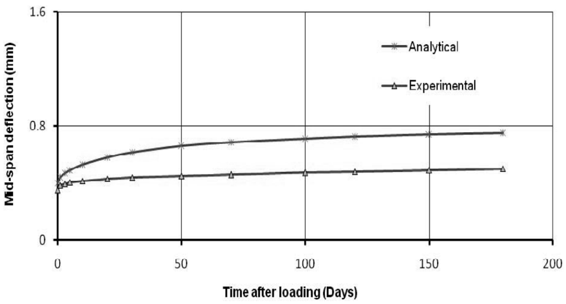

Fig. 11 Long-term deflection of 2-layers strengthened un-cracked beam (FBU-2L)

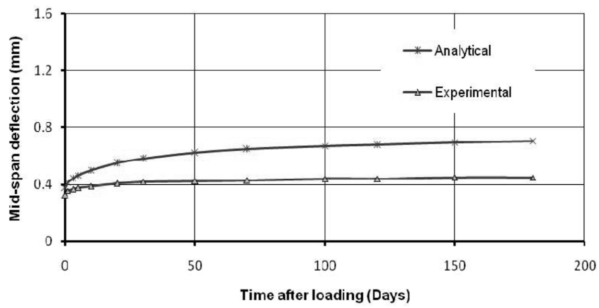

Fig. 12 Long-term deflection of 3-layers strengthened un-cracked beam (FBU-3L)

get the close comparison with the experimental results. The creep strain of the CFRP composite laminate also needs to be evaluated. Unidirectional carbon fiber is considered to behave as linear elastic materials and it was showed by Plevris and Triantafillou (1984) that CFRP laminates are practically creep free. Based on the outcome of that study, the creep coefficient of CFRP laminates is considered as zero for the long-term analysis of the section. Once the concrete creep coefficient, shrinkage strains and CFRP laminates creep coefficient are known, and then the instantaneous and long-term deflections are calculated using the effective modulus approach.

Test results were collected up to 180 days after the sustained loading as mentioned in Table 1 were imposed on the experimental beams. Transformed gross sectional properties were used in the calculation. The predicted mid-span deflection are compared to the experimental results in Fig. 9 to Fig. 12 due to the inclusion of creep and shrinkage effects under sustained loading for un-cracked beams with different CFRP ratios. In the case of un-cracked beams CBU, FBU-1L, FBU-2L and FBU-3L, a reasonable prediction of the deflection is achieved using the effective modulus method for the beams strengthened with CFRP laminates, and this includes instantaneous deflection Instantaneously after loading throughout the entire loading period . The total deflection predicted using effective modulus approach is slightly higher than the experimental results. Due to the unequal reinforcement at top and bottom faces, along with the creep, the shrinkage deformation will also occur in these beams. In general, the analytical results give conservative estimations for the long-term deformation of the test beams.

Beam with crack section compares the theoretical prediction of deflections at mid-span to the

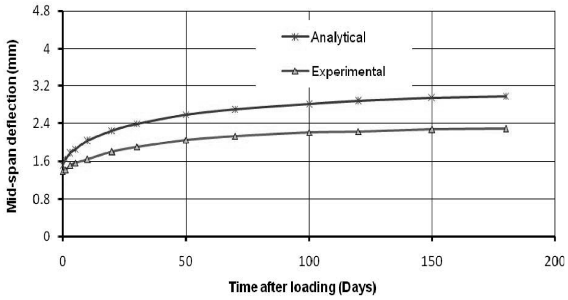

Fig. 13 Long-term deflection of un-strengthened cracked beam (CBC)

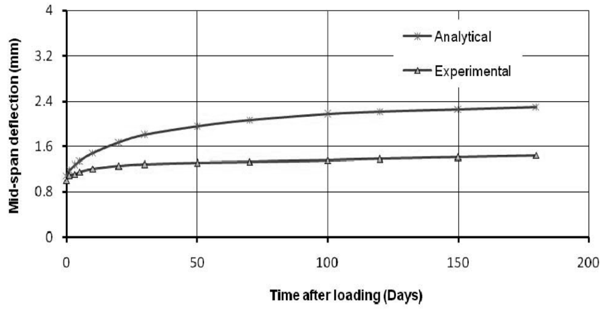

Fig. 14 Long-term deflection of 1-layer strengthened cracked beam (FBC-1L)

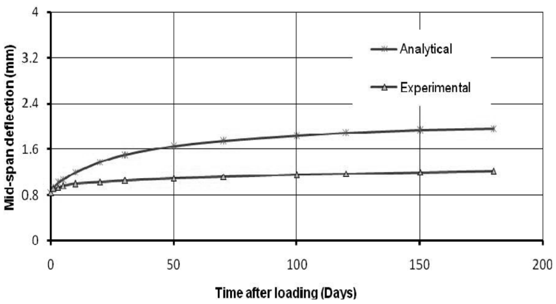

Fig. 15 Long-term deflection of 2-layer strengthened cracked beam (FBC-2L)

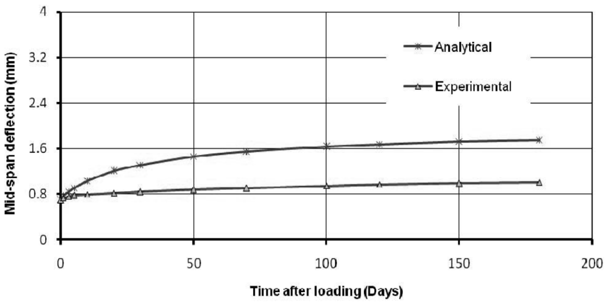

Fig. 16 Long-term deflection of 3-layer strengthened cracked beam (FBC-3L)

experimental results of the beams subjected to a sustained load greater than their cracking load. Typical comparison of experimental defections for beams CB, FBC-1L, FBC-2L and FBC-3L with the theoretical predictions are presented in Fig. 13 to Fig. 16. It can be seen that experimental deflection is slightly lower than the theoretical predicted deflection. The experimental defection for the beams reinforced with CFRP compares well with the theoretical computations. In general, the long-term deflection of the beams using analytical approach mentioned in this paper again gives conservative estimate of the experimental results.

For the cracked beam section, beside the creep coefficient and ultimate shrinkage strain, another factor which can influence the theoretical result is the tension stiffening, noting that concrete has the ability to carry tensile stress between cracks in the tension zone due to the bond between the steel and concrete. Calculations without concrete tension stiffening overestimate the deflection. The tension stiffening model used in this study is based on Branson formula (refer to section 2.1). This model needs modification by including factors for CFRP bonded section. Inclusion of a material parameter in tension stiffening model can give closer estimation of the experimental results.

5. Conclusions

The following observations can be made based on the experimental test results and analytical predictions for long-term deflection:

1. From the experimental investigation, it is seen that the long-term deflection after six month period was 64% and 65% higher to that of instantaneous deflection for the controlled un-cracked and cracked beams; whereas, it was on average 42% and 46% higher for the strengthened un-cracked and cracked beams respectively. This indicates attachment of CFRP laminates not only reduces the instantaneous deflection but it is also effective in controlling the long-term deflection.
2. CFRP laminates attachment has considerable effects on the time–dependent deflection of reinforced concrete beams. In general, the larger the CFRP reinforcement ratio, the smaller was the long-term deflection. For the same sustained loading, a maximum reduction of 35% in deflection was observed in un-cracked 3-layers strengthened beam (FBU-3L) as compared to the control one (CBU). Whereas for the cracked section (FBC-3L), the corresponding reduction in deflection was 56% as compared to the un-strengthened beam (CBC).
3. In all cases, the theoretical predictions are giving conservative estimate of the experimental results for the test beams.

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