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INTERNATIONAL ADVANCED RESEARCHES
and
ENGINEERING JOURNAL

Journal homepage: www.dergipark.org.tr/en/pub/iarej

e-ISSN: 2618-575X

International Open Access

Volume 05
Issue 01

April, 2021

Research Article

An investigation on the flexural behaviour of RC beams wrapped with CFRP

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ARTICLE INFO

Article history:
Received 30 July 2020
Revised 24 September 2020
Accepted 08 October 2020

Keywords:
Carbon fiber reinforced polymer
Flexural behaviour
RC beams
Strengthening

ABSTRACT

In addition to conventional retrofitting of constructions, new technologies are rapidly being developed to withstand the external effects while sustaining an acceptable level of damage. Reinforced concrete structures strengthened with fiber reinforced polymer composite materials are becoming more and more widespread in structural applications due to their better mechanical properties, resistance to environmental influences, ease of application and light weight, as well as conventional methods of strengthening. In this study, strengthening technique as a methodology for externally bonded with carbon fiber reinforced polymer (CFRP) sheets to increase the flexural resistance of reinforced concrete beams has been investigated. For this purpose, eight reinforced concrete beams were produced considering different types of CFRP configuration and tested under four-point bending loading. The dimensions of the beams are 150×250×2600 mm and concrete cover of the first and second group of test beam are 20 mm and 40 mm, respectively. Finally, load-deflection behavior with the failure mechanism of the tested beams have been discussed and the effect of different schemes of strengthening on the flexural behavior has been evaluated.

1. Introduction

The main purpose of strengthening methods is to bring the strength, ductility and rigidity of the element and/or system to desired level. In addition to conventional techniques, new techniques are being developed for the strengthening of structures and are widely used in the construction sector. In this field, one of these new techniques is the strengthening application with the use fiber reinforced polymer materials (FRP).

FRP materials have a wide usage area for strengthening of reinforced masonry and concrete construction elements depending upon high-grade properties such as light weight, ease of application in the area, high resistance of corrosion and high stiffness- and strength -to-weight ratio [1-6].

Bonding FRP materials is a new retrofitting or strengthening method for enhancing shear and flexural performance of existing reinforced concrete (RC) beams [7-9]. The effects of FRP materials which are externally bonded to the beams on flexure and/or shear capacity of beams have been investigated by previous experimental and numerical studies [3-5], [9-24]. In these studies, it is seen that the FRP composites are utilized as externally epoxy-bonded reinforcement to enhance the structural strength and stiffness, ductility and seismic performance of the RC beams.

Dong et al. [4] performed an experimental investigation on both the shear-flexural and the flexural performance of strengthened RC beams by GFRP and CFRP sheets. For this purpose, fourteen identical beams were fabricated and tested to failure for evaluating how different strengthening configurations of GFRP and CFRP sheets affected RC beams. Results showed that the flexural strengthening plan was less adequate than the shear-flexural strengthening in increasing the ultimate strength. Besides, the numerical analysis was accomplished to evaluate the shear and bending capacities of the tested beams. Analysis results indicated that theoretical predictions were in good agreement with experimental ones. Siddiqui [10] investigated experimentally the effectiveness and

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DOI: 10.35860/iarej.775557

adequacy of different FRP layouts in shear-flexural reinforcing of RC beams. Two groups of beams were fabricated, each group contained three beams as to be strong in shear and weak in flexure in the first group and to be weak in shear and strong in flexure in the second group. All beams were subjected to the same loading and the effectiveness of CFRP applications of different layouts was evaluated. It has been observed that CFRP sheets with U-shaped end anchored applied to the tensile surface of the beams are not only very effective in increasing the flexural capacity but providing sufficient deformation capacity as well. Nayak et al. [15] performed an experimental investigation of externally strengthened reinforced concrete beams by GFRP fabrics. For this purpose, reference RC beam and nine RC beams strengthened with GFRP fabrics in different ways were tested under two-point bending. They also developed a design proposal in addition to IS: 456-2000 to estimate the ultimate design resistance of RC beams which were strengthened with FRP fabric layers. For verification, the experimental flexural strength of strengthening RC beams were compared with the design flexural strength values calculated from the numerical model and the ACI 440-2R-08 design code. In addition, it was indicated that the flexural strength increased with an increase in number of fabrics for all strengthening schemes. Tautanji et al. [16] analyzed the failure mechanism of strengthened beams with FRP sheets. For this purpose, seven identical beams were fabricated and tested until failure. They also developed a moment displacement model and used it on beams which were tested in their study and other similar studies. The results showed that the ductility of strengthened beams by using externally bonded FRP sheets was significantly reduced compared to the reference beam. The outcomes also indicated that the proposed model validated the test results. Al-Amery and Al-Mahaidi [17] accomplished an experimental study to examine the flexural-shear strengthening of RC beams. The researchers tested an unstrengthened RC beam sample in addition to six strengthened RC beam samples which were strengthened in different scheme using CFRP straps and sheets. They indicated that coupling of CFRP sheets and straps improved the beam strength significantly. Also, it has been denoted that a more ductile behavior of RC beams can be obtained if the debonding failure is prevented. Esfahani et al. [18] studied the influence of reinforcement ratio on the flexural strength of reinforced concrete beams by utilizing CFRP layers. For investigation, twelve reinforced concrete beams were produced and four-point bending tests were performed on these beams. Test results and observations showed that an improvement of flexural stiffness and strength of strengthened beams were obtained. Reda et al. [19] performed an experimental study to investigate the behavior of RC beams which retrofitted with near surface mounted (NSM) glass fiber reinforced polymer (GFRP) bars. For this purpose, a reference beam and ten strengthened RC beams were casted and tested under four-point bending. Beams were strengthened with straight GFRP bars and GFRP bars with bent end. In the experimental study, it was observed that the GFRP bars with bent ends increased the load carrying capacity and the concrete cover separation of the beams. Test results stated that load-deflection and GFRP strain-load values for strengthened beams with straight NSM bars were compatible the analytical prediction. Huang et al. [20] studied on the flexural behavior of RC beams strengthened with polyester FRP composite plates. For investigation, six strengthened RC beams and two reference beams were manufactured and tested under four-point bending. The steel reinforcement ratio and the thickness of PFRP plates were chosen by authors as experimental parameters. They also compared the experimental ultimate load values of the beams strengthened PFRP with the equations given in ACI 440.2R-08. Experimental results indicated that the ultimate load, the ductility and the deflection increased in PFRP retrofitted RC beams. Tashiri et al. [21] studied the failure modes, the load-deflection behavior and the crack propagation patterns of strengthened RC beams using RC jacketing and FRP strengthening. Twelve strengthened RC beams (six RC jacketed beams and six CFRP strengthened beams) and three unstrengthened beams were tested under three-point bending. The outcomes indicated that both strengthening techniques increase energy dissipation capacity and strength. Mahal et al. [22] explored the efficiency of different srengthening methods (plate strengthening and NSM bar-strengthening) of RC beams through experimental studies. They conducted four-point bending test with RC beams under fatigue and monotonic loading using unstrengthened and strengthened RC beams. The outcomes showed that the mid-span displacement for beams strengthened with NSM bars was higher than the one for beams strengthened with CFRP plates. Sharaky et al. [23] investigated the effectiveness of near-surface mounted (NSM) fiber reinforced polymer (FRP) reinforcement and axial stiffness on the strengthened beam failure modes and flexural capacities experimentally and numerically. An unstrengthened and seven different strengthened RC beams were tested under four-point loading. The experimental results indicated that the confinement significantly increased the ultimate load of the RC beams. Jawdhari et al. [24] performed an experimental study to examine the effectiveness and behavior of spliced CFRP rod panels (CRPs) using for strengthening of RC beams. Five strengthened RC beams which were strengthened in different scheme using CFRP rod panels and CFRP fabric besides an unreinforced RC beam were tested. The results showed that the failure load and ultimate load increased in strengthened RC beams.

The benefit of the CRP system was emphasized in the study.

In this study, the flexural behavior of CFRP wrapped RC beams have been studied experimentally. For this purpose, three different wrapping schemes have been considered. Based on the flexural behavior of eight RC beams tested under four-point bending loading, existing experimental data are also evaluated.

2. Experimental Program

An experimental research was conducted at Yıldız Technical University Structural Engineering Laboratory for investigating the influence of different CFRP schemes on flexural strengthening of RC beams. The test specimens consisted of eight RC beams and classified into two groups according to the concrete cover. The overall concrete cover thickness of beams groups 1 and 2 were 20 mm and 40 mm, respectively. Both in group 1 and 2, there were an unstrengthened RC beam (reference beam), and three RC beams that were differently bonded with CFRP sheets [6], [25].

2.1 Beam Specimens

A total of 8 RC beams were fabricated in two groups; each group containing 4 beams. The beams of the first group were fabricated to be concrete cover thickness as 20 mm, whereas beams of the second group were fabricated to be concrete cover thickness as 40 mm. All of the beams had identical cross-sectional dimensions, stirrups and longitudinal reinforcement. Beams had rectangular cross sections of 150x250 mm and span lengths of 2400 mm. All beams were reinforced with two 12 mm diameter steel bars on both sides of tension and compression. Shear reinforcement consisted of 8 mm diameter stirrups with 100 mm spacing. The geometry and steel reinforcement of the test beams are shown in Figure 1.

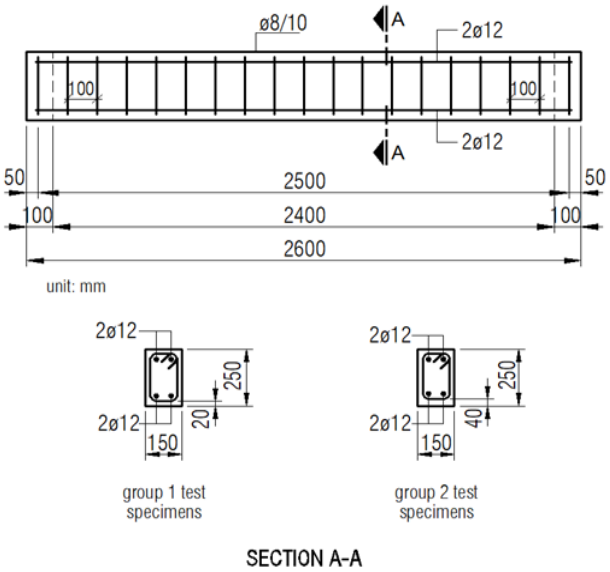


Figure 1. Geometry, steel reinforcement of beams tested in flexure

2.2 Material properties

2.2.1 Concrete and Steel

The concrete used in the fabrication of test beams was supplied from a ready-concrete company. During the concrete pouring, three cubes were taken to specify the 28-days compressive strength. Cube concrete compressive strength average of 25,1 MPa was converted to cylinder concrete compressive strength and determined as 20 MPa. Reinforcing steel bars with a yield strength of 420 MPa were used as stirrup and longitudinal reinforcement in beams. The properties of steel and concrete are summarized in Table 1.

2.2.2 Primer, Epoxy and CFRP sheet

Master Brace P3500, a two-component, low viscosity primer (Table 2), was used. Master Brace SAT4500 epoxy based adhesive (Table 3) which has a two-components, high strength, low viscosity and easy to apply was used to adhere the CFRP material to the beam surfaces. As for the strengthened material, Master Brace FIB 300/50 CFS unidirectional carbon fiber reinforced polymer (CFRP) was used. The properties of CFRP sheet is summarized in Table 4.

2.3 Strengthening procedure

In each group, one of the beams was not strengthened as a reference beam and the other three beams were strengthened using 0.17 mm thick unidirectional CFRP sheet in different arrangement. Firstly, the beam surfaces were sanded to smooth the rough beam surface and cleaned from the dust.

Primer material was applied to the beam surface to provide bonding with the beam surface and to obtain a smooth surface. Then epoxy adhesive was used and CFRP sheet was carefully bonded to the surface of the beam. The application of CFRP sheet bonding is given in Figure 2.

The strengthening schemes of the specimen RC beams are shown in Figure 3. These strengthening schemes are; Type 1: externally reinforcing with one layer of CFRP sheet on the bottom surface of the tension zone (150x2600 mm), Type 2: bonding of CFRP sheet to the bottom surface

Table 1. The properties of concrete and reinforcing steel properties

Material	Properties	Value
Concrete	Mean compressive strength (cube)	25.1 MPa
Concrete	Mean compressive strength (cylinder)	20.0 MPa
Reinforcing steel	Mean yield strength (ϕ12)	463.60 MPa
	Mean tensile strength (ϕ12)	572.07 MPa
	Mean yield strength (ϕ10)	518.03 MPa
	Mean tensile strength (ϕ10)	761.77 MPa
	Modulus of elasticity	2.10^5 MPa

Table 2. Technical properties of the primer

Compressive properties	**Value**	**Tensile properties**	**Value**
Yield strength	26.2 MPa	Yield strength	14.5 Mpa
Elastic modulus	670 MPa	Elastic modulus	717 Mpa
Ultimate strength	28.3 MPa	Ultimate strength	17.2 Mpa
Rupture strain	10 %	Rupture strain	40 %
Flexural properties	**Value**	**Physical properties**	**Value**
Yield strength	24.1 Mpa	Installed thiskness	0.075 mm
Elastic modulus	595 Mpa	Density	1102 kg/m3
Rupture strain	Large deformation with no rupture	Poisson ratio	0.48

Table 3. Technical properties of the epoxy adhesive

Compressive properties	**Value**	**Tensile properties**	**Value**
Yield strength	86.2 MPa	Yield strength	54 MPa
Elastic modulus	2620 MPa	Elastic modulus	3034 MPa
Ultimate strength	86.2 MPa	Ultimate strength	55.2 MPa
Rupture strain	5%	Rupture strain	3.5%
Flexural properties	**Value**		
Yield strength	138 MPa	Poisson ratio	0.40
Elastic modulus	3724 MPa		
Rupture strain	5%		

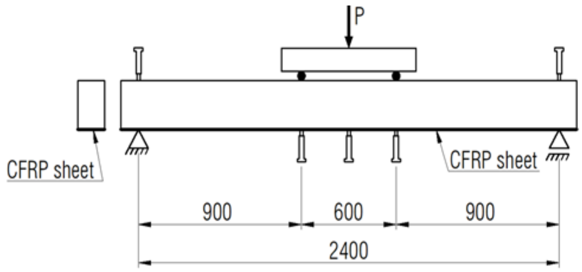
Table 4. Properties of CFRP sheet

Properties	**Value**
Modulus of Elasticity	230000 N/mm^2
Tensile strength	4900 N/mm^2
Thickness of design cross-section	0.166 mm
Weight	300 gr/m^2
Rupture strain	2.1%
Width	500 mm

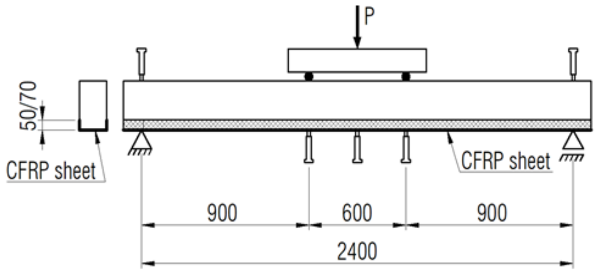
and to both lateral side surfaces of 50 mm and 70 mm height to the tensile reinforcement including the concrete cover (250x2600 mm; 290x2600 mm), and Type 3: bonding of CFRP sheets to bottom surface and most of lateral sides (500x2600mm).

(a) (b)

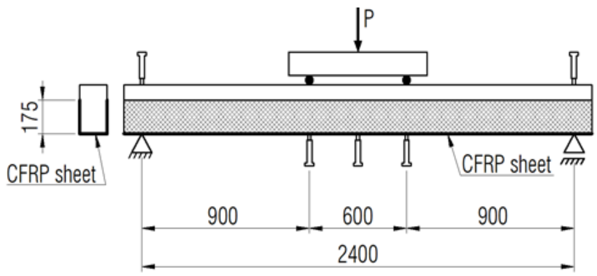
Figure 2. CFRP application of test beams a) epoxy adhesive application b) bonding of CFRP



(a) K20KG00 and K40KG00



(b) K20KG50 and K40KG70



(c) K20KGU and K40KGU

Figure 3. External strengthening arrangement of the beams tested in flexure

2.4 Experimental set up and instrumentation

As can be seen in Figure 4, eight rectangular concrete beam specimens were tested until failure under symmetric two point loads at spacing of 0.375 L = 900 mm from the support points.

The load was then implemented using hydraulic actuator of 400 kN capacity with a constant loading rate of 2 mm/min. Vertical displacements at the midpoint of the beam, at the points where the load was implemented and on the supports were measured by linear variable differential transformers (LVDTs) [6].

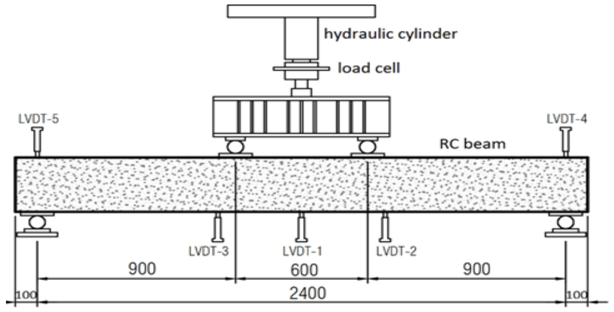


Figure 4. Experimental set-up

LVDTs were located with a measuring length of 300 mm in mid-span and with a measuring length of 100 mm at other points. The recording process was also continued until the completion of the test.

3. Results and Discussion

3.1 Failure modes and load-deflection behavior

In literature, failure mechanisms observed in RC beams externally strengthened with FRP sheets are flexural failure (concrete crushing and CFRP rupture), shear failure and FRP debonding [2], [26-30].

The most observed failure mechanisms are debonding of the CFRP material. Debonding usually takes place at the concrete-CFRP interface in a region of high stress concentration. Around the flexural and shear cracks and the ends of the CFRP material are debonding region [26]. Many researchers [2], [8], [26-30] refer to three different CFRP debonding failure modes: intermediate crack induced debonding, critical diagonal crack debonding and plate end debonding (Figure 5). Two different rupture modes are observed strengthened RC beams by CFRP composites: rupture prior to debonding and rupture after intermediate crack debonding [30].

3.1.1 Results for the 1st group of test specimens

Four RC beams (K20R, K20KG00, K20KG50, K20KGU) were loaded up to failure and their experimental ultimate loads are summarized in Table 5.

Failure modes observed for the first group of RC beams are indicated in Figure 6. The load-mid span deflection curves of the first group of RC beams are given in Figure 7. The ultimate load of the tested beams differed with the configuration of CFRP sheets.

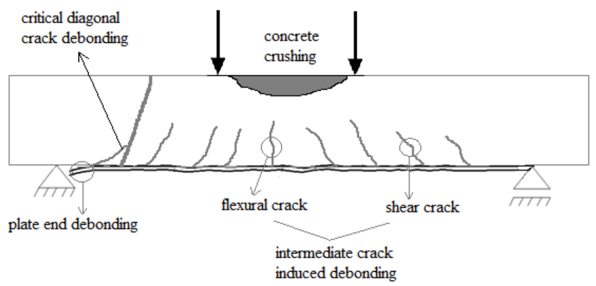


Figure 5. Failure modes of FRP [26], [27], [30]

Table 5. Test results of first group of beam

Beam ID	Ultimate Load (kN)	Failure Mechanism
K20R	51.97	Flexural failure
K20KG00	80.43	Debonding and rupture of CFRP
K20KG50	93.56	Debonding of CFRP
K20KGU	108.19	Debonding and rupture of CFRP

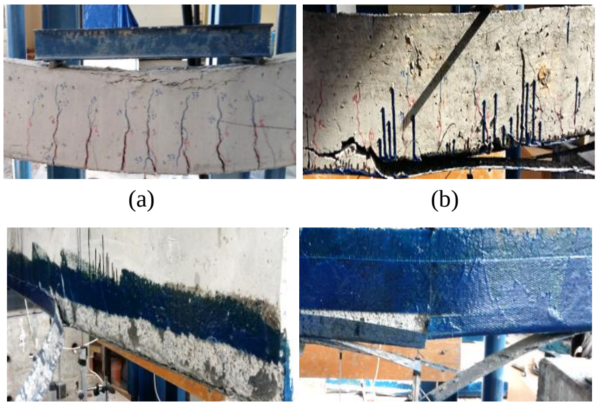

(a) (b) (c) (d)

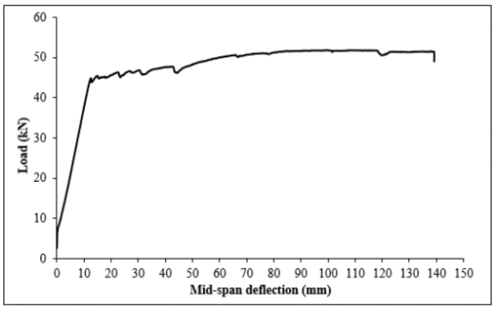
Figure 6. Failure modes of first group of RC beams
a) flexural failure (K20R) b) intermediate crack induced debonding and rupture of CFRP (K20KG00) c) plate end debonding of CFRP (K20KG50) d) debonding and rupture of CFRP (K20KGU)

Typical flexural crack in the mid-span section and concrete crushing at compression region was observed for the reference beam (K20R) as seen in Figure 6(a). The first crack was monitored at the load level of 35 kN During the experiment, mid-span deflection of 99.76 mm at the ultimate load level of 51.97 kN was monitored as seen in Figure 7(a). While the load remained constant, the displacement increased to a maximum value of 139.35 mm. In addition to the concrete crushing at compression region of beam, large crack widths and deflections were finally observed especially at the points where the load was applied. Finally, flexural failure was observed for the reference beam.

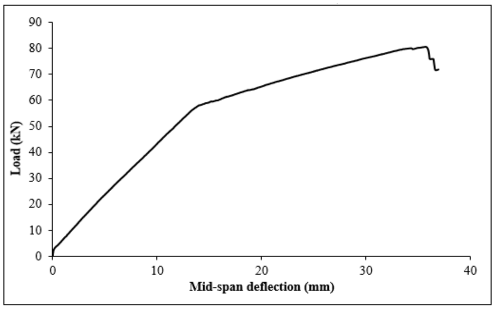
The failure mode for K20KG00 beam, intermediate crack induced debonding and rupture of CFRP was observed as seen in Figure 6(b). The first crack was monitored at the load level of 51 kN During the experiment, mid-span deflection of 35.72 mm at the ultimate load level of 80.43 kN was monitored. Besides, maximum mid-span deflection of 36.93 mm was recorded as seen in Figure 7(b). The appearance of cracks significantly delayed and the displacement decreased compared to the reference beam (K20R). The mid- span deflection was decreased with the increase in the flexural rigidity due to the CFRP strengthening as expected.

Besides, the ultimate load was measured 54.8% greater than for the K20R beam.

The failure mode for K20KG50, plate end debonding of CFRP was observed as shown in Figure 6(c). The first crack was monitored at the load level of 66 kN During the experiment, mid-span deflection of 33.88 mm at the ultimate load level of 93.56 kN was monitored. The maximum mid-span deflection of 39.15 mm was recorded as seen in Figure 7(c). The measured ultimate load of the test specimen K20KG50 is 80% greater than the K20R beam. Besides, maximum deflection at failure for K20KG00 and K20KG50 were lower than K20R beam.



(a)



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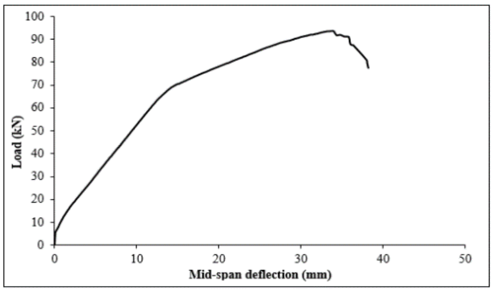
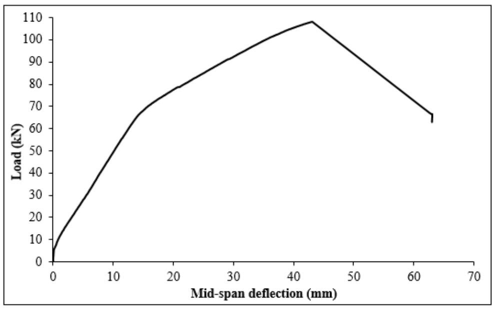


(c)



(d)

Figure 7. Load-mid-span deflection relationships for first group of beams a) K20R beam b) K20KG00 beam c) K20KG50 beam d) K20KGU beam

The failure mode for K20KGU, debonding and rupture of CFRP was observed as seen in Figure 6(d). During the experiment, mid-span deflection of 43.15 mm at the ultimate load level of 108.19 kN was monitored. Also, maximum mid-span deflection value of 63.07 mm was recorded as seen in Figure 7(d). The ultimate load was measured 108.2% greater than the reference beam (K20KG). The ultimate load increased by 34.5% and 15.6% compared to those of other strengthened beams (K20KG00 and K20KG50).

3.1.2 Results for 2nd group of test specimens

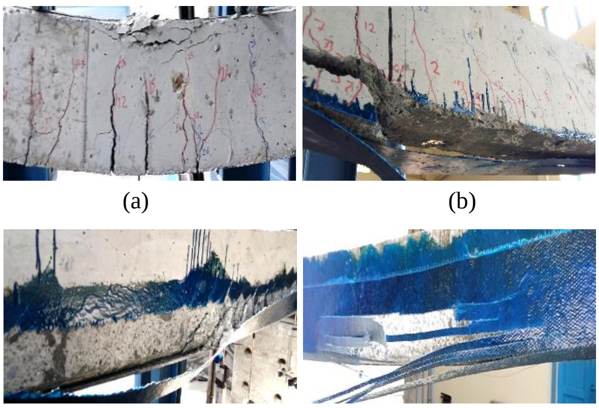
Experimental ultimate loads of four RC beams (K40R, K40KG00, K40KG70, K40KGU) are presented in Table 6.

Experimentally observed failure modes for the second group of RC beams are exhibited in Figure 8. The load-mid span deflection graphs of the second group RC beams are given in Figure 9.

Reference beam (K40R) was failed due to flexural crack at the mid-span section and crushing of concrete at the compression region as presented in Figure 8(a). The first crack was observed at the load level of 28 kN which was 0.8 times lower than K20R. During the experiment, mid-span deflection of 79.32 mm at the ultimate load level of 45.87 kN for K40R beam was monitored as seen in Figure 9 (a).

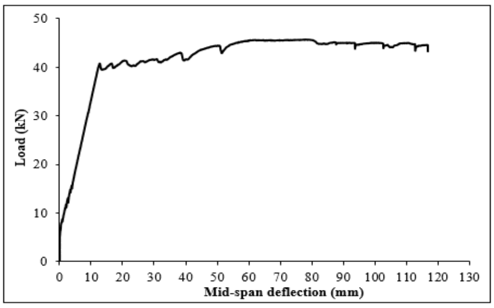
Table 6. Test results of the second group of beams

Beam ID	Ultimate Load (kN)	Failure Mechanism
K40R	45.87	Flexural failure
K40KG00	76.78	Debonding and rupture of CFRP
K40KG70	91.43	Debonding of CFRP
K40KGU	98.95	Debonding and rupture of CFRP

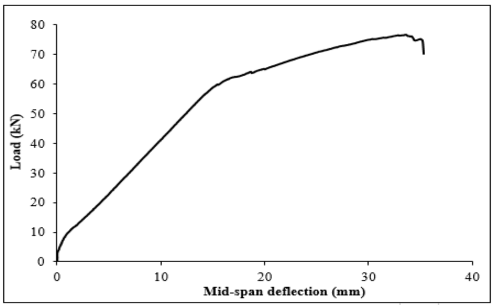


(a) (b) (c) (d)

Figure 8. Failure modes of second group of RC beams a) crushing of concrete (K40R) b) intermediate crack induced debonding and rupture of CFRP (K40KG00) c) plate end debonding of CFRP (K40KG70) d) debonding and rupture of CFRP (K40KGU)



(a)



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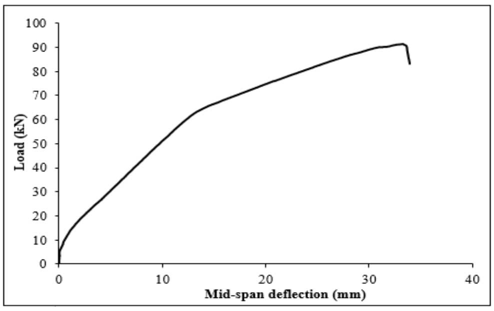
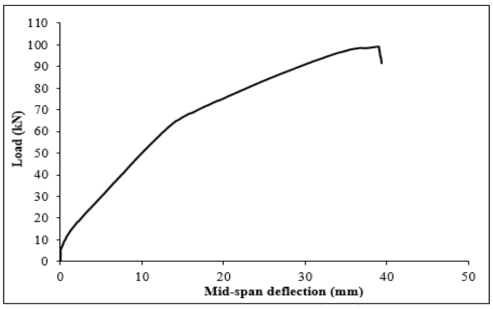


(c)



(d)

Figure 9. Load-mid-span deflection relationships for second group of beams a) K40R beam b) K40KG00 beam c) K40KG70 beam d) K40KGU beam

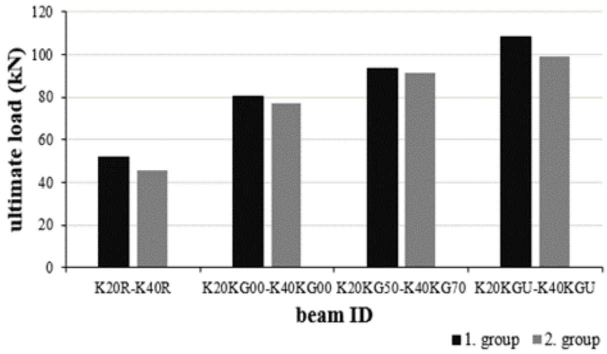
While the load remained constant, the displacement increased to a maximum of 117.13 mm. The large crack widths and deflections were observed until the failure. Crushing of concrete in the pressure zone of K20R and K40R beams was one of the reasons for the collapse these beams.

The strengthened beam K40KG00 failed due to intermediate crack induced debonding and rupture of CFRP at load of 76.78 kN as shown in Figure 8(b). The first crack was monitored at the load level of 46 kN during the experiment, mid-span deflection of 34.63 mm at the ultimate load level of 76.78 kN was monitored. Besides, maximum mid-span deflection of 36.51 mm was recorded as seen in Figure 9(b). The ultimate and cracking loads of K40KG00 were much lower than K20KG00 as expected. The ultimate load of K40KG00 increased by 67.4% compared to that of the reference beam (K40R).

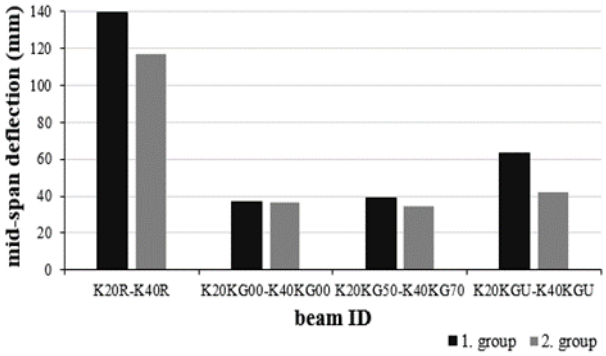
The failure mode for K40KG70, plate end debonding of CFRP was observed as shown in Figure 8(c). During the experiment, mid-span deflection of 33.82 mm at the ultimate load level of 91.43 kN was monitored. Maximum mid- span deflection of 34.56 mm was recorded as seen in Figure 9(c). First crack was monitored at the load level of 61 kN The ultimate load of the test specimen K40KG70 increased by 99.3% compared to K40R.

K40KGU failed by debonding and rupture of CFRP at beam surface (Figure 8(d)). The ultimate load of the beam K40KGU was measured as 98.95 kN which was 115.7% greater than the reference beam K40R. The mid span deflection value was observed 40.04 mm at this load level. Also, maximum mid-span deflection value of 41.82 mm was recorded as seen in Figure 9(d). The ultimate load for K40KGU increased by 28.9% compared to that of K40KG00. Maximum deflection at failure for K40KGU was higher than the other strengthened beams (K40KG00 and K40KG70).

The effect of strengthening on the load and mid-span deflection for the experiment beams are given in Figure 10.



(a) Ultimate load



(b) Mid-span deflection

Figure 10. The effect of strengthening on the load and mid-span deflection

The ultimate load and maximum mid-span deflection at failure for K20R beam were more than the K40R beam. Although the ultimate load for K20KG00 beam was more than K40KG00, the maximum mid-span deflection at failure was nearly the same.

The measured values of ultimate load and maximum mid-span deflection were bigger in K20KG50 compared to K40KG70 and also bigger in K20KGU compared to K40KGU beams.

The first cracks in the K20KGU and K40KGU beams were observed at higher load levels that were compared to the other strengthened beams. Although the cost of strengthening was higher for the K20KGU and K40KGU beams than the K20KG50 and K40KG70 beams, there was no difference in load carrying performance significantly.

The ultimate loads for test beams having 20 mm concrete cover (K20R, K20KG00, K20KG50, K20KGU) increased when compared to the test beams having 40 mm concrete cover (K40R, K40KG00, K40KG70, K40KGU); an increase of specimens' ultimate load by 13.3%, 4.8%, 2.3% and 9.3% respectively. The difference in ultimate load (13%) between the reference beams K20R and K40R was caused by the effective depth values that are chosen as 216 mm and 196 mm respectively. This difference was considerably reduced by external bonding of CFRP sheet to bottom surface and to both lateral side surfaces of 50 mm and 70 mm height.

The mid-span deflection in strengthened beams decreased when compared to reference beams by 73.5%, 71.9%, 54.7% for K20KG00, K20KG50, K20KGU and 68.8%, 70.5%, 64.3% for K40KG00, K40KG70 K40KGU, respectively.

Considering the ultimate loads for test beams, this experimental study indicated that the strengthening scheme Type 2 is almost as effective as the Type 3.

4. Conclusions

In the context of this study, the flexural behavior of CFRP wrapped RC beams under four-point bending loading were investigated experimentally. The below mentioned conclusions can be achieved from this study:

- Experimental tests confirmed that the unstrengthened beams failed flexural failure and strengthened beams with CFRP sheets failed in two different modes; CFRP debonding and CFRP rupture.
- Ultimate loads for experimental beams wrapped with CFRP sheets are substantially increased compared to the reference beams.
- Mid-span deflection in strengthened beams is decreased in comparison with the reference beams. Externally bonded CFRP sheet leading to a decrease in flexural deformation as expected.
- It is concluded that the strengthening schemes Type 2 and Type 3 compared to Type 1 are an effective and successful method for obtaining a better flexural performance. It is observed that the strengthening scheme, which includes the concrete cover of RC beams, increases the flexural performance. Due to the amount of material used in strengthening scheme Type 3, this increase, when compared with Type 2 provides less performance-cost value. The strengthening scheme Type 2 is more effective than Type 1 in terms of flexural capacity and it is more economical than Type 3.

Acknowledgment

This work supported by Yildiz Technical University under Scientific Research Projects (project no: 2016-05-01-DOP06), Turkey.

Declaration

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The author(s) also declared that this article is original, was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

Author Contributions

Authors planned the experiment. İ. Dalyan conducted experiments of beams. B. Doran evaluated experimental methods, measuring techniques and results. İ. Dalyan wrote the article. Editing and proofreading have been done by B. Doran.

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