Experimental Examination of Intact and CFRP Retrofitted RC Beams under Monotonic and High-Cycle Fatigue Loadings

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Received: 30 July 2012, Revised: 16 October 2012, Accepted: 31 December 2012

Abstract: The aim of this research is to investigate the effect of Carbon Fiber Reinforced Polymer (CFRP) composite fabric on monotonic and fatigue behaviors of reinforced concrete beams. To control the failure occurrence, a small notch was induced at the middle span in bottom surface for all of the studied RC specimens. Totally 12 beams were tested out of which 6 beamswere tested under monotonic loading and the other 6 beams were tested under fatigue cyclic loading. Every group of 6 tested beams consisted of 3 intact and 3 CFRP retrofitted RC beams. Dimensions of the specimens were 150×150×1000 mm and a 150 mm-deep notch was cut at the center of all of the specimens. The experimental examination was conducted to study stresses distributed throughout the critical regions in reinforced concrete and carbon fiber reinforced plastic (CFRP) strengthened RC beams. Fundamentally, these critical regions were cracked zones in CFRP-retrofitted RC beams. Results from monotonic and fatigue tests were compared to each other. In the monotonic test, measurements of shear stress distribution and stiffness were carried out until the failure of the specimens. In the fatigue test, the ceiling of applied load was considered at the level of design service load for bridges. In addition, strain measurements led to the calculation of interfacial shear stresses between concrete substrate and the CFRP layer. The variation of such load cycles are presented and discussed. Load–deflection curves, strain responses and propagation of tensile cracks would provide an insight into the performance of the CFRP strengthened beams subjected to different cycles of fatigue loading.

Keywords: Carbon Fiber Reinforced Polymer, Fatigue, Interfacial Shear Stresses, Propagation of TensileCracks

Reference: Kabir, M. Z., and Hojatkashani, A., "Experimental Examination of Intact and CFRP Retrofitted RC Beams under Monotonic and High Cycle Fatigue Loadings", Int J of Advanced Design and Manufacturing Technology, Vol. 6/ No. 3, 2013, pp. 63-70.

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1 INTRODUCTION

Externally bonded carbon-epoxy fiber reinforced polymers have been used extensively to restore or increase the capacities of reinforced concrete structures [1-3]. Considering the benefits such as high strength to weight ratio, easy installation and cost effectiveness, using FRP fabrics for concrete structures rehabilitation has become common during recent years[4]. Considering flexural FRP-strengthened RC beams it is important to prevent premature interfacial failure modes such as debonding. In fact, distributed stresses adjacent to junction zones of a FRP-concrete interface are found to depend on the tensile strength of concrete, the concrete surface preparation, and the thickness and strength of adhesive [5], [6],[7].

The remaining factors lead to an interfacial failure mode resulting from the propagation of concrete cracks parallel to the bonded plate and adjacent to the adhesive-to-concrete interface, thus leading to local concrete failure [8]. To achieve a better understanding of the developed shear stress distribution in the cracked zones, delamination and normal stresses at the plate end in the FRP-retrofitted RC beams, others have proposed theoretical and numerical models [9-14]. In previous research considering the interfacial stresses in FRP-retrofitted RC beams, the main focus was on the interfacial bond stresses, or adhesion, between the FRP layer and the concrete substrate. In the present paper, however, the main subject is the examination of interfacial concrete stresses at the vicinity of CFRP layers in the CFRP-retrofitted RC beams.

What enjoys importance considering the fatigue behavior of FRP retrofitted RC structures is the fatigue crack propagation. This aspect can be considered for the plain concrete and interfacial part between CFRP and the concrete substrate. Experimental investigations about fracture under cyclic loading have been extensively presented in literatures, whereas the fatigue fracture of concrete requires more examinations [15-18]. The fatigue behavior of CFRP retrofitted RC beams was examined in the current research as well. In this part of the research, the main subject was to identify variation of stiffness versus the fatigue loading cycles. Moreover, strains at the middle section cracked zone in the CFRP retrofitted RC beams were recorded.

2 EXPERIMENTAL PROGRAM

The applied concrete for the specimens in the present research was a mixture of water, cement, sand and aggregate with the ratios (by mass): 0.55:1:2.2:1.7, respectively. By using a series of standard cylindrical specimens with 150 mm diameter and 300 mm height, the concrete compressive strength was determined approximately as 50 MPa on the date of beam testing. The typical geometry and reinforcement of the tested beams are illustrated in Fig. 1.

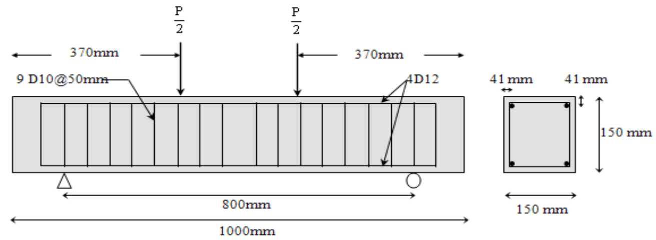


Fig. 1 Concrete beam geometry and reinforcement

Longitudinal reinforcement was comprised of 12 mm-diameter bars, which `exhibited a yield stress of approximately 365 MPa and a Young's modulus of approximately 200 GPa. Stirrups were made of 10 mm diameter steel bars with a yield stress of 260 MPa and a Young's modulus of 180GPa. The strengthening procedure was wet lay up using two layer unidirectional CFRP sheets on the tension face of the concrete beams, which strengthened the specimens in flexure. Additionally, U wrap CFRP sheets were applied at the supports. The carbon fibers used in the CFRP sheets were of Sika Wrap-200C type and the adhesive utilized for bonding the CFRP sheets to the concrete substrate was of Sikadure-300 epoxy resin type, all produced by Sika company. The specifications of the carbon fiber, epoxy resin, and assembled CFRP sheets are presented in Table 1.

Table 1 Mechanical properties of Carbon utilized fibers, epoxy resin and CFRP composite

	Tensile Strength (MPa)	Modulus of Elasticity (MPa)	Failure Strain (%)
Fibers	3900	230000	1.5
Epoxy Resin	45	3500	1.5
CFRP Composite	500	50000	1

A 150 mm-deep + was made at the middle bottom surface of all the studied RC beams. The retrofitted specimens consisted of two layer CFRP sheets on the tension face of the specimens with a thickness of approximately 1 mm. The schematic presentation of the retrofitted RC beams is illustrated in Fig. 2.

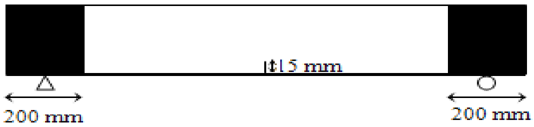


Fig. 2 Schematic illustration of the CFRP-strengthened RC beam

For all of the specimens, one strain gauge was placed at the top surface to measure compressive strains; two strain gauges were placed at the cross of the depth at about one third and one fourth of the height to measure longitudinal strains. For the CFRP retrofitted RC beams two strain gauges were mounted at the vicinity of major flexural cracks positions which were already predicted from previous FE analysis. Three additional strain gauges were also positioned on the bottom of CFRP parallel to those attached at the vicinity of the major flexural cracks. Locations of all mounted strain gauges are shown in Fig. 3.

3 RESULTS AND DISCUSSION

Analysis of load deflection curves and strain measurements obtained from testing of both intact and CFRP strengthened RC beams are discussed in the proceeding. Testing of specimens consisted of two sets of loadings: monotonic quasi-static loading and fatigue loading. The instrument used for testing was the servo-hydraulic universal testing DARTEC 1900. Measurements obtained from the tests included mids-pan deflections and strains at the critical regions where the possibility of major flexural cracks formation were predicted. Results were collected and analyzed through the following stages:

3.1. Monotonic Testing

The first set of specimens including 3 intact RC beams and 3 CFRP retrofitted RC beams, were tested under monotonic quasi-static loading up to the failure of specimens. The beams were tested under four-point bending using servo-hydraulic test machine with a controlled displacement rate of 0.005 mm/s.

The load-deflection diagrams of control and CFRP strengthened beams are illustrated in Fig. 4. As can be noticed from this figure, although the use of two-layer CFRP fabric decreased the ductility of the intact RC beams but led to the increase of load-carrying capacity about 70%. Further, initial observed slope changes of the load-deflection diagrams were attributed to the stiffness changes originated from the initial crack formation at the tip of the pre-cracked section of the beams. The magnitudes of these slopes were about 64 kN/mm and 45 kN/mm for the CFRP and intact beams, respectively. The second slope changes observed in Fig. 4 were related to the yielding of rebars. Comparison of both sets of slope changes for the current two sets of beams suggested a more plastic deflection behavior in case of the CFRP retrofitted RC beams.

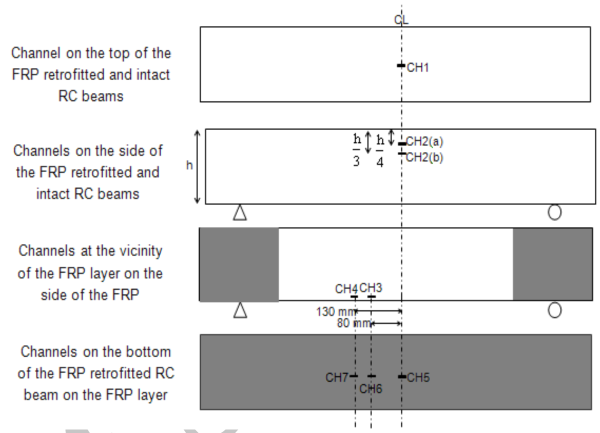


Fig. 3 Mounting positions of strain gauges used in the experimental study

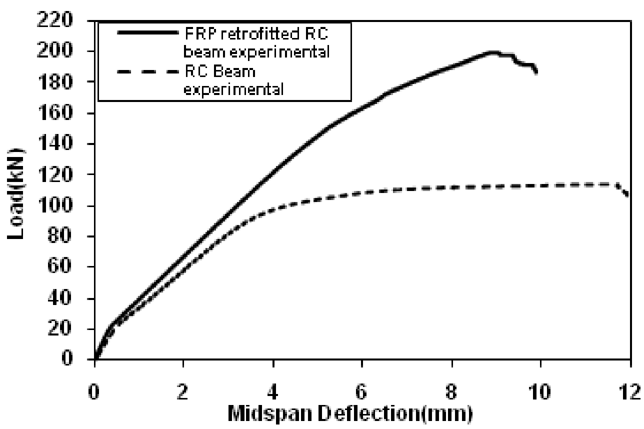
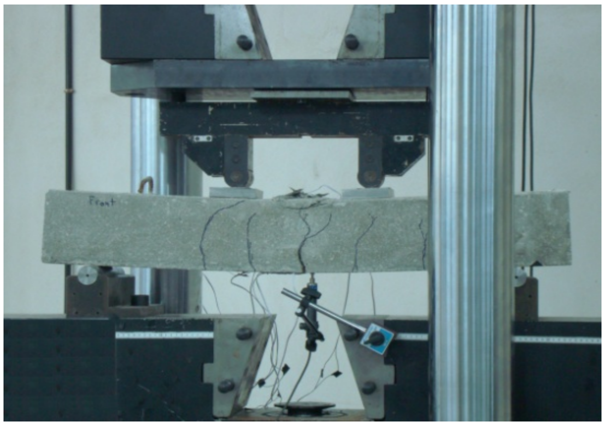


Fig. 4 Load-deflection curves for intact and CFRP retrofitted RC beams subjected to monotonic loading

Figs. 5(a), 5(b) display crack patterns for the monotonic testing stage. As can be noticed from these patterns, the existence of more distributed flexural cracks along the beam can be clearly observed for the CFRP retrofitted beams in comparison with those of intact ones.

In Fig.6, load versus compressive concrete strains measured at the channel 1 is illustrated. As shown, with increase in the load-carrying capacity, the crushing strain of the specimens was about -3200 µs.



(a)

(b)

Fig. 5 Cracking patterns for the experimental test of RC control and CFRP retrofitted RC

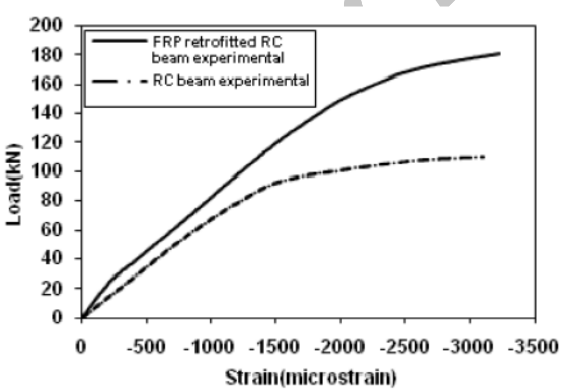


Fig. 6 Strains of the compressive concrete at the channel1 for the intact and CFRP retrofitted RC beams

Strains on the concrete at the junction zone of the CFRP-concrete at the tension part of the CFRP retrofitted RC beams resulted in the interfacial stresses between the CFRP layer and the concrete. It should be noted that such strains were difficult to measure because of the brittleness of concrete, and any discrete crack caused the gauges work improperly.

The gauges on the interfacial tensile concrete were mounted at the vicinity of the major flexural cracks. Figs. 7 and 8 show strains at such zones on the concrete and its corresponding location on the CFRP layer. The preceding results were obtained from the experimental measurements at the locations of channels 3-7. For the concrete, the tensile strength (or the rupture modulus) was 4.5 MPa, and the corresponding strain is about 160 µs.

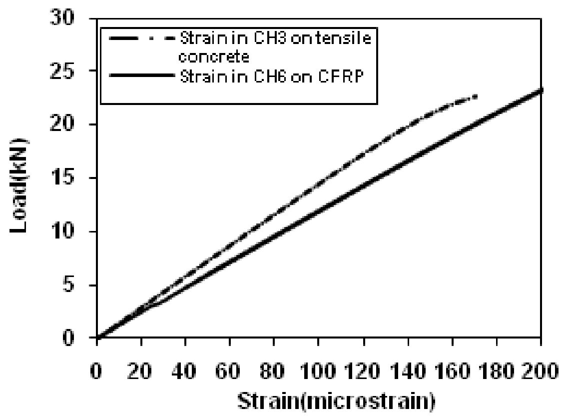


Fig. 7 Load versus strain diagram for CFRP retrofitted RC beam under monotonic loading up to the concrete crack initiation

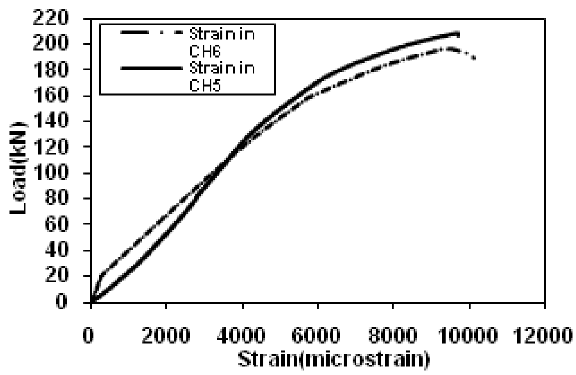


Fig. 8 Load versus strain diagram for CFRP retrofitted RC beam under monotonic loading up to the failure of the specimen

The observed slight non-linearity could be related to the brittle manner of the concrete and spreading of the micro-cracks at the very initial steps of loading. Referring to Fig. 7, it can be concluded that at the range of the concrete cracking, channel 3 experienced the mean strain of about 165 µs and the CFRP experienced strain of 200 µs. In Fig. 8, slope change was resulted from the crack initiation at the middle section of the beams and at the location of the strain gauges on the concrete which happened almost simultaneously at the load of about 25 kN.

Fig. 8 also shows strains on the CFRP at the channel 5 at the range of the specimen failure. In this figure, first change in the slope indicates the crack initiation which as mentioned previously happened at the load of 25 kN, that was the first step of loading. Second change in the slope was due to the yielding of longitudinal steel rebars.

3.2. Fatigue testing

In the second stage of loading, specimens including 3 RC and 3 CFRP retrofitted RC beams were subjected to 50000 cycles of constant amplitude fatigue loading. Frequency of the loading was 0.5 Hz and the data were recorded at every 0.2 s. The specimens were tested under the constant amplitude of 6.5-65 kN for the intact RC beams and 8.5-85 kN for the CFRP retrofitted ones with the constant R-ratio of 0.1. The fatigue testing procedure exhibited in the current research consisted of the following three steps:

3.2.1. PRE – Fatigue monotonic loading

At the beginning of the tests and at the range of service loads, specimens were subjected to pre-fatigue monotonic loading. The behavior of control RC beams subjected to the monotonic loading was almost identical. Moreover, behavior of the CFRP retrofitted RC beams subjected to the monotonic loading was also analogous to the intact beams with a quite difference in the flexural stiff nesses in both initial and post-failure. Fig. 9 illustrates the applied load versus mid-span deflection under monotonic loading prior to the fatigue test. The initial slope of both intact and CFRP retrofitted beams were almost similar indicating little effect of externally bonded method on the linear elastic bending stiffness. However, crack propagation at the induced notch was faster in intact beams rather than in strengthened specimens. Fig. 9 indicates that the secondary path (the post-failure stiffness) is quasi linear with superiority of CFRP strengthened RC beams. The initial stiff nesses of the intact and CFRP retrofitted RC beams were measured as 38.29 kN/mm and 46.15 kN/mm, respectively. These amounts were reduced for the secondary stiff nesses to 19.12 and 27.4 kN/mm.

Fig. 10 shows the longitudinal compressive strain at the top surface of the beams versus applied load at the range of service loading. It was obviously seen that the CFRP strengthening materials could increase flexural capacity of the RC section and, therefore, reduce the rate of the compressive strain. Variation of strains at the channels 2(a) and 2(b) on the side of the specimens versus the monotonic loading is illustrated in Fig. 11. It can be seen that at the location of channel 2(a), h/4 from the top of the beam, longitudinal strains remained totally compressive during the loading for both intact and CFRP retrofitted beams.

However, at the location of channel 2(b), h/3 from the top of the beam, longitudinal strains were compressive for both intact and CFRP retrofitted beams up to the applied load of 15 and 40 kN, respectively. This difference refers to the effectiveness of externally bonded CFRP sheets which prevented further propagation and growth of tension cracks at the bottom surface of RC beams. Longitudinal strains were first compressive and then turned to tensile.

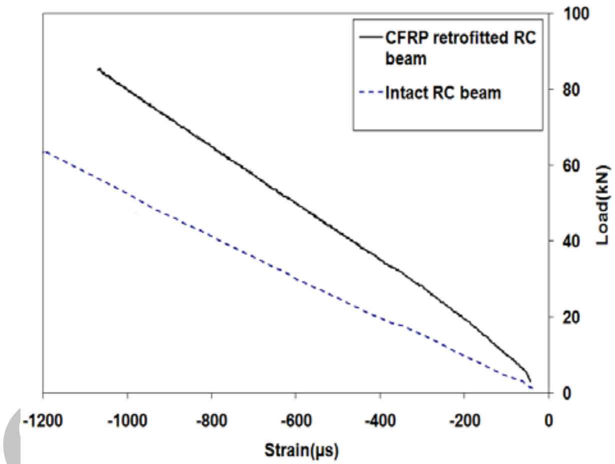


Fig. 9 Load-midspan deflection diagram in pre-fatigue monotonic test of intact and CFRP retrofitted RC beams

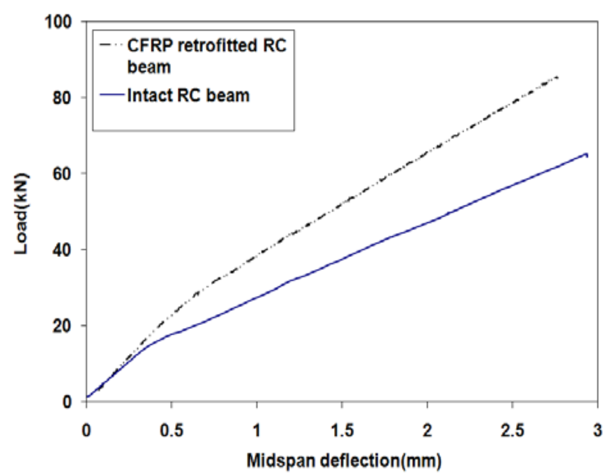
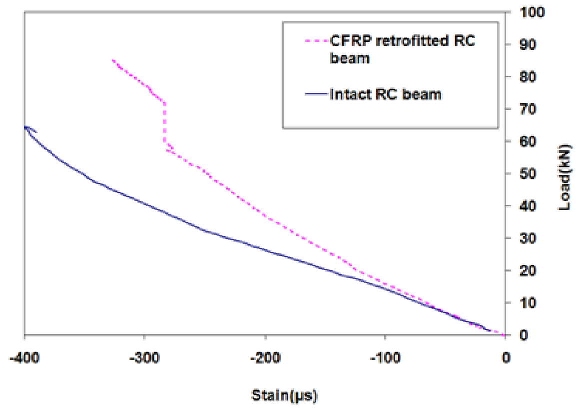


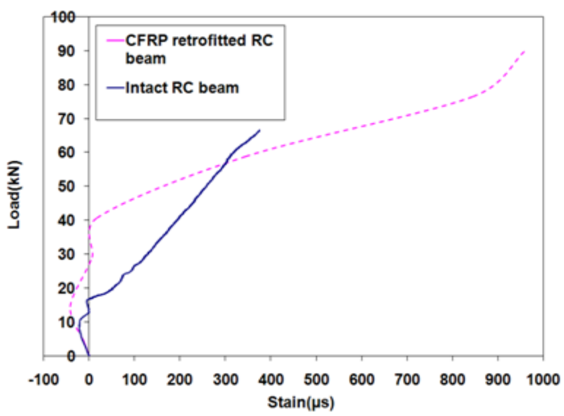
Fig. 10 Load-compressive strain diagram at channel1 in pre-fatigue monotonic test of intact and CFRP retrofitted RC beams

This fact would be explained as a reason of crack initiation and propagation at the middle notched section. Prior to the crack initiation, as the loading was increased, the longitudinal strains progressed in the negative region. When the crack initiation occurred, strains moved backwards to the positive zone. This shift in the strains progression happened at the load of

10 kN and 15kN for the intact and CFRP retrofitted RC beams, respectively. By increasing the level of applied loading, the sign of the measured strains recorded at channel 2 changed into positive indicating the fact that neutral axis of the section moved to the upper position due to the propagation of flexural cracks initiated from the induced notch moving upward.



(a)



(b)

Fig. 11 a. Load- strain diagram at channel 2(a) in the pre-fatigue monotonic test. b. Load- strain diagram at channel 2(b) in the pre-fatigue monotonic test

3.2.2. Fatigue loading

In the experimental program all the specimens were subjected to 50000 loading cycles. Typical load cycle graphs for RC and CFRP retrofitted ones are illustrated in Figs. 12, 13. In addition, cracking patterns of RC and CFRP retrofitted RC beams at the last fatigue cycle 50000 obtained are illustrated in Fig. 14. As mentioned earlier, prior to the application of fatigue loading, all of the specimens were subjected to monotonic loading at the level of service load. This experience caused some residual deformations in all of the specimens. Fig. 14 presents cracking patterns for tested specimens at the end of the fatigue test. Crack propagation at the induced notch led to the degradation of CFRP-concrete interface, and consequently the beams reached their final strength. Effect of the debonding zone can be observed in Fig. 15.

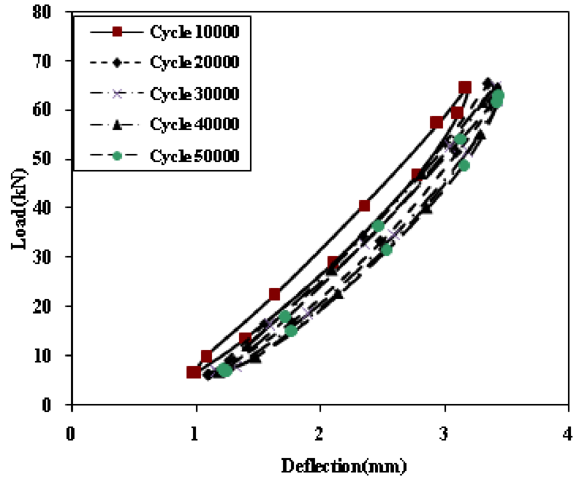


Fig. 12 Load-deflection curvesversus fatigue cycles resulted from the fatigue test of RC beams

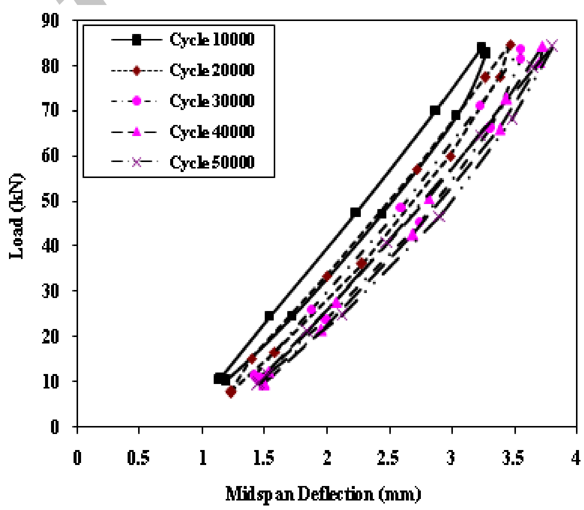
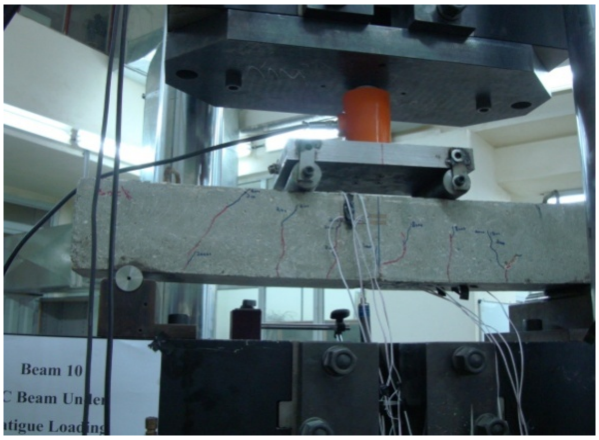


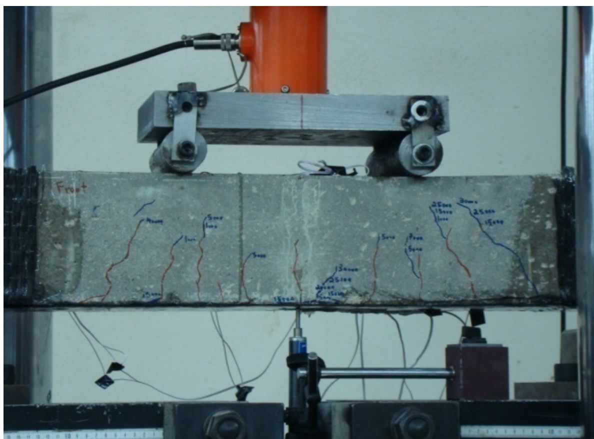
Fig. 13 Load-deflection curvesversus fatigue cycles resulted from the fatigue test of CFRP retrofitted RC beams

3.2.3. Post- fatigue monotonic loading

After the application of 50000 fatigue loading cycles, the specimens were subjected to monotonic quasi-static post-fatigue loading until the failure. In Figs. 16 and 17, load-deflection diagrams of monotonic and post-fatigue monotonic loadings of specimens are illustrated. An obvious point depicted in the current figures is the comparison of load-carrying capacities and stiffnesses between monotonic and monotonic post-fatigue testing of specimens. Decrease of the failure load of RC specimens was about 30% and of CFRP retrofitted ones was about 20%. The applied fatigue cycles had another effect on the quasi-static load-deflection diagrams and that was a drop in the initial stiffnesses. The average decrease of initial stiffnesses was estimated about 60% for RC specimens and 70% for CFRP retrofitted ones.



(a)



(b)

Fig. 14 Fatigue cracking patterns at the fatigue cycle 50000 fora) RC beams and b) CFRP retrofitted RC beams

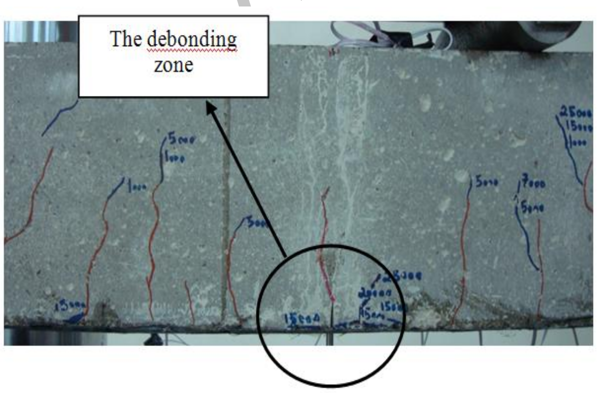


Fig. 15 Fatigue cracking patter at the local debonded zone resulted from fatigue loading of CFRP retrofitted RC beam

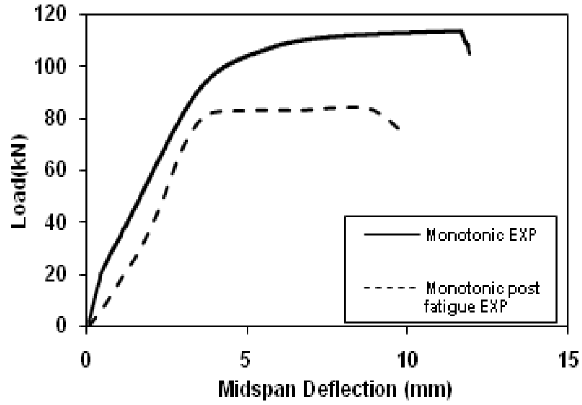


Fig. 16 Comparison between monotonic and monotonic post-fatigue load-deflection curves of RC specimens

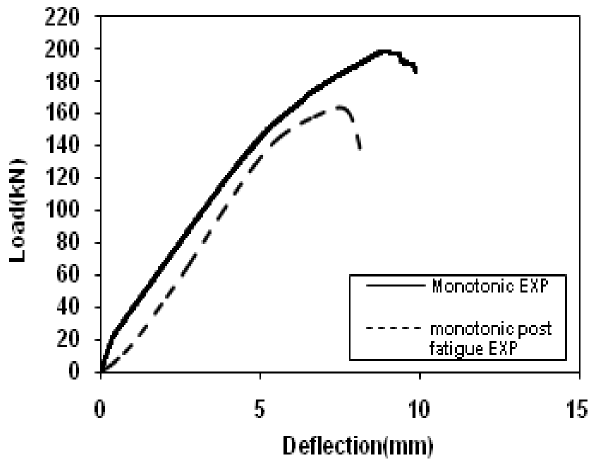


Fig. 17 Comparison between monotonic and monotonic post-fatigue load-deflection curves of CFRP retrofitted RC specimens

6 CONCLUSION

An experimental program has been carried out to examine the monotonic and fatigue behavior of intact and CFRP retrofitted RC beams. The main objective of this paper was to study variation of strains at the critical regions through fatigue loading cycles.

In the first stage of testing, 6 beams out of which 3 were strengthened with two-layer CFRP sheets were tested under quasi-static monotonic loading. According to the results presented in the load-deflection diagrams, using the two-layer CFRP composites increased the load-carrying capacity about 70% and lessened the ductility. The drop in the diagrams in the CFRP retrofitted beams was resulted from one or more modes of failure, including crushing of the compressive concrete, rupturing of the CFRP, and debonding of the

CFRP from the concrete substrate. In the performed test, the mentioned modes of failure occurred almost simultaneously.

It can be noticed by observing the Fig. 7 that the tensile crack spreading in the concrete was so sudden. Drop of the strain was resulted from the initiation of flexural cracks at the tensile concrete at the vicinity of the CFRP-concrete, i.e., the interfacial concrete. At this region the flexural cracks began to propagate.

In the second stage, 6 beams out of which 3 were strengthened with two-layer CFRP sheets were subjected to fatigue testing. Load-deflection diagrams and load strains versus fatigue cycles were presented. The proposed method consisted of three stages including the monotonic loading before the fatigue loading, during fatigue loading, and monotonic post-fatigue loading. A slight shift in the load-deflection diagrams indicated the debonding process during specific load cycles.

This phenomenon took place due to the unstable crack growth at the interface zone. Load cycles, enjoying progression, were made thinner by the existing stable flexural growth. Nevertheless, in general, the RC beams showed almost consistent fatigue response independent from the number of fatigue cycles. It appears that the primary cycles dissipate more energy than other cycles through the cracking and micro cracking.

In the stage of monotonic-post fatigue loading, the important point as shown in Figs. 16 and 17, was the comparison of load-carrying capacities and stiffnesses between monotonic and monotonic post-fatigue testing of specimens. Decrease of the failure loads and initial stiffnesses in the load-deflection diagrams were parameters which are considered in these figures.

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