

Experimental examination of CFRP strengthened RC beams under high cycle fatigue loading

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Abstract

The aim of current study is to investigate the effect of Carbon Fiber Reinforced Polymer (CFRP) composites on the fatigue response of reinforced concrete beams. 6 reinforced concrete (RC) beams from which 3 were retrofitted with CFRP sheets, were prepared and subjected to fatigue load cycles. To predict and trace the failure occurrence and its growth, a small notch was induced at the middle span in bottom surface of all RC specimens. At the certain points, strains in concrete and CFRP were measured in each cycle. The upper limit of applied load was considered at the level of design service load of bridges. In addition, strain measurements facilitated to the calculation of interfacial shear stresses between concrete substrate and the CFRP layer. The variation of such stresses through load cycles has been presented and discussed. Also, a discussion on possibility of the local debonding phenomenon resulted from such interfacial stresses was presented. Load-deflection curves, strain responses and propagation of tensile cracks provided an insight on the performance of the CFRP strengthened beams subjected to different cycles of fatigue loading. Variation of load-deflection curves through fatigue load cycles depicted stiffness degradation which was discussed in the research.

Keywords: Carbon fiber reinforced polymer, Fatigue, Interfacial shear stresses, Tensile cracks.

1. Introduction

The use of fiber reinforced polymer composite materials specially for strengthening of concrete structures has become a common practice in structural rehabilitation industry during the last decades. In this respect, externally bonded Fiber Reinforced Plastic (FRP) composites has been considered as an interesting candidate for repairing and retrofitting of RC beams due to their high strength to weight ratio, easy installation and cost effectiveness [1]. Lots of researches have been conducted on the FRP retrofitted RC structures subjected to monotonic and cyclic loadings. Among them, in a work done by [2] monotonic and cyclic response of FRP reinforced concrete cantilever beams was discussed. Also, in other work effect of cyclic loading on shear strength of CFRP retrofitted slabs was examined [3]. From the numerical investigations in this area, the finite element study of CFRP flexurally

strengthened RC beams can be noted [4].

Fatigue behavior of such structures requires further investigation. When referring to fatigue, a distinction should be made between low-cycle fatigue, which involves few load cycles ($<10^4$) with high stresses (similar to those induced by earthquakes); and high-cycle fatigue, characterized by a larger number of cycles with lower stresses (such as those induced by rotating machines). The latter has been the target of the majority of research in literatures.

The high-cycle fatigue is significant in structures subjected to long term loading such as bridges. Most of the transportation infrastructures were constructed in the middle of the twentieth century. Considering increases in load requirements over that time, the need for a quick, reliable, efficient and most of all durable rehabilitation method, is inevitable. In this respect, the need for study and examination of structures subjected to such long lasting repeated loadings that are of the high cycle fatigue type is evident. There are many researches considered the fatigue behavior of concrete and reinforced concrete beams. For example, investigating the behavior of CFRP-strengthened beams subjected to monotonic loading or a combination of fatigue and monotonic loadings [5].

An important issue when considering the fatigue behavior of

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FRP retrofitted RC structures is monitoring of fatigue crack propagation. Experimental investigations on damage mode under cyclic loading have been extensively presented in literatures [6-9], whereas the fatigue fracture of concrete requires more examinations.

Another significant point that should be considered in the fatigue performance of FRP strengthened RC structures is the degradation of consisting components of the retrofitted RC beams under fatigue loading. The significance of the fatigue test of RC beams externally bonded with FRP reinforcement lies on quantifying the fatigue strength increase as compared to the plain RC beams. A few fatigue tests on FRP reinforced RC beams can be found in studies by [10,11]. Their findings show that the primary failure was the rupturing of the tensile steel bars, followed by debonding of the FRP reinforcement.

Several key researches [12-14] have clearly demonstrated that FRP-strengthened structures presented better fatigue performances than unstrengthened ones. In most cases, it has been observed that the failure of the structure is initiated by successive yielding of the reinforced steel in tension. When debonding of the FRP laminate occurred, it was considered to be a secondary failure mode.

Studies on the fatigue behaviors of the FRP-concrete joint have been done by [15]. That work presented results from an experimental investigation of bonded FRP-concrete joints under cyclic loading. The results for the effects of cyclic loading on slip at the FRP-concrete interface, crack opening, and strain profiles along the bonded FRP joint were presented and discussed.

Formulation for the fatigue degradation of concrete and steel is developed in [16]. Also, an important study has been done to evaluate the fatigue properties of CFRP externally bonded to concrete [17]. In this work, single lap FRP-concrete joints and double-lap FRP-concrete joints have been tested under the fatigue loading resulted in the fatigue life prediction for FRPs and the adhesive of bonded joints.

The current research exhibits fatigue behavior of CFRP retrofitted RC beams. The main subject here is to identify degradation of stiffness due to the fatigue cyclic loading. Moreover, strains at the middle section of cracked zone in CFRP retrofitted RC beams were recorded. Analyzing such strains led to the calculation of interfacial shear stresses between CFRP layer and the concrete substrate. Several authors

have proposed theoretical methods to calculate the shear stress at the FRP-concrete interface [18,19]. Variation of such stresses through loading cycles was discussed in this paper in details.

2. Experimental Program

This section describes the main characteristics of the tested specimens, properties of their constituent material, loading equipment, instrumentation and testing sequences. In this study, 6 RC beams were prepared for testing from which three beams were retrofitted with CFRP fabrics. The concrete was made from a mixture of water, cement, sand and aggregate with the ratios (by mass) of: 0.55:1:2.2:1.7, respectively. The average compressive strength of the concrete using a series of standard cylindrical specimens of 150 mm in diameter and 300 mm in height was about 50 MPa at the date of testing the beams. The Typical geometry and reinforcement of the tested beams are illustrated in Figure 1.

Longitudinal reinforcement was consisted of 12 mm diameter steel rebar with yield stress of 365 MPa and Young modulus of 205 GPa. Stirrups have been made of steel bars with 10 mm diameter, yield stress of 260 MPa and young modulus of 200 GPa. The strengthening procedure is wet lay up with two layer unidirectional CFRP sheets at the tension face of the concrete beams, which strengthens the specimens in flexure. Further, U wrap CFRP sheets have been implemented at the supports to prevent possibility of debonding at the free edge of longitudinal CFRP sheet. The carbon fibers used in the CFRP sheets is of Sika Wrap-200C and the employed adhesive for bonding CFRP sheets to the concrete substrate is Sikadure-300 epoxy resin, all produced by the Sika Company. Specifications of the carbon fiber, epoxy resin, and assembled CFRP sheet are presented in Table 1.

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

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

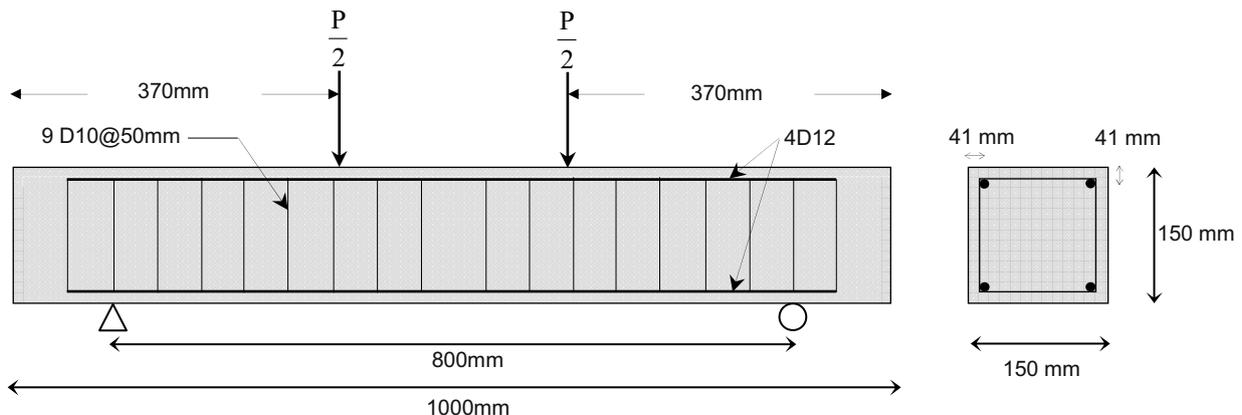


Fig. 1. Typical concrete beam geometry and reinforcement

A notch with 150 mm height was made at the middle bottom surface for all studied RC beams. Retrofitted specimens have been strengthened with 2 layers of CFRP at tension face of the specimens with a thickness of 1mm. The schematic presentation of the retrofitted RC beams is illustrated in Figure 2.

Prior to the testing, strain gauges were attached to the specimens. Two types of strain gauges were used to record data, PFL type for concrete and BFLA type for composite. Both of the gauges are made by TML Company, Japan and have an electrical resistance of 120 Ω. An LVDT at the bottom middle section of the specimens was used for measuring the deflection. In addition, a load cell was placed between top surface of the specimens and the machine grip. Thus, the collected data was consisted of strains (using strain gauges), mid-span deflection (using LVDT) and the applied load (using load cell) which were recorded by a dynamic data logger of TML type.

All beams were subjected primarily to a flexural monotonic loading up to the service load using four point bending method

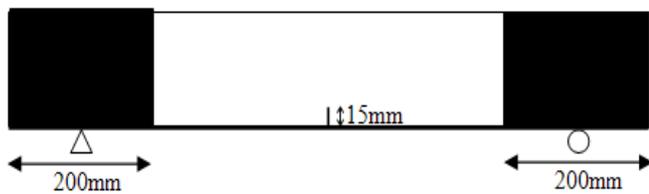


Fig. 2. Schematic presentation of the CFRP strengthened RC beam

(Figure 1). The specimens were then subjected to 50000 cycles of constant amplitude fatigue loading. Frequency of the loading was 0.5 Hz and the results were recorded every 0.2 s. The tests were carried on under the constant amplitude of the load with 6.5-65 kN for the intact RC beams and 8.5-85 kN for CFRP retrofitted ones with a constant R-ratio of 0.1. Eventually, all specimens were subjected to monotonic loading till the failure. Figure 3 illustrates the test setup and the equipments.

3. Results and discussion

Load deflection curves and strain measurements for both intact and CFRP strengthened RC beams from testing of all specimens were analyzed as follows.

Figure 4. shows positions of installed strain gauges on intact and CFRP retrofitted RC beams. For all specimens, one strain gauge was placed at the top surface of RC beams to measure compressive strains; two strain gauges were placed across the depth at one third and one fourth of the height to measure longitudinal strains whether it is positive or negative. For the CFRP retrofitted RC beams two strain gauges were mounted at the vicinity of the 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. Results obtained from experimental tests would be examined and discussed through the following loading stages.

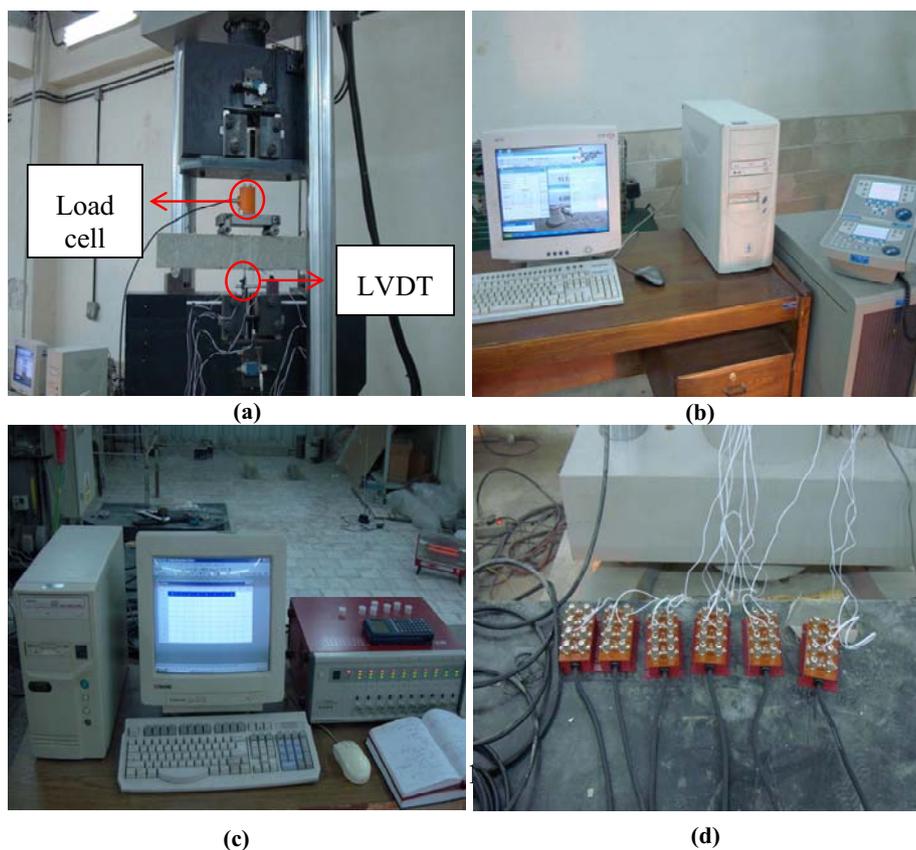


Fig. 3. Fatigue test set up and related devices
 (a) Test setup, (b) Control panel of the servo-hydraulic machine, (c) Dynamic data logger
 (d) Bridge boxes used for connecting strain gauges to the data logger

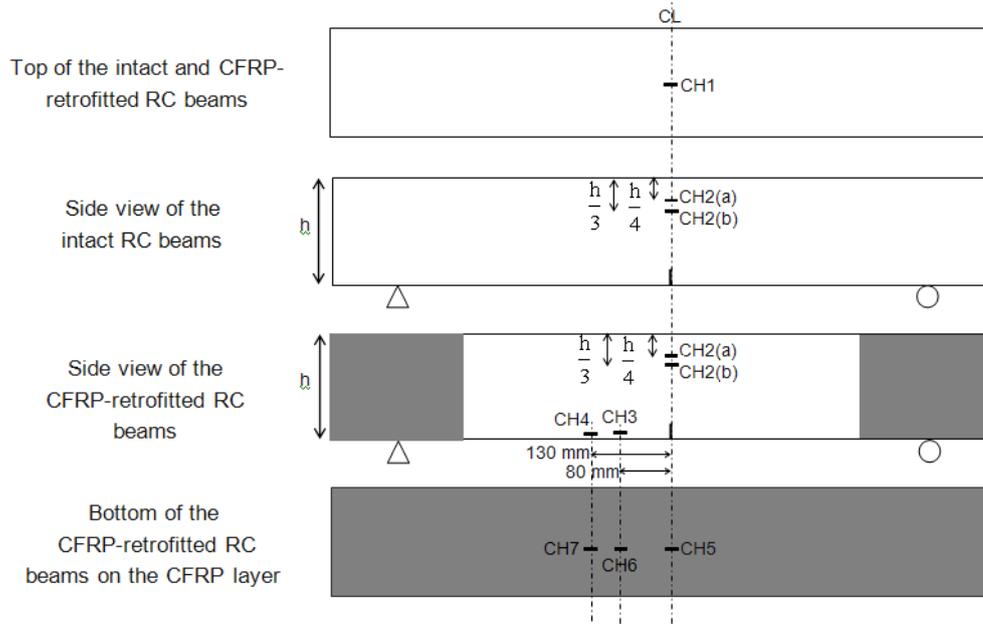


Fig. 4. Demonstration of mounted strain gauges

3.1. Pre-fatigue monotonic loading

At the beginning of the tests, the specimens were subjected to pre-fatigue monotonic loading. The behavior of intact and CFRP retrofitted RC beams subjected in terms of mid span deformation versus applied load is shown in Figure 5. The initial slope for both intact and CFRP retrofitted are almost similar indicating little effect of externally bonded method on linear elastic bending stiffness. However, the induced notch initiates tensile cracks at the bottom surfaces with faster growth in intact beam with respect to strengthened beam.

The initial stiffness 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 post cracked stiffness to 19.12 and 27.4 kN/mm.

Figure 6 shows the variation of compressive normal strain at the top surface of the beams versus applied load within the range of service load. It was obviously seen that the CFRP strengthening materials could increase the flexural capacity of the RC section and, therefore, reduce the rate of the

compressive strain. Variation of strains at channels 2a and 2b of the specimens versus the monotonic loading is illustrated in Figure 7. It can be seen that at the location channel 2a, $h/4$ distance from the top of the beam, the longitudinal strain remained in compression during the loading for both intact and CFRP retrofitted. However, for channel 2b, located $h/3$ apart from the top of the beam, the longitudinal strain was compressive up to 15 kN for intact beams and 40 kN for CFRP retrofitted beams. This difference refers to the effectiveness of externally bonded CFRP sheet which prevented further growth of tensile cracks at the bottom face of RC beam. By increasing the applied load the longitudinal strain changed into tensile. This fact would be explained as a reason of crack initiation and propagation at the middle notched section. By increasing the level of applied load, the sign of measured strain in channel 2 was changed into positive indicating the neutral axis of the section has moved to the upper position due to the propagating of flexural cracks started from induced notch moving upward. Figure 8 shows the variation of measured normal strains at channels 3 and 4, see their places in Figure 4, versus applied

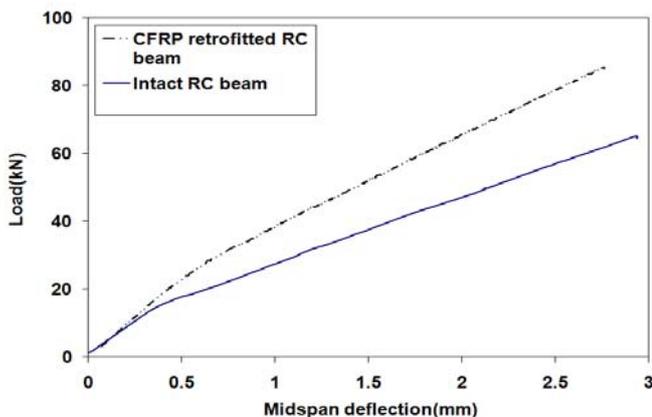


Fig. 5. Load-midspan deflection diagram in pre fatigue monotonic test for intact and CFRP retrofitted RC beams

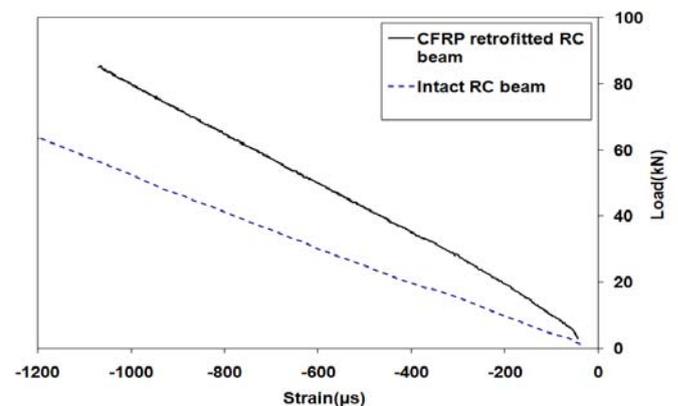


Fig. 6. Load-midspan deflection diagram in pre fatigue monotonic test for intact and CFRP retrofitted RC beams

load. The results in channel 3 indicate multiple disturbs in the curve. These sudden changes refer to the flexural cracking at the bottom surface. The measured strain in channel 4 has also shown the occurrences of flexure cracks at the bottom surface when the applied load reached 30 kN. At this point strain grew dramatically due to bottom tensile cracks in nonlinear manner. Strains obtained from strain gauges belonging to the channels 5 to 8, on the tensile CFRP sheet, are illustrated in Figure 9.

3.2. Fatigue loading

In this part, specimens were subjected to 50000 cycles of constant amplitude fatigue loading and the measured results were reported every 10000 cycles. The behavior of the intact RC beams was almost similar in all stages except a drop in flexural stiffness due to the crack propagation in the bottom face of RC beam and minor degradation in material elastic modulus (see Figure 10). The amplitude for upper and lower limit of applied load and the corresponding mid-span measured deflection in all reported cycles are approximately

close to each other. The same procedure was repeated for CFRP retrofitted RC beams, see Figure 11.

As mentioned earlier, prior to applying the fatigue loading, all specimens were subjected to the monotonic loading at the level of service load. This experience remained residual deformation in all specimens, see Figures 10 and 11. Tables 2 and 3 compare responses of intact and CFRP retrofitted RC beams under fatigue loading. In these tables, upper and lower limit deflections refer to maximum and minimum mid-span deflections according to maximum and minimum applied loads in fatigue loading cycles. Other results in these tables consist of flexural stiffness variations for intact and CFRP retrofitted RC beams.

In the first cycle of the tests that is pre-fatigue monotonic loading, mid-span deflections were recorded as about 2.94mm for intact RC beams and 2.76mm for CFRP retrofitted RC beams. Next two columns of these tables exhibit lower limit and upper limit deflections normalized to the mid-span deflection of specimens at pre-fatigue monotonic loading stage, so called as lower limit deflection ratio and upper limit deflection ratio.

As mentioned in the pre-fatigue monotonic loading stage, the load-deflection diagrams contained two slopes referring to

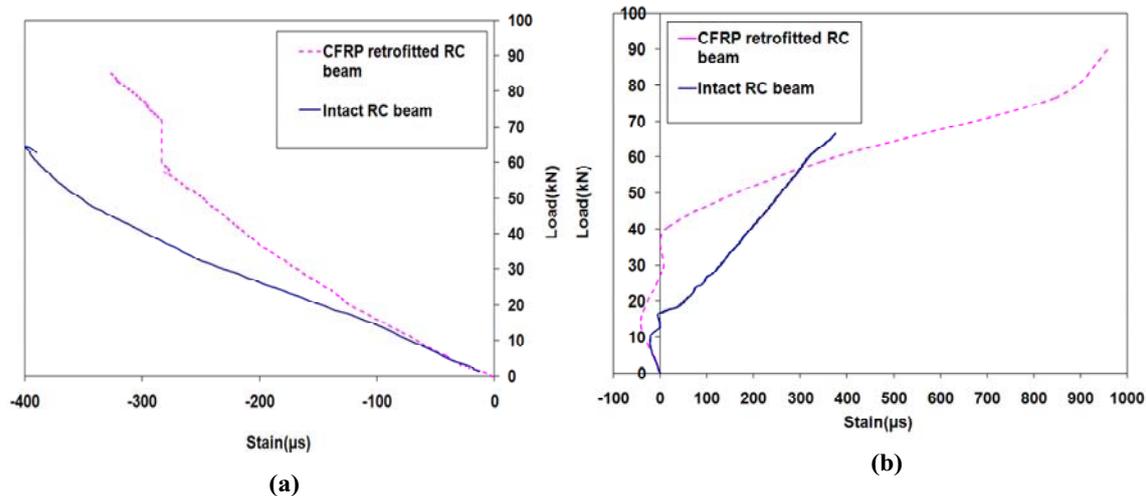


Fig. 7. The variation of longitudinal strain at channel 2
a. Load-strain diagram at channel 2a in the pre fatigue monotonic test
b. Load-strain diagram at channel 2b in the pre fatigue monotonic test

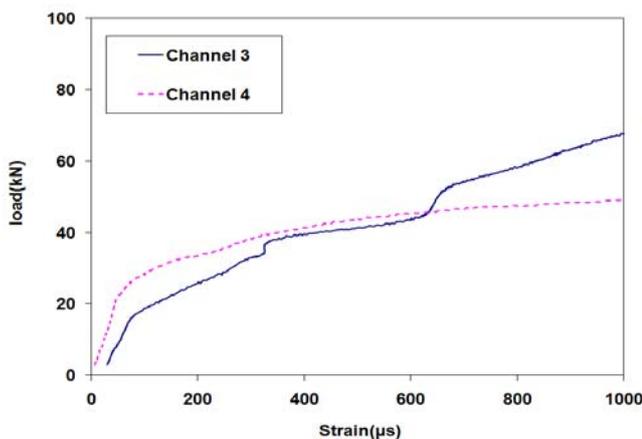


Fig. 8. Load-strain diagram at channels 3 and 4 in pre fatigue monotonic test for CFRP retrofitted RC beams

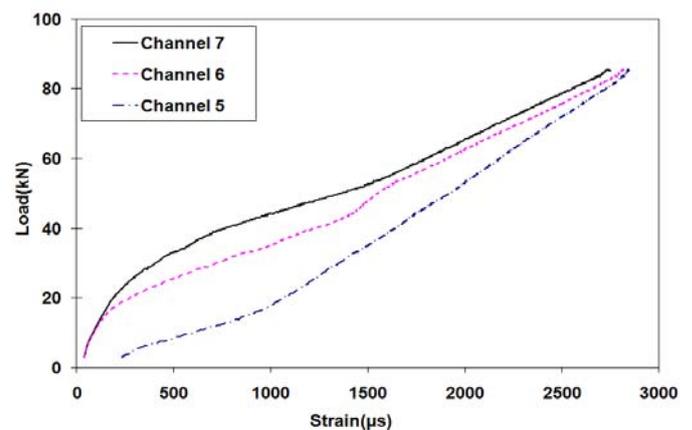


Fig. 9. Load-strain diagrams at channels 5,6 and 7 in pre fatigue monotonic test for CFRP retrofitted RC beams

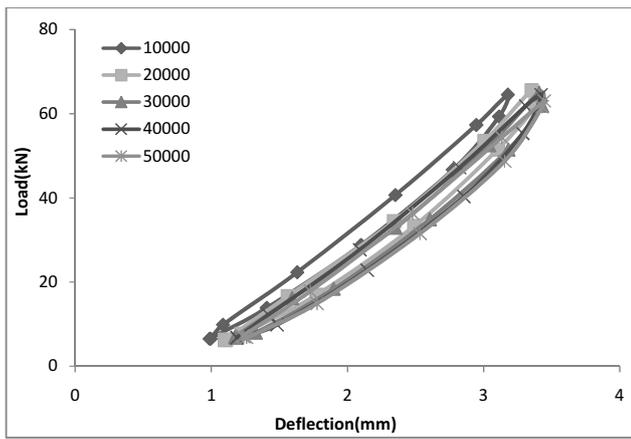


Fig. 10. Load-deflection diagram for the fatigue test of RC beams

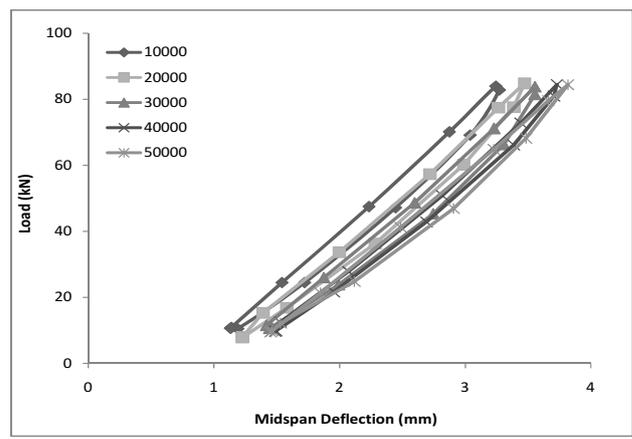


Fig. 11. Load-deflection diagram for the fatigue test of CFRP retrofitted RC beams

initial and secondary stiffnesses. The secondary stiffness is important and stiffnesses in other stages of loading are compared to the secondary stiffness in the pre-fatigue monotonic loading stage. Thus, the last column of tables 2 and 3 is allocated to the relationship of fatigue loading flexural stiffness to the secondary stiffness in the pre-fatigue monotonic loading, named as stiffness ratio.

From these tables one can observe the contribution of CFRP composite materials, which is approximately 30% increase of the flexural stiffness of the retrofitted specimens under fatigue loading. For detailed studies, the measurement explanation from strain gauges can help in interpreting of the results calculated in Tables 2 and 3.

Figure 12 shows the variation of the compressive strain in channel 1 at the top surface of the beam for different stage of loading cycles of intact and retrofitted RC beams. The change in the slope of load- strain curve shows contribution of CFRP in strengthening of RC beams under fatigue loading.

In addition, the variation of longitudinal strains on CFRP versus applied load is depicted in Figures 13 to 15 for channels 5 to 7, respectively. The curves are almost linear except for channel 5 which is located at the center of the beam. In this case, when the number of cycles increases to 50000, the load-strain curve is markedly moved to different range of load deformation due to the formation and propagation of tensile cracks and increase in crack opening.

Table 2. Comparison study on measured results in intact RC beams

Cycle	Lower limit deflection (mm)	Upper limit deflection (mm)	Flexural Stiffness (kN/mm)	Lower limit deflection ratio (%)	Upper limit deflection ratio (%)	Stiffness Ratio (%)
1	0.96	2.94	38.29	32.65	100	100
5000	0.975	3.066	26.96	32.99	104.29	70.4
10000	0.988	3.178	26.47	33.61	108.1	69.14
20000	1.1	3.38	26.02	37.41	114.97	67.93
30000	1.174	3.426	25.84	39.93	116.53	67.49
40000	1.188	3.428	25.76	40.41	116.6	67.27
50000	1.228	3.444	25.35	41.77	117.14	66.2

Table 3. Comparison study on measured results in CFRP retrofitted RC beams

Cycle	Lower limit deflection (mm)	Upper limit deflection (mm)	Flexural Stiffness (kN/mm)	Lower limit deflection ratio (%)	Upper limit deflection ratio (%)	Stiffness Ratio (%)
1	0.82	2.76	46.15	29.78	100	100
5000	0.99	3.12	35.03	35.94	112.97	75.91
10000	1.13	3.27	34.33	41.01	118.55	74.4
20000	1.23	3.47	34.29	44.42	125.8	74.29
30000	1.42	3.56	34.21	51.38	128.84	74.13
40000	1.49	3.73	33.37	53.91	135.14	72.3
50000	1.5	3.82	32	54.35	138.41	69.34

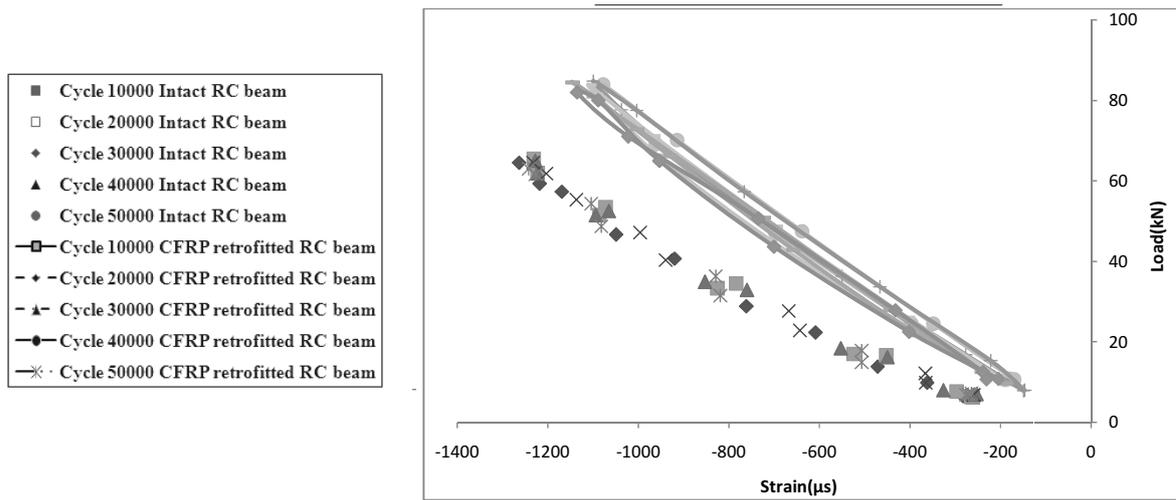


Fig. 12. Load-strain diagram at channel 1 for the fatigue test of CFRP retrofitted RC beams

It can be seen in Figures 14 and 15 that the cycles become thinner as the loading cycles increase. This can be explained as the result of a limited or small zone of debonding and existence of stable cracks due to the fatigue loading. Stable cracks here mean cracks with small rate of propagation due to the cycles. When a crack remains almost stable, cycles go thinner as the specimen reflects behavior similar to an elastic material.

Figure 16 shows crack patterns for a CFRP strengthened RC beam at the end of the fatigue test. Crack propagation through induced notch led to degradation strength of the CFRP-concrete interface. Figure 16 illustrates crack propagation and the debonding zone in the CFRP retrofitted specimens.

Figure 17 demonstrates distribution of longitudinal strain across the beam section at the instant of maximum fatigue loadings for both intact and CFRP retrofitted RC beams. The results were gathered from strain gauges installed on the depth of mid-span of the specimens. Even though the collected information for strains in non retrofitted RC beams was limited to the elastic zone and the gauges at the half bottom of the beam section entered into the post yield domain due to the

tensile crack formation at this region, the trend of current data shows considerable diverge between strain profile in intact and strengthened RC beams.

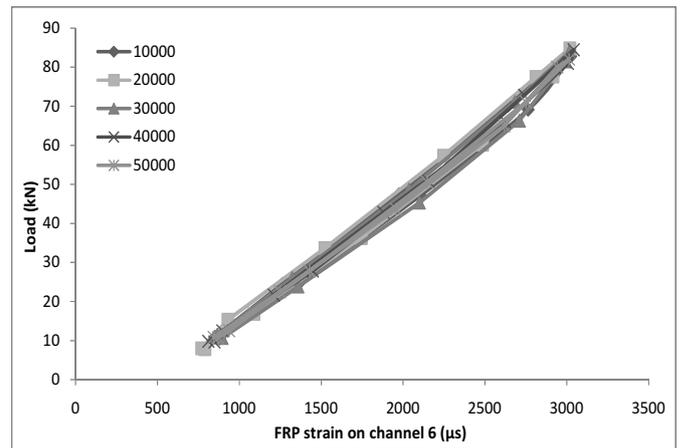


Fig. 14. Load-strain diagram at channel 6 for the fatigue test of CFRP retrofitted RC

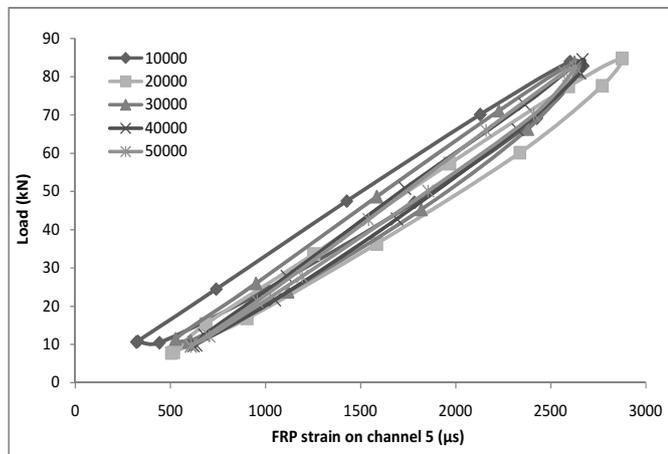


Fig. 13. Cyclic loading-strain at channel 5 diagram for the fatigue test of CFRP retrofitted RC beam

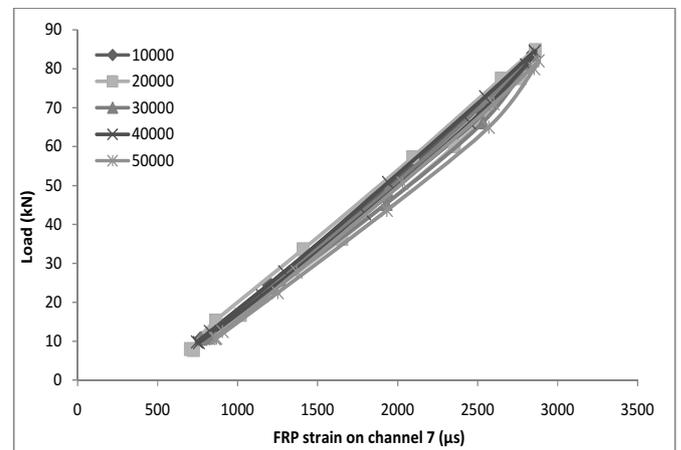


Fig. 15. Cyclic loading-strain at channel 7 diagram for the fatigue test of CFRP retrofitted RC beam

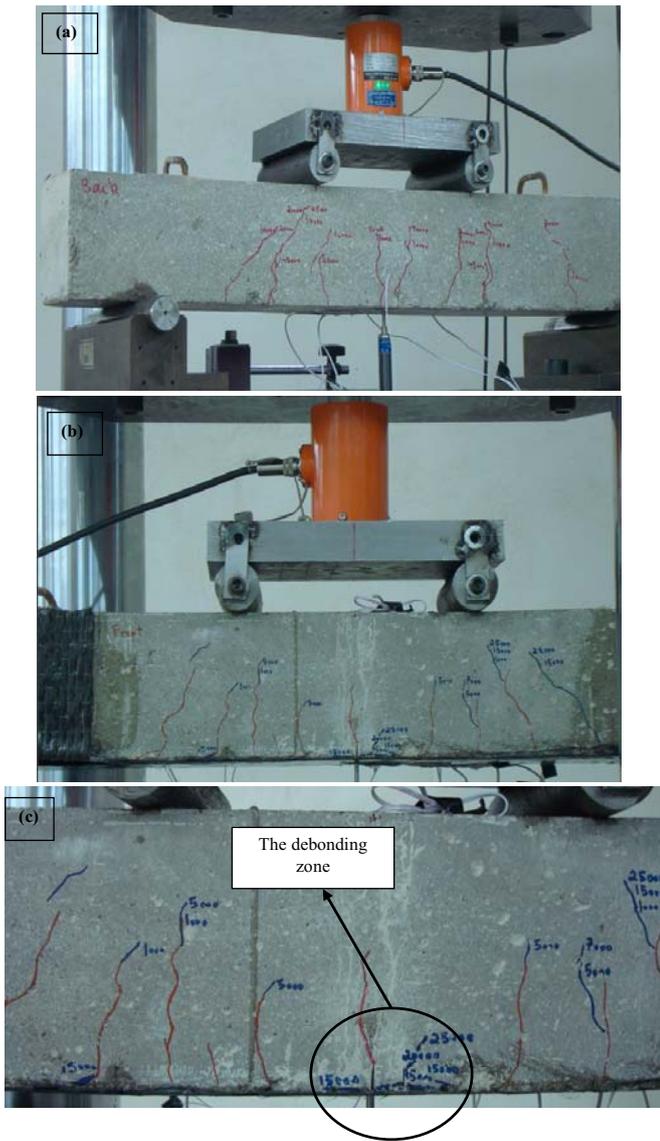


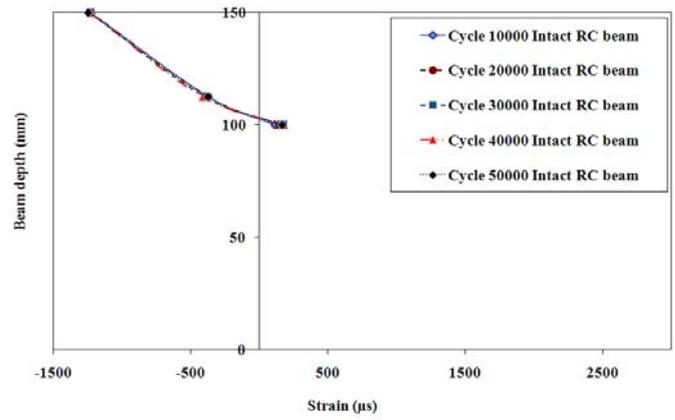
Fig. 16. Crack propagation of a. unstrengthened RC beam , b.,c. CFRP retrofitted RC beam under fatigue loading

The concept of debonding resulted from the fatigue loading would be more illuminated when one examines interfacial shear stress distribution at the critical region. From the measured strains along the CFRP sheet, a mean interfacial shear stress can be computed between two consecutive gauge positions. Given two strain readings g_i and g_j at positions i and j , the laminate thickness t_p , its elastic modulus E_p , and the distance Δl_{i-j} between the two consecutive gauges positions, one can determine the average shear stress τ_{i-j} between the gauges as follows which is reported in [20]:

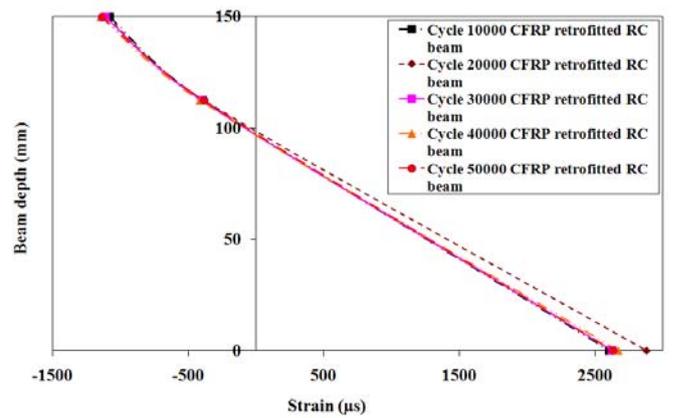
$$\tau_{i-j} = \frac{t_p \cdot E_p \cdot (g_i - g_j)}{\Delta l_{i-j}} \quad (1)$$

However, modulus of elasticity was degraded through the cycles. The curve of Young's modulus against the number of loading cycles N has been obtained and fitted using the relation below [21,22]:

$$E_{fN}(N) = m - n \cdot \log(N) \quad (2)$$



(a)



(b)

Fig. 17. Variation of strain distribution along the beam depth at mid span section for intact and CFRP retrofitted RC beams, at peak levels of fatigue loading cycles

Where m and n are:

$$m = 50000$$

$$n = 1100$$

The current relation matches with the carbon-epoxy material used in this research. Consequently, variation of the reduced Young's modulus through the loading cycles is given in Table 4.

Figures 18 and 19 illustrate variation of interfacial stresses between channels 5 and 6 and channels 6 and 7 through fatigue loading cycles. The change of shear stress versus the fatigue loading in the double lap joint test carried out in [18] presents a downward curve resulted from the fatigue interfacial crack propagation. The variation, however, in this paper for CFRP retrofitted RC beams consists of two stages through loading cycles, which can be observed in Figures 18 and 19.

The first stage belongs to the loading up to the cycle 20000 in which the debonding took place. At this stage of loading crack propagation occurred mainly in the interfacial part between CFRP layer and the concrete substrate. Interfacial shear stresses reached the maximum limit in the pre-fatigue monotonic loading. Due to the existence of notch at mid span, the intensity of the interfacial shear stress between channels 5 and 6 was higher than channels 6 and 7. During fatigue cycles, the amount of shear stress was reduced from 0.75 MPa to 0.22 MPa between channels 5 and 6 and from 0.45 to 0.27 MPa

Table 4. Degradation of Elastic modulus of CFRP layer in the fatigue cyclic loading, with respect to $E_0=50\text{GPa}$

Cycle	Young's modulus(MPa)
1	% 100 E0
10	% 97.8 E0
100	% 95.6 E0
1000	% 93.4 E0
10000	% 91.2 E0
20000	% 90.5 E0
30000	% 90.1 E0
40000	% 89.8 E0
50000	% 89.69 E0

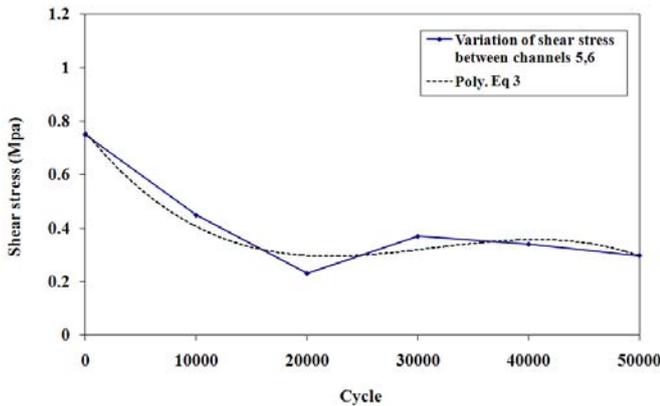


Fig. 18. Interfacial shear stress v.s. cycles at the region between channels 5,6.

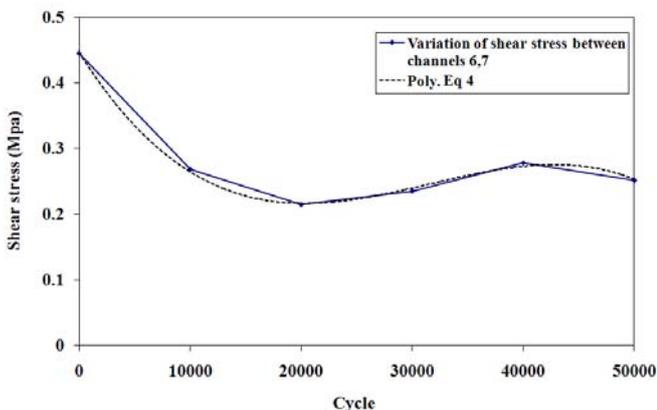


Fig. 19. Interfacial shear stress v.s. cycles at the region between channels 6,7

between channels 6 and 7. The downward stage is due to the interfacial crack propagation. Eventually, at the second stage after the cycle 20000, there was almost no interfacial debonding. However, occurrences of flexural crack propagation resulted in slightly rising interfacial shear stresses.

In favor of curve fitting on the interfacial shear stress-number of cycles, two polynomials of order 3 was achieved for expressing the interfacial shear stress in terms of fatigue cycles as follow:

The Interfacial shear stress between channels 5 and 6 would

be obtained from

$$\tau = -2 \times 10^{-14} N^3 + 2 \times 10^{-9} N^2 - 5 \times 10^{-5} N + 0.7602 \quad (3)$$

The Interfacial shear stress between channels 6 and 7 would be obtained from

$$\tau = -10^{-14} N^3 + 10^{-9} N^2 - 3 \times 10^{-5} N + 0.4465 \quad (4)$$

In which N is the loading cycle.

3.3. Post-fatigue monotonic loading

After the application of fatigue loading, specimens were subjected to monotonic loading until the failure. Observing Figure 20, it can be seen that for the CFRP retrofitted RC beams, load carrying capacity was about 90% higher than that of unstrengthened ones. However, the ductility of CFRP retrofitted RC beams was measured to be 12.9% less than that of the intact RC ones. Thus, using CFRP composites would be useful in fatigue loading. Also, it can be observed that significant part of the diagram illustrated in Figure 20 exhibits a linear relationship.

4. Conclusions

An experimental program was 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 the variation of strains at the critical regions through fatigue loading cycles. Furthermore, the effect of interfacial debonding on the fatigue behavior of CFRP retrofitted RC beams was examined.

The proposed method consisted of three stages, the primarily monotonic loading, fatigue loading and monotonic post fatigue loading. In the first stage, strains at the critical regions versus loading were measured and sketched.

In the second stage, load-deflection diagrams and load-strains through fatigue cycles were presented. A slight shift in the load-deflection cycles diagram indicates debonding process during specific load cycles. This phenomenon took place due to the unstable crack growth in

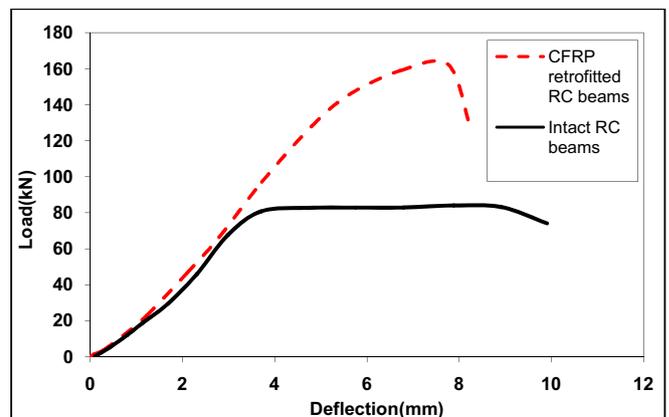


Fig. 20. Monotonic post-fatigue load-deflection diagrams of intact and CFRP retrofitted RC beams

the interface zone. With the progression of load cycles, there was stable flexural growth made load cycles thinner. Nevertheless, in general, the RC beams showed almost consistent fatigue response independent of the number of fatigue cycles. It appears that the primary cycles dissipate more energy than other cycles through the cracking and micro cracking.

Maximum deflection at the mid span was increased about 17% and 38% from the initial value for intact and the CFRP retrofitted beams, respectively, under fatigue loading with respect to the monotonic loading. Moreover, it can be concluded that because of interfacial crack growth, the interfacial shear stresses between CFRP and substrate was decreased up to the load cycle 20000. At the subsequent stage, flexural crack propagation resulted in a slight increase in the interfacial stresses. The change of the shear stress through fatigue examination could be formulated as a result of curve fitting.

Finally, after experiencing fatigue loading, specimens were subjected to post-fatigue monotonic loading till the failure. In this stage, strengthened specimens exhibited about 90% increase in the load carrying capacity.

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