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Flexural Fatigue Behavior of R.C. Beams Strengthened with Externally Prestressed CFRP

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Abstract: *This paper investigated, experimentally, the flexural performance of reinforced concrete beams strengthened with externally post-tensioned Carbon Fiber Reinforced Polymer (CFRP) tendons, under fatigue loading. Fatigue experiments on five beams (160x280x3500 mm) were undertaken. Mid-span –deflection, steel bar and CFRP tendons strain and cracks width were measured at different numbers of load cycles and varying fatigue loading levels during the test . Test parameters included the tendon profile and the load levels applied to the beam during the fatigue life (27%, 35%, 43% and 48% of their ultimate load). The CFRP tendons were post-tensioned at 35%, 40%, 45% and 55% respectively of its ultimate capacity. The empirical equation for crack width was established using curve fitting at various fatigue loading levels and numbers of load cycles. The fatigue performance of reinforced concrete beams strengthened with externally prestressed CFRP tendons was evaluated. A very good performance of the strengthened beams was observed under fatigue loading. The fatigue life of the beams was mainly governed by the fatigue fracture of the internal steel reinforcing bars at a flexural crack location. Fracture of the bars occurred at the root of a rib where high stress concentration was likely to occur. The enhancement in the fatigue life of the strengthened beams was noticeable at all load levels applied. Post- tensioning considerably decreased the stresses in the steel reinforcing bars and, consequently, increased the fatigue life of the beams. At the same load level applied to the un-strengthened and strengthened beams, the fatigue life of strengthened beam is bigger than un-strengthened beam.*

Keywords: *Reinforced concrete beam, CFRP tendon, External prestressed, strengthening method, Fatigue life, deflection; cracks width.*

I. Introduction

There is an increasing interest in the use of externally prestressed CFRP tendons for repair and rehabilitation of reinforced concrete elements. Since most of these elements are structural members of bridges, there is a need to understand the behavior of strengthened elements under repeated loading. Few researchers have investigated the fatigue properties of reinforced concrete beams strengthened with externally prestressed CFRP tendons.

Saeki et al. [1] studied the behavior of reinforced and prestressed concrete beams strengthened by external prestressed Aramid Fiber Reinforced Polymer (AFRP) tendons under fatigue loading. Twelve, 3-metre long, reinforced and prestressed concrete beams with rectangular cross sections were tested. The external tendons were prestressed at 34% of their tensile strength. One concentrated load was applied at mid-span of the beams. It was reported that the fatigue loading applied for two million cycles at 33% of the ultimate load (with a constant lower limit for all beams) had an insignificant effect on the rigidity of the tested beams.

Taniguchu et al. [2] tested three prestressed T-beams (100x100x400 mm) post-tensioned with external Aramid Fiber Reinforced Polymer (AFRP) tendons under fatigue loading for two million cycles. The beams were internally prestressed with CFRP tendons. CFRP transverse reinforcement was used in the specimens to increase the ductility of the beams. The cracking load and the load at which the maximum crack width became 0.5 mm were selected as lower and upper limits for the fatigue load ranges applied to the beams, respectively. Two prestressing levels were investigated: 40% and 53% of the ultimate capacity of the AFRP tendons. All the beam specimens survived two millions cycles without failure. A decrease between 12% and 15% in the prestressing forces was recorded in the AFRP external tendons. This was attributed to either the relaxation of the tendons or the slippage of the tendons within the anchors used. The beams were then tested statically to failure. No reduction in the ultimate capacity of the beams was reported due to fatigue.

Grace and Abdel-Sayed. [3] Used a combination of bonded internal CFRP tendons with un-bonded external double draped Carbon Fiber Composite (CFC) cables in the construction of four bridge models having a double-Tee cross section. The post-tensioning forces in the external tendons varied between 57% and 78% of their ultimate capacity. The four models of the bridges were tested under fatigue loading at different load ranges within the working load limit (less than the cracking loads). The bridge models withstood millions of repeated cycles without failure, and an infinite fatigue life was reported. Insignificant losses in the prestressing forces were encountered in the externally draped tendons (about 3% of the initial force). The four models were then loaded statically up to failure. Failure of the tested models was governed by concrete crushing with no premature rupture occurring in the tendons. The mentioned investigations were conducted mainly to obtain the fatigue strength of the strengthened beams.

In this paper an analytical model is presented which can be used to predict the increase in deflection and crack width of reinforced concrete beams strengthened with externally prestressed CFRP tendons. The analytical results are compared with the available experimental data.

II. Experimental Investigation

Five concrete beam specimens were tested under cyclic load. Four beams were strengthened with externally prestress Carbon Fiber Reinforced Polymer (CFRP) tendons with various prestressing force and one beam without strengthening. The specimens were tested under single point bending at mid-span. Cyclic load was applied with various numbers of load cycles and fatigue loading levels.

III. Specimen Design Configuration

The reinforced concrete beams prepared for this project were 3500 mm long, having a cross section of 160× 280 mm and were simply supported over a 3300 mm span. These beams were made with a mixture of cement, fine aggregate, coarse aggregate and water at ratio of 1, 1.82, 3.16 and 0.5 by weight, respectively. The compressive strength of the concrete cubes was 30 MPa, which was determined by compression test on 6 cubic specimens with each side dimension of 150mm .The design of shear and flexural reinforcement was based on ACI 318 Code procedures [4]. All beam specimens reinforced with two 16 mm bars as flexural reinforcement, and two 10mm were placed in the compression region for fabrication ease. Thirty two 10 mm stirrups were placed in the beam as shear reinforcement at a spacing of 80 mm in the two outer thirds of the beam, and four stirrups were spaced evenly in the center, zero-shear/constant-moment third of the beam. The design of the flexural and shear steel reinforcement ensured a flexural failure of the beams. A clear cover of 40 mm was provided on all sides. The top and bottom longitudinal bars were Grade HRB335 steel with nominal yield strength of 335 MPa and stirrup was Grade R235 steel with nominal yield strength of 235 MPa. The CFRP was a commercial available material. The material properties reported by the manufacturer included ultimate tensile strength of 1975 MPa, elastic modulus of 150GPa and ultimate tensile force of 76kN, the nominal diameter of CFRP tendon was 7mm.Specimen details are shown in Fig. 1.

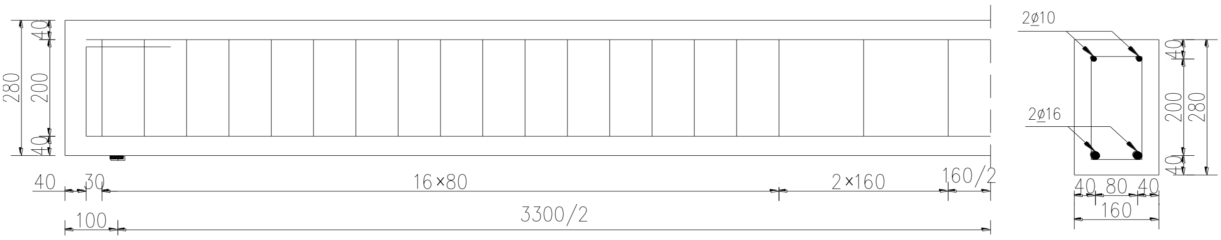


Fig. 1 Typical dimensions and reinforcement details of the control beam specimen (unit in mms)

Strengthening Method: Strengthening of the beam specimens was achieved by using two external commercially available CFRP material with doubly draped tendons post-tensioned, the angle at deviator was 5^o with different tension force 0.35、0.4、0.45 and 0.55 of its ultimate capacity. Draped tendons had a distance of 60 mm from the bottom fiber of the beam, in the constant moment region, with no eccentricity at the anchor. Double draped profile is achieve by means of two steel curved deviators locate at the third points of the beam. The inclined portions of the draped tendons in the shear spans made an angle of approximately $\theta = 5^O$ with the horizontal axis of the beam. Fig. 2 show general views of the strengthened beams with double draped tendon profiles. The specimen specific parameters are shown in Table 1.

Two designations: O and P for un-strengthened reinforced concrete beams and strengthened beams with externally prestressed CFRP tendons under fatigue load respectively were used.

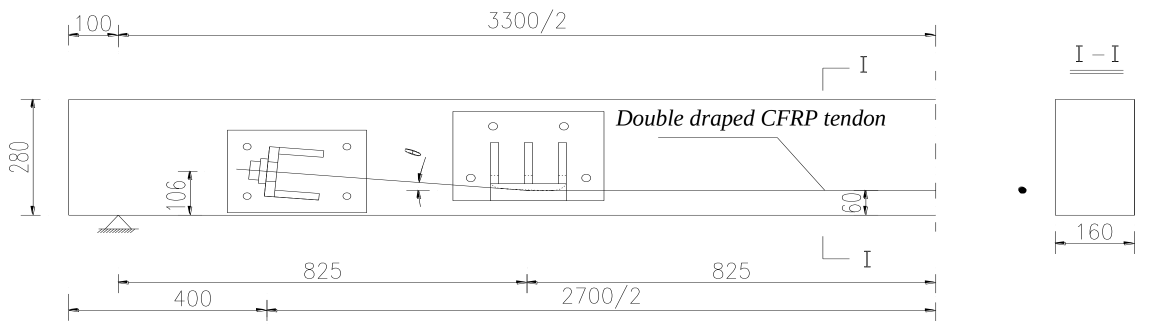
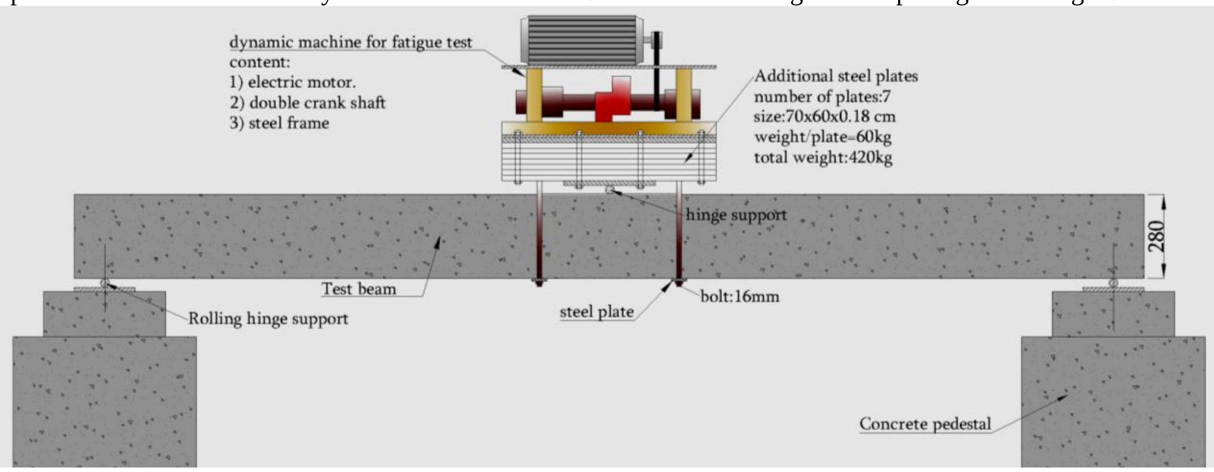


Fig. 2 A schematic view of test beams double draped tendon profile (All dimensions are in mms)

IV. Loading test setup and instrumentation.

Loading test setup: All specimens were tested under single-point bending at mid-span with a clear span of 3300 mm. The loads were applied by double crankshaft machine with a maximum weight 350 kg at mid-span point in addition to steel base plate weight 60 kg. The specimens were supported on a pair of roller and hinged supports rested on concrete pedestals. In order to prevented beams from moving out of the test plane it used fixing spreader steel beam restraint system at both beam-ends. The beams loading test setup are given in Fig. 3.



(a) A schematic view- Loading test-setup of test Beams

(b) Photo

Fig.3. Loading test-setup of RC. Beam (Elevation (All dimensions are in mms)

Instrumentation of the Beams:

1) Beam Strain Measurements:

Electrical resistance strain gages which were bonded to the surface of steel reinforcement are using to monitor the strain at different locations, the strain gages were placed on the bottom of the two reinforcing bars, two were placed at mid-section, four were placed under the points (525 mm away from the mid-span), Fig.4 show the locations of the strain gages installed on the surface of the steel.

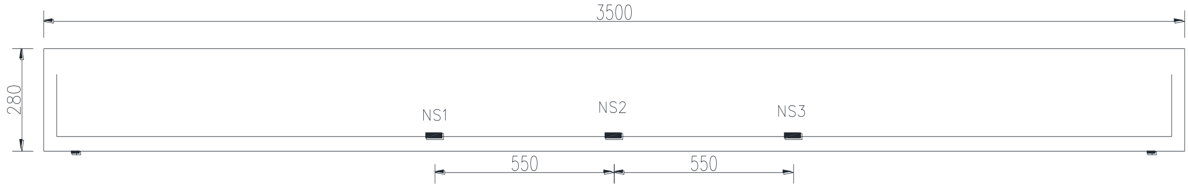


Fig.4.Location of strain gages on the steel bars (unit: mm)

2) Beam Deflection Measurements

The beam deflection was recorded by linear variable differential transducers (LVDT's) placed at mid-section of the longitudinal span to record the maximum deflection in the midspan.Fig.5 show schematic views of the dial indicator locations.

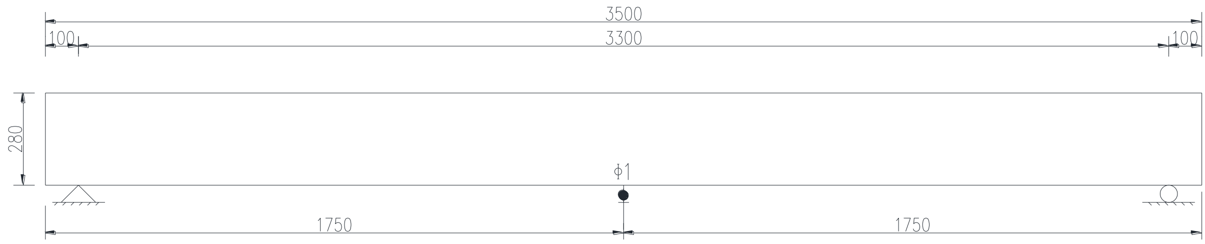


Fig.5.A schematic view of the dial indicator location

Test procedure: Single-point bending tests were performed as shown in Fig. 3 for all specimens .Five beams O-1, P-1, P-2, P-3 and P-4 were tested under cyclic loading at different fatigue loading levels (S) and numbers of load cycles (N) to evaluate fatigue performance, among the five beams one unstrengthened beam was used as a reference beam and the other strengthened with externally prestressed CFRP tendons with different tension forces. The test beams and the applied fatigue load levels are shown in Table 1.

Cyclic load was applied in a sinusoidal wave at frequencies of 15 to 20 HZ .the tests were carried out by load control. All beams were tested under fatigue loading until failure or the number of load cycles reached 2,000,000 cycles, except P-3 which was loaded firstly under fatigue loading and followed by static. For this beam when the number of load cycles reached the predetermined value, loading was terminated and the specimen was unloaded to zero. Then the specimen was loaded statically to the upper limit of fatigue load in 5 steps. The steel bar and CFRP tendons strain, mid-span-deflection, crack width were measured in various cycles load numbers, and at each loading step for beam P-3. Moreover the cracks propagation progress was also detected by inspection using the pre-drawn gridlines of 5 by 5 cm on the concrete beam surface at various cycles load number for all beams.

Table 1 Fatigue Test Data

Beam test ID	Frequency [HZ]	P_{min} [kN]	P_{max} [kN]	P_{ult} [kN]	load level $S=P_{max}/P_{ult}$
O-1	15	1	15	32	0.48
P-1	15	1	15	56	0.27
P-2	17	1	19	56	0.35
p-3	19	1	24	56	0.43
P-4	20	1	27	56	0.48

V. Experimental Results and Discussion

A large amount of data was gathered during the structural tests. An appropriate common link for the data is the cycles load number. Therefore, the experimental cycles load number -rebar strain, cycles load number –CFRP strain, cycles load number-deflection and cycles load number -crack width relationships were prepared for every test, and are detailed as following:

Strain in the Steel rebar and the CFRP tendon: The strain in steel reinforced bars and CFRP tendons at mid-span are shown in Figures 6 and 7, respectively. All the strains are plotted in absolute values. For some beams, the plot for steel strains is terminated after several cycles as the strain gauges were spoiled. For strengthened beams, the bigger fatigue load level, the higher was the strain.

For strengthened beam P-4 and control beam O-1, subjected to the same fatigue load level 0.48 of their respective static flexural strength Figures 6 showed that the steel bars strain in beam P-4 is bigger than in beam O-1.

The recorded strains on the steel reinforcement, CFRP tendons, and concrete (top surface) for P-3 and P-4, in both beams the strain in the concrete increased, indicating crushing of concrete at top fiber and the crack width was also increased at bottom fiber. At that point, strains in the steel bars and CFRP tendons increased but remained lower than strains corresponding to expect ultimate behavior, 0.0022 for steel bars and 0.0095 for the CFRP tendons. These figures indicate that the failure was due to the crushing of the concrete caused by fatigue. There was distinguishable difference in behavior between the strengthened and un-strengthened beams. For unstrengthened beam the failure was due to the steel bars fractured caused by fatigue and for strengthened beam the failure was due to the concrete crushing when steel rebar yielding fractured caused by fatigue.

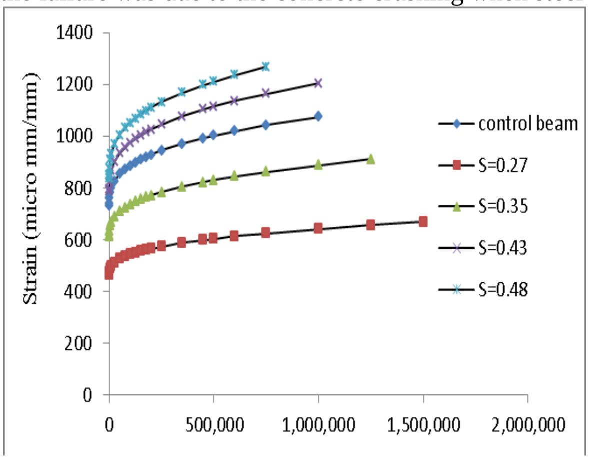


Fig.6 Steel bar tensile strain at mid-span section

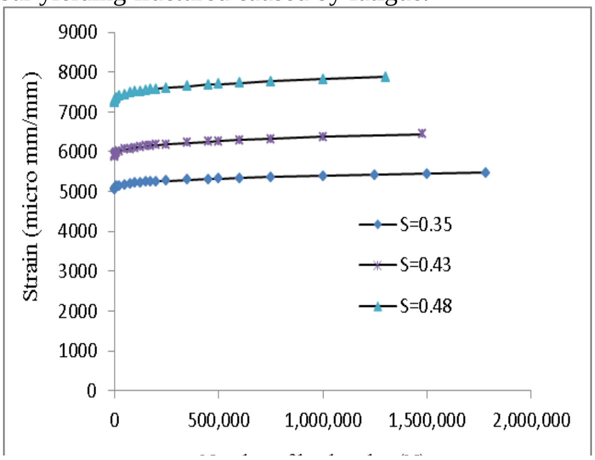


Fig.7 CFRP tendons tensile strain at mid -span section

For specimen P-3 which subjected to fatigue loading followed by static loading, at predetermined cycles load numbers, the strain for steel bars and CFRP tendons at mid-span were increased continuously with respect to the number of cycles until failure. Figs.8 and 9 shows a static load-steel bars strain curve and static load-CFRP strain curve, respectively, conducted at different stages during the fatigue load history. For this beam the following observations can be made:

1. At each predetermined number of load cycle, the strain increased with an increase in the load.
2. With an increase in the number of load cycles, there was an increase in the strains. When the static load reached the upper limit of fatigue load, with an increased number of load cycles, the strain increased from 419 to 1267 and from 4768 to 5373 micro strains for steel bars and CFRP tendons at mid-span, respectively.

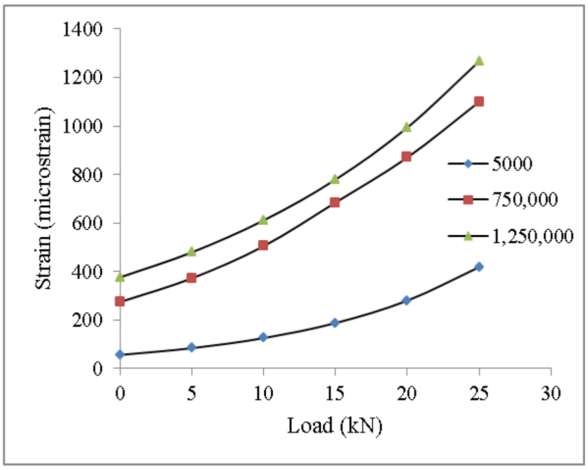


Fig.8 Steel bars strain versus Load for P-3

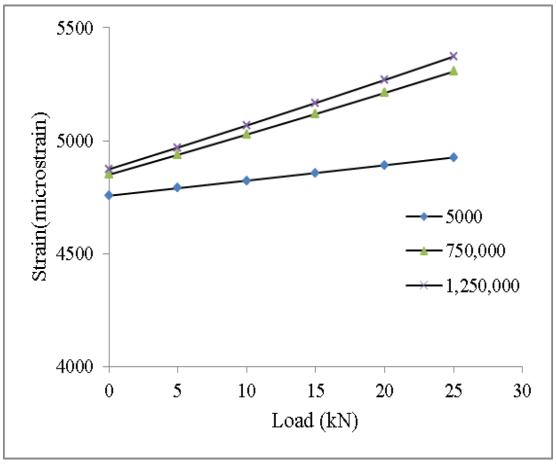


Fig.9 CFRP tendon strain versus Load for P-3

Mid-span – Deflections: The changes of the mid-span deflections with the increase of the number of cycles for beams P-2, P-3 and P-4 tested under fatigue loading only are given in Fig. 10. For each beam, the deflection was recorded during periodic load cycling. It can be seen that in all beams there was an initial increase of the mid-span deflection, followed by a stable region where the deflection remained relatively constant through many cycles, followed by an abrupt increase of deflection just before failure. It can also be observed that, in all beams, there is a more gradual increase in the deflections as the beam approaches its fatigue life.

The mid-span deflection of P-3 increased continuously with respect to the number of cycles until failure. Fig.11 shows a static load-deflection curve, conducted at different stages during the fatigue load history. The following observations can be made:

1. At each predetermined number of load cycle, the mid-span-deflection increase with an increased in the load. After cracking, the mid-span- deflection appeared to be linear with the applied load.
2. With an increase in the number of load cycles, there was an increase in the mid-span deflection. The flexural stiffness of the beam decreased with an increase in the number of load cycles. When the static load reached the upper limit of fatigue load, with an increased number of load cycles, the mid-span-deflection increased from 5mm to 7mm.

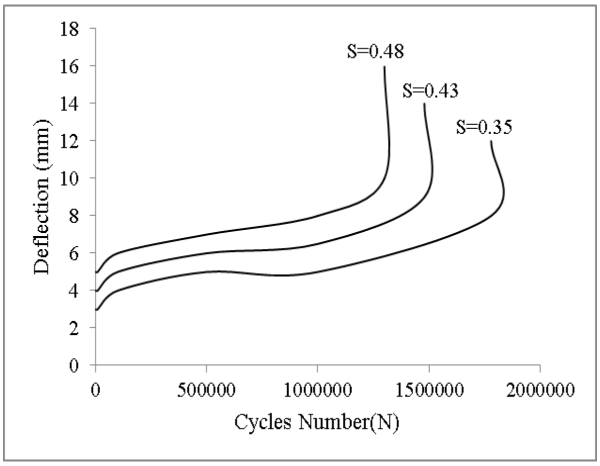


Fig. 10 Deflection versus Number of Cycles Due to Fatigue

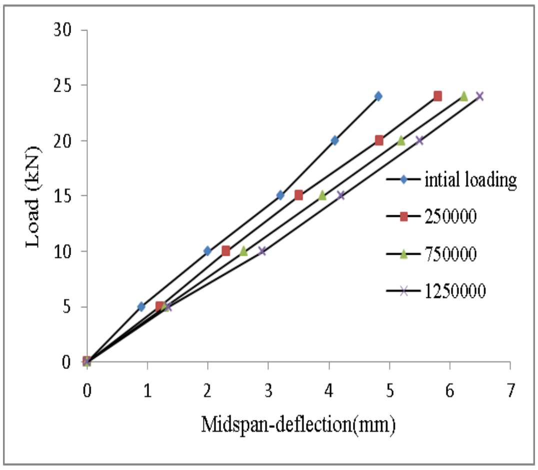


Fig. 11 Test beam P-3 Midspan-deflection vs. Load

Fatigue Damage and Crack Distributions. Concrete cracking under cyclic load is an indication of accumulation of fatigue damage in the concrete beams. The crack distribution on the beam specimens are indications of the fatigue resistance of the beams. For beams O-1, P-1, P-2 and P-4 the crack width was measured under various cycles load numbers. Fig.12 through Fig.14 shows crack distribution map on the beams with various load cycles at fatigue loading level of 0.27, 0.35, 0.43 and 0.48, respectively. Compared to unstrengthened specimen O-1, all strengthened specimens showed few cracks with smaller crack spacing in a short range on the beams. For unstrengthened beam O-1, cracks appeared mainly in the middle portion of the beam in the early loading stage. Crack propagation started in the first step and developed very quickly. The test showed that the cracking resistance of beams strengthened with externally prestressed CFRP tendon was improved significantly compared to unstrengthened beam. This is mainly due to the tensioning action of the CFRP tendon, which restricted the crack opening and growth in concrete. Application of externally prestressed CFRP tendon increased the depth of the concrete compressive zone, resulting in a wide crack distribution on the beams, an increase in the number of cracks, and a decrease in crack spacing, all indications of improved fatigue performance.

With the four strengthened beams, the higher the fatigue loading level, the more cracks appeared in the early loading stage. With the same number of load cycles, the higher the fatigue loading level for beam P-1 was small. The results indicated that the higher the fatigue loading level, the earlier the development of crack, resulting in concrete cracking at the bottom of beams.

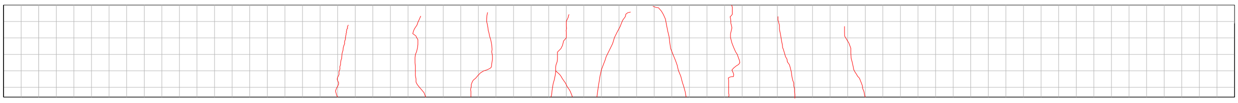


Fig.12 beam test O-1 Crack distribution map at failure (1,261,000 load cycles)

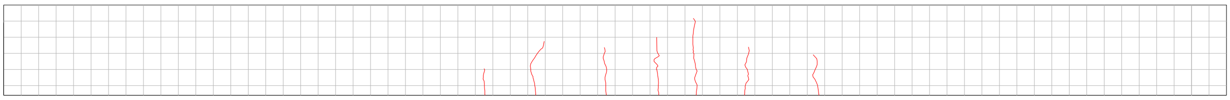


Fig.13 beam test P-1 Crack distribution map at 2,000,0000 load cycles

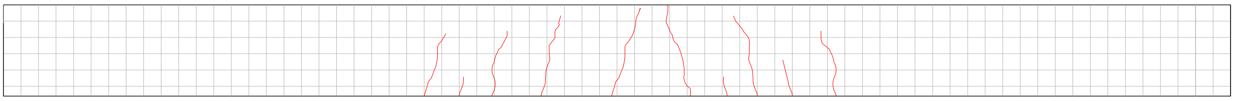


Fig.14 beam test P-3 Crack distribution map at failure (1,480,000 load cycles)

Crack Width. Crack width was obtained under various cycles load numbers. The relationship between maximum crack width and the number of load cycles is shown in Figure 15. This figure shows three stages of crack initiation and propagation, including:

Stage 1 initial fatigue loading stage: in this both crack width and number of cracks increase rapidly. The slope of crack width increase is significantly higher than that of curves beyond, indicating crack opening at a higher rate in this stage.

Stage 2 stable fatigue load stage: takes the major portion of the curves. With an increase in number of load cycles, there is an increase in crack width but with a much smaller rate, indicated by much flatter curves. No new cracks were observed to occur in this stage and cracks were tended to be stable.

Stage 3 fatigue failure stages: in this stage, it was observed that only few new cracks appeared but the crack width increased rapidly. In a very short period of time, concrete crushing.

With the same number of load cycles, as the increase of fatigue loading level, S, there is increase in maximum crack width, indicating that more energy was absorbed by beam with higher fatigue loading level. The crack width at fatigue loading level is larger than that with smaller fatigue loading level.

Fatigue life: A run out for fatigue failure is taken here to be 2,000,000 cycles. Table 2 gives fatigue data for the

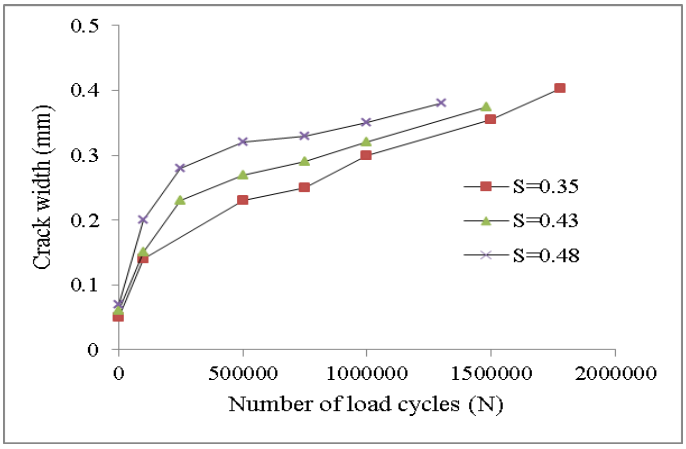


Fig.15 Maximum crack width versus number of load cycles(N)

unstrengthened beam and strengthened beams; the fatigue endurance limit for the beams was found to be 16kN load range when the minimum cyclic load was 1kN. The control beam failed by a fatigue failure of the tension reinforcing bars and all of the strengthened beams failed by a fatigue failure of the concrete crushing when steel rebar yielding, this is the reason that used of externally prestressed CFRP tendons.

The applied load range versus number of cycles to failure is presented in Fig.16. Fitting curves from regression analysis of experimental results are also plotted. The regression analysis showed that the fatigue life of the strengthened beams for the same load range is about three times greater than the fatigue life of the un-strengthened beam. CFRP tendons increase the strength and the stiffness of reinforced concrete beams and consequently reduces the stress on the steel reinforcement, prolonging the fatigue life of the beams.

Table 2 Fatigue test Cycles Number and Mode of Failure

Group	Description	Load range [kN]	Load level %	Number of cycles N	Mode of failure
A	Control beam	14	48	1,261,000	Steel fracture
B	Strengthened beams	14	27	Run out	No Failure
		18	35	1,780,000	Concrete crushing
		23	43	1,480,000	Concrete crushing
		26	48	1,300,000	Concrete crushing

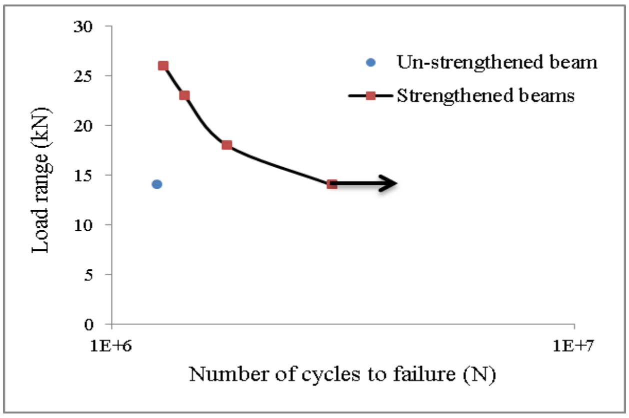


Fig.16 Load range versus Number of load cycles Curves from experimental Data

VI. Conclusions

From the investigation carried out, the following conclusions can be drawn:

1. The test results showed that failure mode of reinforced concrete beams strengthened with externally prestressed CFRP tendons under fatigue loading followed reinforcing steel yielding and concrete crushing.

2. Externally prestressed CFRP tendons reduce the stress in reinforcing steel and contribute to bridge the cracks after concrete cracking.
3. With an increase number in load cycles, there was a gradual increase in the mid-span-deflection.
4. At the same fatigue loading level, the strengthened beams cycles load number is bigger than un-strengthened beam.
5. The strengthened beams showed fewer cracks and smaller crack size compared to the unstrengthened beam.
6. CFRP tendons have a good performance under fatigue loading.

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