Retrofitting of reinforced concrete beams using externally bonded FRP plates

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Abstract

The need of increasing the serviceability loads, upgrading of provisions or deterioration of the structures due to corrosion or other types of degradation generally lead to the necessity of repair and/or strengthening. Although a variety of strengthening techniques are available such as jacketing or strengthening with externally bonded steel plates, it is getting more popular to use FRP materials because of their excellent properties.

This study is about the experiments in which RC beams were retrofitted with FRP (Fiber Reinforced Plastics) materials. All beams have the same material properties and dimensions. The effect of FRP ratio and reinforcement ratio on the behaviour of test specimens has been investigated as well as the effect of anchorage and, finally, conclusions were drawn.

1 Introduction

In recent years, repair and retrofit of existing structures have been among the most important challenges in civil engineering. The primary reasons for strengthening of structures can be summarized as follows: 1) Upgrading of resistance due to underestimated loads, 2) Increasing the load-carrying capacity for larger loads, 3) Eliminating premature failure due to inadequate detailing, 4) Restoring lost load carrying capacity due to corrosion, 5) Other types of degradation caused by time dependent factors such as creep and shrinkage [1]. Strengthening of RC beams can be accomplished using several methods such as
employment of shotcrete jacket, externally bonded steel plates or FRP plates and/or fabrics etc.

Since the use of steel plates is associated with some drawbacks such as difficulties of transporting, handling and installing, corrosion of plates, limited delivery lengths and the need to prepare the steel surface for bonding, researchers have tried to find an alternative material. Finally, fibre reinforced plastic materials have been adopted [2]. Application of FRP materials in civil engineering has assumed an important role in the recent years due to their quite favorable properties especially considering disadvantages and drawbacks in the employment of steel plates. Low weight, corrosion to chemicals, ease of application, unlimited delivery length and high strength have been some of the outstanding properties of FRP materials.

FRP plates generally consist of carbon glass or aramid, which are bonded with a polymeric matrix such as epoxy [3]. Meier [4] indicates that carbon has more superior properties than aramid or glass as far as tensile strength, compressive strength, long term behaviour, alkaline resistance etc. are considered.

Many researchers have investigated different parameters on FRP-strengthened beams. The effect of the number of FRP layers used [5], reinforcement ratio [6,7], the effect of anchorage and plate thickness [8], and the effect of FRP ratio on the failure mechanism [9] were some of the investigated parameters.

2 Research significance

Deterioration of concrete structures due to different reasons results in the need for retrofitting and/or repair of them. A relatively a new technique having many advantages over others to strengthen of R.C. beams is presented herein. This paper concentrates on the effect of different parameters such as reinforcement ratio anchorage and FRP ratio on the behaviour of the beams.

3 Experimental study

Ready-mixed concrete with water cement ratio of about 0.42 and maximum particle size of 10 mm was used in this study. The mean compressive strength ($f'_c$) of test specimens at 28-day was approximately 30 MPa. The clear distance between the tension bars through which the ready mixed concrete can pass was the criterion for the choice of maximum particle size.

Two types of reinforcing steel bars have been used in the test specimens. For compression zone $\phi 8$ steel re-bars were used whose yield strength was approximately 530 MPa. For tension zone $\phi 12$ steel re-bars were used whose yield strength was approximately 341 MPa. While yield strains of tension steel and compression steel were about 0.00155 and 0.00218, modulus of elasticities of tension steel and compression steel were about 220000 MPa and 240000 MPa respectively.
In all experiments, FRP laminates with tensile strength of 2800 MPa, two-component epoxy adhesives and carbon fiber fabrics for wrapping have been utilized.

In this study, the behaviour of RC beams strengthened with FRP laminates has been investigated. Experimental program has included 9 beams one of which has been pilot test beam and which has been used to minimize unforeseen drawbacks. All beams were 200x205 mm in cross section and 2840 mm long. The effective depth of the beams was 181 mm. Each beam had a clear span of 2600 mm. The beams were divided into two different groups as compared to reinforcement ratios and CFRP ratios. The beam specimens in the first series are named as R1, R1P1, R1P1W, R1P2, R1P2W, while the second series are referred as R3, R3P1, R3P2. Two different deformed steel bar ratios and two different CFRP ratios have been employed. Each beam has been designated with specific letters. Letters for the variables to be used can be summarized in the following. R1, R3 have represented reinforcement ratios of \( \rho_1=0.0094 \), \( \rho_3=0.0156 \) respectively. P1 and P2 have stood for CFRP ratios of \( \rho_{p1}=0.0017 \), \( \rho_{p2}=0.0033 \) respectively. Finally W indicates that the beam had carbon fiber fabric at the end of the CFRP at a distance of 100 mm to the cut-off point of the plate on both supports.

The beams which were in two groups were reinforced with 3\( \phi \)12, 5\( \phi \)12, tension steel re-bars respectively each one of which was also reinforced with 2\( \phi \)8 compression steel re-bars. The stirrups have been formed with 135\( ^\circ \) end hooks. Since there was no shear the zone between the applied loads, no stirrups have been used at this zone. The zone outside of the applied loads has been reinforced with vertical stirrups of 8 mm diameter at a spacing 90 mm center to center. CFRP plates, which were used to improve the structural behaviour of the beams, have been 1.2x50 mm in cross section and 2500 mm long. CFRP strips were applied from support to support so as to neglect undesirable failure mode due to distance effect between supports and CFRP cut-off points.

Two different epoxy adhesives were used, one used to bond CFRP to the concrete surface while the other used to wrap carbon fiber fabric to the concrete substrate. In order to make sure that FRP works effectively, such parameters as temperature and humidity of substrate and ambient, roughness of the surface, obtaining uniform adhesive thickness etc. were carefully considered as specified by the manufacturing group for the efficient application because those factors can easily affect the behaviour of the composite structure.

### 3.1 Test procedure

The beams were tested under four point loading up to failure. The test machine has been manually controlled hydraulic ram which had 20 ton capacity. Details of the beams and locations of LVDTs are depicted in Figures 1 and 3. The test specimens were instrumented by six displacement-measuring devices dial gage or LVDT, 50-ton load cell, analog to digital converter and a computer program named as Data Collect v1.0. Before testing of specimens, all devices
were calibrated. During the tests, two dial gages (Linear Variable Differential Transducers) were placed at two supports so as to measure the vertical settlements. Two dial gages mounted at midspan 50 mm to the tension face at both sides of the beams were used to determine vertical deflection at midpoint. These two dial gages have been placed on two straight steel bars which were mounted in the holes drilled on both sides of the beams. One of the other two dial gages was placed over the beam using clamps and the other one was located at the bottom of the beam. Both were at a distance of 100 mm to the midpoint at both sides. Average values of these two-dial gages were used in order to determine curvature at midspan. Besides, at every stage crack opening was measured by a pair of crack binoculars and noted.

4 Test results and discussion

The effects of reinforcement ratio, FRP ratio and presence of anchorage are presented as follows:

4.1 Reinforcement ratio

Only virgin specimens, a single layer of one FRP plated beams and a single layer of two FRP plated beams will be considered for discussion. It can be seen that an increase in reinforcement ratio has resulted in a decrease of crack width gradually. Moment versus crack width diagrams are depicted in Figure 4.

Crack width values around 0.4 mm which is a limit case for interior beams in TS 500 [10] have been calculated using recorded data. It was observed that reinforcement ratio has increased the loads corresponding to the 0.4 mm-crack width for the test specimens. For virgin specimens the increase was about 44 per cent for R3 beam with respect to R1 beam. For a single layer of one FRP plated beams that value was about 30 per cent for R3P1 beam with respect to R1P1 beam. For a single layer of two FRP-plated beams, the ratio which was similar to the previous one was 31 per cent for R3P2 beam. Table 1 shows the trend for loads corresponding to the max crack width precisely.

Reinforcement ratio is one of the major factors which influences flexural capacity or load-carrying capacity. Different researches have been carried out so as to investigate the effect of reinforcement ratio on the behaviour of the beams such as those by Ross et al., [7] and Spada et al., [6]. It is found that an increase in reinforcement ratio has resulted in an enhancement in the ultimate load capacity as expected. Enhancement ratios which are defined as the ratio of the peak load of the strengthened beam to the ultimate load of the virgin specimen in each group [7] are listed in Table 1. It was observed that while tension steel ratio increases enhancement ratio decreases for both virgin specimens and CFRP-plated specimens. In other words, for lightly reinforced beams, enhancement ratio is greater than those of the heavily reinforced beams. According to the Table 1, while R1P1 beam sustains 57 per cent much more than R1 beam, R3P1 which is heavily reinforced beam can sustain only 37 per cent much more than
R3 beam. It can be concluded that reinforcement ratio has an explicit effect on the load-carrying capacity. Load-center deflection curves of a single layer of one FRP plated beams and virgin specimens obtained are depicted in Figure 2. As indicated in these figures, an increase in stiffness and strength with increasing reinforcement ratio for plated beams can be observed more explicitly for the series of P1 beams.

4.2 FRP ratio

FRP-strengthened beams can perform an important role to reduce crack width and crack spacing. Moment versus crack width diagrams are shown in Figure 4 while FRP ratio is changing. As can be seen from these figures increasing FRP ratio has a positive effect so as to decrease crack width for the same moment or load values. These results agree with the study of Ritchie et al.,[11]. It has been reported that externally bonded FRP plates have altered several widely spaced and large width cracks to many more closed spaced, narrower cracks [11]. Minimum, average and maximum crack spacings are also shown in Table 1.

Due to the restraining effect of FRP plates on tensile cracks, first cracking loads increase in FRP-plated beams in that first cracking load for FRP-plated beams can exceed the load at which tension steel yields for virgin specimens [12] as indicated in Table 2. Load-deflection curves can be depicted in Figure 5 for the group of R1 beams. Those curves indicate the effect of FRP on the behaviour of test beams while reinforcement ratio is being kept constant. Increases in strength and stiffness can be seen clearly in those figures. Behaviour of all beams is linearly elastic up to the first cracking after the first cracking stiffnesses of all beams are changing due to the shifting moment of inertia. As it can be easily observed from the following figures, FRP starts to have an effect on the behaviour of the beams after yielding of steel. The effectiveness of FRP is better realized for lightly reinforced beams. For instance, strength and stiffness increases in the series of R1 beams are much higher than the beams of R3 series. In addition to that, while an increase in ultimate load for the beam of R1P1 is about 98 per cent with respect to virgin specimen of R1 beam, it is approximately 62 per cent for the beam of R3P2 with respect to the beam of R3. The decrease recorded in ultimate load can manifest the effectiveness of strengthening on the lightly reinforced beams.

4.3 Presence of external anchorages

Carefully designed external anchorages generally tend to increase the effectiveness of CFRP plates. In this study, only the beams of R1 series have included external anchorages obtained by wrapping of the curtailment zone of FRP at both sides.

The presence of the anchorages has a tendency to decrease crack width for the same load with respect to the virgin specimen significantly. Moment crack width diagrams are shown in Figure 4. Besides, wrapping of shear span in this study has shown that crack width decreases at the same load in R1P1W with
respect to R1P1 up to the crack width of 0.40 mm which is the limit crack width in TS-500 for interior beams. For R1P2W beam, while crack width is greater than R1P2 at the same load in the beginning of crack opening, the difference between crack widths decreases rapidly. The same crack width values are encountered after approximately 0.24 mm up to the crack width of 0.40 mm. If anchorage length of R1P2W had increased, crack width values probably would have decreased in the same load for R1P2W with respect to R1P2.

Wrapping of shear span, however, has not increased the load corresponded to the limit crack width of 0.4 mm in TS-500. The load values obtained corresponding to the limit crack width of 0.4 mm in TS-500 are 70.2 kN, 71.5 kN, 92 kN and 92 kN for R1P1, R1P1W, R1P2 and R1P2W respectively. In addition to crack width, while presence of anchorage in the beam of R1P1W has decreased crack spacing from 7.9 mm to 7.3 mm with respect to R1P1, crack width has not decreased in the beam of R1P2W with respect to R1P2. This probably occurred due to inadequate anchorage length for the beam of R1P2W.

Presence of plate end anchorages reduces slip between FRP and concrete. Since composite action of the FRP plated beams with plate end anchorage continues longer time than those without anchorages, the beams with plate end anchorages, R1P1W and R1P2W, as far as enhancement ratios are considered carry on approximately 25 per cent higher load with respect to R1P1 and 18 per cent higher load with respect to R1P2 respectively. These values also show the importance of carefully designed anchorages since anchorage length and placing, which were kept constant, should be higher when FRP ratio increases. As a result, the effectiveness of anchorages decreases 7 per cent as far as enhancement ratios are considered while plate ratio increases with constant steel ratio.

Load deflection curves are illustrated in Figure 5. As indicated in this figure, changes in stiffness become insignificant before cracking. Stiffness of the beams starts to change beyond cracking. After yielding of tension steel, end anchorages become more effective but changes in stiffness of the beams which have end anchorages remain insignificant with respect to FRP plated beams without anchorage. Presence of plate end anchorages increases ultimate deflection values with respect to the plated beams without anchorage as shown in Figure 5.

5 Conclusions

Some conclusions based on experimental investigations can be drawn as follows:

- As FRP ratio increases, load carrying capacity and ultimate moment will increase, as also indicated by Triantafillou, T.C. and N. Plevris [9],
- When an increase in the reinforcement ratio occurs while FRP ratio is kept constant, load carrying capacity and therefore ultimate moment also increase, the same tendency has been observed by Ross et al [7],
- Strengthening with FRPs are much more effective for lightly reinforced beams, resulting in an increase in the load capacity up to 100%. Ross et al [7], indicated an increase which was up to 200%. This rather large increase may be due to not only different quality of concrete, steel, FRP and epoxy strengths
used in both tests (which were mostly higher in this reference), but also due to
the fact that the steel reinforcement of 0.0033 indicated in this reference is much
smaller than that of used in our experiment (0.0094).
- Presence of anchorages increases max load values as expected,
- Failure modes of the beams strengthening with FRP plate are more brittle
and load values after the maximum loads sharply decrease,
- The rupture of FRP has not occured in any of the tests, but debonding
failure has been dominant,
- As indicated in Table 1, an increase in FRP ratios generally results in a
decrease in crack spacing.
- Reversed cyclic loading can be applied to strengthened beams with FRP
materials for possible future research works.
- For possible future research work, R.C. beams already damaged by
previous loadings and then strengthened by FRP materials can be tested under
four point loading as well.

The above conclusions agree with the available results obtained by other
researchers even though input data in the tests was mostly different from those
available in literature. Failure modes generally convert from ductile flexure with
yielding of steel followed by crushing of concrete to brittle manner and losses of
load occur suddenly. Triantafillou, T.C. and N. Plevris [9] have observed the
same tendency. Similarly debonding type of failure was usually recorded as
indicated by this reference. Besides, cracks were formed in a finely distributed
manner while widely spaced cracks form if FRP is not used. A similar tendency
was indicated by Ritchie et al., [11].

Table 1. Enhancement ratios, crack spacings and loads corresponding to limit

<table>
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<tr>
<th>BEAMS</th>
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<th>Limit crack width (mm)</th>
<th>Enhancement ratio</th>
<th>Crack spacings (cm)</th>
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<td>Min.</td>
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Table 2. Loads and deflections

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<td>P first crack</td>
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<td>P residual</td>
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<td>δ for max load</td>
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<td>δ first crack</td>
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Table 3. The modes of failure

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<td>R1</td>
<td>Yielding of tension steel</td>
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<td>De-bonding of CFRP plate due to peeling off</td>
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<td>R3</td>
<td>Yielding of tension steel</td>
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<td>R3P2</td>
<td>De-bonding of CFRP plate due to peeling off, crushing of concrete</td>
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Figure 1. Details of reinforcement

Figure 2. Load deflection curves
Figure 3. Location of LVDTs

Figure 4. Moment crack width diagrams

Figure 5. Load center deflection curves while FRP ratio changes
Acknowledgements

FRP materials used in the tests were provided by SIKA, Turkey.

References