Title:

BOND PERFORMANCE OF DIFFERENT FRP STRENGTHENING SYSTEMS

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ABSTRACT

The use of bonded fibre reinforced polymers (FRP) has gained a widespread acceptance as an excellent method for strengthening, retrofitting and upgrading of existing concrete structures. This paper presents the preliminary results of an experimental program conducted to evaluate bond characteristics of CFRP reinforcement bonded to concrete beams. A total of 24 concrete beams were constructed and tested under monotonic static loading. Three different strengthening techniques were investigated, including near surface mounted CFRP bars, strips and externally bonded CFRP sheets. For each strengthening technique, different bond lengths were considered. Design guidelines for the development length of CFRP bars, strips and sheets, used in strengthening concrete beams are proposed. Ultimate capacity as well as failure mechanism of concrete beams strengthened with different FRP systems are presented.

INTRODUCTION

Rapid deterioration of infrastructure became a principal challenge facing concrete bridge industries worldwide. Both serviceability and ultimate load carrying capacity of an existing concrete structure became inadequate to meet the users demand. High tensile strength, lightweight, adequate ductility and corrosion resistance characteristics of FRP make it ideal for retrofitting applications. Many studies [1-3] have shown that significant increase in stiffness and strength can be achieved using FRP strengthening techniques. However, a wide variety of failure modes were also observed in the retrofitted concrete beams including: crushing of concrete, shear failure, rupture of FRP and debonding of FRP along the adhesive-concrete interface. Among these failures, the first three modes could be avoided in design and their corresponding ultimate strength could be predicted using conventional flexural and shear theories.

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This paper summarizes a completed study and provides experimental evidence and insight of the bond properties of CFRP reinforcement. Up to date, very limited research is available addressing the bond behaviour of FRP strengthening systems. A total of 24 concrete beams were constructed and tested under monotonic static loading to characterize the bond mechanism and load transfer between CFRP reinforcement and concrete. Three different strengthening techniques were investigated, including near surface mounted CFRP bars and CFRP strips as well as externally bonded CFRP sheets. The feasibility and effectiveness of these techniques were examined formerly by the authors [3]. Test results revealed excellent performance in terms of strength enhancement and overall cost of construction. The bond length was varied for each strengthening technique to examine its effect on the failure mode and ultimate load carrying capacity of the strengthened beam. Design guidelines for the development length of CFRP bars, strips and sheets, used in strengthening concrete beams are provided.

TEST SPECIMENS

A total of 24 concrete T-beams with a total length of 2.7 m and a depth of 300 mm were tested. The beams were simply supported with a 2.5 m span. The beams were tested under a concentrated load acting at the middle of the specimen. The cross section dimensions were designed to avoid compression failure due to crushing of the concrete. The length of the specimens was selected based on testing six pilot beam specimens to ensure that rupture of FRP reinforcement can be achieved if they are bonded along the full length of the beam. The arrangement of the bottom reinforcement was selected to ensure that the failure of the strengthened beams will always occur at the mid-span section and not at the section where the FRP reinforcement is terminated. Reinforcement details of the tested specimens is shown in Figure 1. Three series of beam specimens designated as A, B, and C were cast, respectively. In series A, the beams were strengthened using near surface mounted C-BAR CFRP bars. The bars are manufactured by Marshall Industries Composites Inc., USA and have a modulus of elasticity of 111 GPa and an ultimate strength of 1918 MPa. The performance of two different epoxy adhesives used for bonding the bars was investigated. In series B, the beams were strengthened using near surface mounted CFRP strips. The CFRP strips are produced by S&P Clever Reinforcement Company, Switzerland. The strips have a modulus of elasticity of 150 GPa and an ultimate strength of 2000 MPa.

Figure 1. Reinforcement details of the tested specimens
In series C, the beams were strengthened using externally bonded CFRP sheets. The sheets are manufactured by Master Builders Technologies, Ltd., Ohio, USA. With the maximum moment occurring at the mid-span section of the beam, two types of failure were expected: (1) bond failure; (2) rupture of FRP. Specimens were adequately designed to avoid concrete crushing and premature failure due to shear. In case of bond failure, the bond length of the FRP reinforcement was increased in the following specimens. In case of flexural failure, the bond length was decreased in the following specimens. This scheme was applied until an accurate development length of each strengthening technique was achieved.

**STRENGTHENING PROCEDURES**

In series A, each beam was strengthened using one C-BAR CFRP bar inserted inside a groove cut at the tension side of the specimen. A special concrete saw was used to cut a groove of approximately 16 mm wide and 30 mm deep at the bottom surface of the beam. The procedures of cutting the groove, filling the groove with epoxy, and inserting the bar inside the groove are illustrated in Figure 2. In series B, the beams were strengthened using near surface mounted CFRP strips (25x1.2 mm). Each beam was strengthened using one strip. The groove dimensions were approximately 5 mm wide and 25 mm deep. The same procedures, in terms of cutting the groove and placing the CFRP strip were applied. In series C, the beams were strengthened using CFRP sheets bonded to the bottom surface of the beams. The concrete surface was prepared by grinding and sandblasting. Two coats of MBrace primer and putty were applied to the surface with a paintbrush. A coat of MBrace saturant was applied using a nap roller. Following these procedures, the CFRP sheet was applied. The sheet was again covered with a final coat of MBrace saturant.

**TESTING SCHEME**

The beams were tested under a concentrated load applied at mid-span. A closed-loop MTS 1000 kN testing machine was used to apply the load using stroke control mode. The rate of loading was 1.0 mm/min until yielding of steel reinforcement takes place, beyond which the rate was increased to 3.0 mm/min up to failure. The instrumentation used to monitor the behaviour of the beams during testing is shown in Figure 3.

![Figure 2. Strengthening procedures for series A beams](image-url)
TEST RESULTS AND DISCUSSION

Series A

A total of eight beams were tested from series A. One beam was tested as a control specimen while the other seven beams were strengthened with near surface mounted C-BAR CFRP bars. Embedment lengths, L, of 150, 550, 800, and 1200 mm were tested using Duralith-gel as an epoxy adhesive for bonding the bars. The adhesive is commonly used as a mortar binder for vertical and overhead repairs of structural concrete. To investigate the suitability of the epoxy adhesive, three embedment lengths of 550, 800, and 1200 mm were examined using Kemko 040 as an alternative epoxy adhesive. Kemko 040 is designed specifically for grouting bolts, dowels and steel rebars in concrete. Its non-sag consistency allows for application in horizontal and overhead surfaces. The load-deflection behaviour of series A beams is shown in Figure 4. In general, as the embedment length increased, the ultimate load increased up to a certain limit (L=800mm) beyond which no significant increase in the ultimate load was observed. The control specimen, A0, failed due to crushing of concrete with corresponding yield of the steel bars. The failure load of the control specimen was 56 kN. Strengthening the beam with a C-BAR CFRP bar of an embedment length of 150 mm achieved the same failure load. Insignificant enhancement in stiffness and strength was observed.
Failure of beams A2, A3, and A4 with embedment lengths of 550, 800, and 1200 mm, respectively was due to debonding of the CFRP bar. The ultimate loads for these beams ranged between 67.3 kN to 78.9 kN, with an increase of 20 to 41 percent over the control specimen. Identical behaviour was observed for the beams retrofitted with the two sets of adhesives at different embedment lengths. Altering the type of the epoxy adhesive has a negligible effect on the ultimate loads of the strengthened beams. The observed mode of failure for all beams strengthened with CFRP bars was splitting of the concrete cover followed by complete debonding of the bars. After splitting failure, the beams behaved as conventional concrete beams reinforced with steel bars. The load dropped to the yielding load of the steel bars until crushing of the concrete occurred. Using an embedment length greater than 800 mm provided inconsiderable enhancement in the ultimate load carrying capacity of the strengthened beams. Test results indicated a failure load of 73.2 kN when using an embedment length of 800 mm. Increasing the embedment length by 50 percent resulted in an increase in the ultimate load carrying capacity by only 7 percent.

**Series B**

A total of nine beams were tested from series B. One beam was tested as a control specimen while the other eight beams were strengthened with near surface mounted CFRP strips. Embedment lengths of 150, 250, 500, 750, 850, 950, 1050, and 1200mm were examined. Epoxy adhesive, Denopox CFL, approved by the manufacturer, was used for bonding the strips. The sequence of testing started first by testing beams B1, B2, B3, and B4 with embedment lengths of 150, 250, 500, and 750mm, respectively. Based on the results of these tests, beams B5 to B8 with embedment lengths ranged between 850mm and 1200mm were tested. The load-deflection behaviour of series B beams is shown in Figure 5. The behaviour of the control specimen is also shown for comparison. The control specimen, B0, failed due to crushing of concrete at a load level of 52.3 kN. The figure clearly indicates that using embedment lengths up to 250mm provides insignificant improvement in strength. This is attributed to the early debonding of the CFRP strip at a load level of 20 kN as shown in Figure 6.

![Series B graphs](image-url)

*Figure 5. Load-deflection behaviour for series B beams*
A considerable enhancement in strength was observed for embedment lengths greater than 250mm. Beams B3 and B4 with embedment lengths of 500mm and 750mm, respectively failed due to splitting of the concrete cover. The failure loads for both beams were 67.3 and 74.2 kN, respectively. This indicates that full composite action has not yet been developed and hence the ultimate load was increasing with the increase of the embedment length. Beams B5, B6, B7, and B8 were strengthened with CFRP strips of embedment lengths ranged between 850mm and 1200mm. The failure of these beams was due to rupture of the CFRP strips as shown in Figure 6. The strength of the beams was controlled by the maximum tensile strain in the CFRP strip, which was approximately 1.3 percent. This behaviour has been confirmed experimentally by measuring almost identical failure loads for the four beams.

Series C

A total of seven beams were tested from series C. One beam was tested as a control specimen, while the other six beams were strengthened with various lengths of CFRP sheets. The bonded length of the sheets was varied from 150mm to 750mm. Figure 7. shows the load-deflection behaviour of series C beams. The strengthened beams exhibited concrete cracking at load levels higher than the control specimen. The control specimen, C0, showed traditional non-linearities at cracking of the concrete and yielding of steel. The failure load of the control specimen was 52 kN. The failure was due to crushing of the concrete at the top surface. Specimens C1 and C2 with bond length of 150mm and 250mm, respectively showed identical behaviour to the control specimen. The beams experienced no enhancement in strength as is evident by the failure loads of both specimens, which ranged between 51 and 52 kN. Delamination process was observed to initiate well before yielding of the steel bars. Delamination was initiated at the end of the sheet and propagated toward the mid-span of the beam. This process continued until the strains in the sheet were reduced to zero and delamination occurred resulting in peeling of the sheet, adhesive and a thin layer of the concrete.
Longer sheets also demonstrated brittle failure with sudden delamination along the entire span. Initial cracking in the concrete substrate was typically observed after yielding of the steel. These initial cracks were often accompanied by audible noises. Changes in the stiffness were also observed in the mid-span deflection curves. Shorter sheets were found to fail at lower loads with less brittleness. The failure load was found to increase by increasing the bonded length up to a certain limit (L=500mm), beyond which no significant enhancement in strength was observed. The failure load was 76.7 kN when a bond length of 500 mm was used. Increasing the bond length by 50 percent resulted in an increase in strength by only 3 percent.

DESIGN GUIDELINES

The variation of the ultimate strain in the CFRP reinforcement with the bonded length is shown in Figure 8 for the different strengthening techniques. The distribution of the strain can be divided into three distinct zones: (1) “destressed zone” at bonded lengths less than 250mm. In this stage, the CFRP reinforcement debonded from the surrounded adhesive and the beam behaved as conventional concrete beam reinforced with steel bars; (2) “bond development zone”, where the strains are increasing linearly with the bonded length. In this stage, increasing the bonded length will results in a considerable enhancement in the ultimate load carrying capacity of the concrete beam; (3) “composite zone”, where the CFRP behaved compositely with beam. In this stage, increasing the bonded length will not provide extra strength to the retrofitted beam. The observations suggested that strain at the transition point between the bond development zone and composite zone varies depending on the type and configuration of the CFRP reinforcement. In case of using C-BAR CFRP bars, the strain ranged between 0.7 to 0.8 percent depending on the adhesive used in bonding the bars. When CFRP strips were used, the strain at the transition zone could reach the rupture strain of the strip (1.3 percent). Finally when CFRP sheets were used the strain was found to be 1.9 percent.
CONCLUSIONS

1. Ultimate loads of concrete beams strengthened with CFRP reinforcement were found to increase with longer bond length. For every strengthening technique, there is a certain length beyond which no further increase in beam strength can be obtained.

2. Using epoxy adhesives that were commonly used for bonding steel rebars into concrete proved its efficiency in bonding near surface mounted CFRP bars to the surrounding concrete.

3. Rupture of C-BAR CFRP bars is not likely to occur regardless of the embedment length or the type of the epoxy adhesive used. The maximum allowable strain in the bars should be limited to 0.7-0.8 percent depending on the type of epoxy adhesive.

4. The development length of C-BAR CFRP bars inserted inside grooves should not be less than 800 mm for 10 mm diameter bars.

5. The development length of CFRP strips (25x1.2 mm) inserted inside grooves should not be less than 850 mm. Rupture of the strips can be achieved provided that the embedment length is greater than the development length.

6. The development length of CFRP sheets bonded to the soffit of concrete specimens should not be less than 500 mm. Extending the CFRP sheets beyond this value would not provide additional strength for the retrofitted beam.

REFERENCES

