FLEXURAL AND SHEAR STRENGTHENING OF REINFORCED CONCRETE STRUCTURES WITH NEAR SURFACE MOUNTED FRP RODS

ABSTRACT

The use of Near Surface Mounted (NSM) Fiber Reinforced Polymer (FRP) rods is a new and promising technology for increasing flexural and shear strength of reinforced concrete (RC) members. This study investigated the structural performance of full-size simply supported RC beams externally strengthened with NSM FRP rods. Both flexural and shear strengthening were examined. Carbon and Glass FRP rods of different sizes were used for flexural strengthening. Carbon FRP deformed rods were used for shear strengthening. The variables examined in the shear tests were spacing of the rods, strengthening pattern, end anchorage of the rods and presence of internal steel shear reinforcement. Performance of the tested beams and modes of failure are presented and discussed in this paper. The test results confirm that NSM FRP rods can be used to significantly increase the flexural and the shear capacity of RC elements, with efficiency that varies depending on the tested variables.
INTRODUCTION

The use of Near Surface Mounted (NSM) Fiber Reinforced Polymer (FRP) rods is a promising technology for increasing flexural and shear strength of deficient reinforced concrete (RC) members. Advantages of using NSM FRP rods with respect to externally bonded FRP laminates are the possibility of anchoring the rods into adjacent members, and minimal installation time. Furthermore, this technique becomes particularly attractive for flexural strengthening in the negative moment regions of slabs and decks, where external reinforcement would be subjected to mechanical and environmental damage and would require protective cover which could interfere with the presence of floor finishes.

The method used in applying the rods is as follows. A groove is cut in the desired direction into the concrete surface. The groove is then filled half-way with epoxy paste, the FRP rod is placed in the groove and lightly pressed. This forces the paste to flow around the rod and fill completely between the rod and the sides of the groove. The groove is then filled with more paste and the surface is leveled.

Very limited literature is available to date on the use of NSM FRP rods for structural strengthening. A review of laboratory studies and field applications is reported elsewhere (De Lorenzis, 2000). As this technology emerges, the structural behavior of RC elements strengthened with NSM FRP rods needs to be investigated. Tensile and bond testing of the rods for application as NSM reinforcement were carried out in order to obtain a characterization at the material and sub-system levels (De Lorenzis, 2000). Subsequently, the structural level was examined by testing full-size beams. Both shear and flexural strengthening were investigated. Experimental results are presented in this paper.

FLEXURAL TESTS

Specimens and Procedure

Four full-scale RC beams with a T-shaped cross-section and a total length of 4.5 m were tested. All the beams had a flexural reinforcement of two steel rebars No. 7 (nominal diameter 22.2 mm) on the tension side and two rebars No. 4 (nominal diameter 12.7 mm) in compression. The shear reinforcement, designed to ensure that flexural failure would control, consisted of steel stirrups No. 3 (nominal diameter 9.5 mm) every 127 mm. The dimensions of the beam cross-section are given in Figure 1.

The average concrete strength, determined according to ASTM C39-97 on three 152-mm diameter by 305-mm concrete cylinders, was 36 MPa. The yield strengths of the steel tension and compression reinforcement, as determined from tensile test on three coupon specimens according to ASTM A370-97, were 494 MPa and 357 MPa.
respectively. A commercially available epoxy paste was used for embedding the rods. Its mechanical properties, as specified by the manufacturer, were: 13.8 MPa tensile strength, 4% elongation at break, 55.1 MPa compressive yield strength and 2756 MPa compressive modulus. Glass FRP (GFRP) deformed and Carbon FRP (CFRP) sandblasted rods were the NSM reinforcement. The manufacturer specified for the GFRP No. 4 rods a tensile strength of 800 MPa and a Young’s modulus of 41340 MPa. Properties of the CFRP sandblasted rods were: 1550 MPa tensile strength and 164.7 GPa Young’s modulus, as reported in (Warren, 1998).

Beam BFV (no external strengthening) was used as a baseline comparison to evaluate the enhancement in strength provided by the NSM FRP rods. Beams BFC3 and BFC4 were strengthened with two CFRP sandblasted rods No. 3 and No. 4, respectively. Beam BFG4 had two NSM GFRP deformed No. 4 rods. All the grooves had square cross-section, with size of 19.0 mm for beam BFC3 and 25.4 mm for beams BFC4 and BFG4. The method of application of the rods has been described in the introduction. The epoxy paste was allowed to cure for 15 days (full cure time at room temperature) prior to testing of the beams. The beams were loaded under four-point bending with a shear span of 1830 mm. Load was applied by means of a 200-ton hydraulic jack connected to an electric pump and recorded with a 100-ton load cell. Load was applied in cycles of loading and unloading, with the number of cycles depending on the maximum expected load. Each beam was instrumented with four LVDTs placed at mid-span, at quarter-span and at each support to derive the net deflections. Two more LVDTs were placed horizontally at mid-span to measure the deformation of the cross-section on the tension and compression sides. Another LVDT monitored slip at the end of an NSM rod. Strain gages were also applied on concrete, steel rebars and FRP rods at various locations.

Results

Load vs. mid-span deflection envelopes of the tested beams are reported in Figure 2. Beam BFV, with no external strengthening, failed at a load of 156.6 kN. The failure mode was concrete crushing after yielding of the steel tension reinforcement.

Failure of Beam BFC3, strengthened with two CFRP sandblasted No. 3 rods, occurred under an applied load of 203.6 kN, corresponding to a 30% increase in capacity with respect to BFV. Beam BFC4, strengthened with two CFRP sandblasted No. 4 rods, failed at 226.0 kN, which indicated a 44.3% increase over BFV. Both beams failed by debonding of the NSM rods. A typical crackling noise during the test revealed the progressive cracking of the epoxy paste. Longitudinal splitting cracks developed in the epoxy cover and led to the loss of bond of the NSM reinforcement. The load dropped to a value close to the capacity of the virgin beam and deflection kept on increasing, until the test was stopped. This part of the load-deflection curve has not been reported. When bond controls, increasing the amount of the NSM reinforcement does not produce a significant gain in capacity. BFC4 had twice the area of NSM reinforcement but only 11% more capacity than BFC3.

Beam BFG4, with two GFRP deformed No. 4 rods, failed at a load of 196.9 kN, 25.7% higher than the capacity of beam BFV. Failure was again by debonding of the NSM rods. However, unlike in beams BFC3 and BFC4, the epoxy cover and part of the concrete cover of the internal steel reinforcement were split off in a catastrophic fashion (Figure 3). Also in this case, the load dropped to a value close to the capacity of the control beam, while the beam kept on deflecting until the test was stopped. The difference in failure...
mode is due to the greater tendency of deformed rebars to induce splitting forces in the surrounding material.

Figure 3. Beam BFG4 after Failure

SHEAR TESTS

Specimens and Procedure

Eight full-scale RC beams with a T-shaped cross-section and a total length of 3 m were tested. Six beams had no internal shear reinforcement. Two beams had internal steel stirrups at a spacing that did not satisfy the requirements of the ACI 318 Code (1995). All the beams had a flexural reinforcement of two steel rebars No. 9 (nominal diameter 28.7 mm), designed to ensure shear failure. The dimensions of the beam cross-section were the same of the beams tested in bending.

The average concrete strength was 31 MPa. The internal steel flexural and shear reinforcement had a yield strength of 427 MPa and 345 MPa, respectively. Commercially available CFRP deformed rods were used for these tests. Tensile strength and modulus of elasticity of the rods were determined from laboratory testing. The average values resulted to be 1875 MPa and 104.8 GPa, respectively. The epoxy paste was the same used for the flexural tests.

The specimen details are indicated in Table 1. Beam BV was used as a baseline comparison to evaluate the enhancement in strength provided by the NSM FRP rods. Beam BSV was used to quantify the contribution to the shear strength provided by the NSM FRP rods in presence of steel stirrups. In all the other beams, either vertical or 45-degrees grooves were saw-cut on the surface of both web sides. No. 3 CFRP deformed rebars were then embedded in the epoxy-filled grooves. The variables examined in the experimental
test matrix were: spacing of the rods, inclination of the rods with respect to the longitudinal axis of the beam, anchorage in the flange, presence of internal steel stirrups.

All the grooves had square cross-section, with size of 19 mm. The method of application of the rods has been described in the introduction. Strain gages were applied on the surface of some FRP rods at different locations. The epoxy paste was allowed to cure for 15 days (full cure time at room temperature) prior to testing of the beams. The beams were loaded under four-point bending with a shear span of 1067 mm, corresponding to an $a/d$ ratio equal to 3.0, being $a$ the shear span and $d$ the depth of the longitudinal reinforcement. Load was applied as previously described for the flexural tests. Each beam was instrumented with four LVDTs placed at mid-span on the two sides and at each support to derive the net mid-span deflection. Strain gages were applied on the CFRP rods and on the steel stirrups at various locations.

Results

During loading of beam BV, diagonal shear cracks formed at a load of 109.9 kN. The shear cracks initiated at the center of both shear spans almost simultaneously. As the load increased, one crack widened and propagated until failure resulted at a load of 180.6 kN.

In specimen B90-7, failure occurred at a load of 230.4 kN. This corresponded to an increase in capacity of 27.6% with respect to beam BV. Diagonal shear cracks formed also in this beam, widened and propagated as the applied load increased. A crackling noise revealed throughout the test the progressive cracking of the epoxy paste in which the CFRP rods were embedded. Failure eventually occurred by splitting of the epoxy cover in one of the NSM FRP rods intersected by the major shear crack. Same behavior and failure mode were observed in beam B90-5. The ultimate load was 255.3 kN, corresponding to an increase in capacity of 41.4% over the control beam and 10.8% over specimen B90-7.

Table 1. Specimens Details

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Specimen B90-5A was identical to specimen B90-5, except that the CFRP rods were anchored in epoxy-filled holes drilled through the flange. This led to a change in the failure mode and to a substantial increase in the beam capacity. The ultimate load was 371.4 kN, indicating an increase of 105.7%, 61.2% and 45.5% compared to beams BV, B90-7 and B90-5, respectively. The first diagonal shear cracks became visible at a load level approximately equal to 177.9 kN. As the load increased, more shear cracks formed throughout the shear span, widened and propagated. At higher load levels, secondary cracks formed in the concrete at the level of the longitudinal steel reinforcement as a result of splitting forces developed by the deformed steel bars and of dowel action forces. Failure eventually occurred in a sudden fashion by loss of the concrete cover of the longitudinal reinforcement (Figure 4a).

Specimen B45-7 failed at 330.9 kN, corresponding to an increase in capacity of 83.3% over the control beam. As expected, 45-degree inclined rods were more effective than vertical rods at the same spacing, as showed by the 43.6% increase in capacity of B45-7 with respect to B90-7. Failure, as in B90-7, was controlled by splitting of the epoxy cover that occurred simultaneously in two of the NSM FRP rods intersected by the major shear crack (Figure 4b). In Specimen B45-5, failure occurred at a load level of 355.8 kN, showing an increase in capacity of 97%, 7.5% and 39.4% over BV, B45-7 and B90-5, respectively. The failure mode was the same previously described for specimen B90-5A, that is, formation of splitting cracks along the longitudinal reinforcement and eventual loss of the concrete cover. Figure 5a shows the load vs. net mid-span deflection envelopes of the six beams without steel stirrups.

In beam BSV, shear cracks widened and propagated up to the flange as the load increased. Failure resulted at 306.5 kN. The ultimate load of beam BS90-7A was 413.7 kN, that is, 35% larger than the capacity of beam BSV. The final failure mode was splitting of the concrete cover as previously described for beam B90-5A. In this case, however, it occurred when flexural failure was already ongoing, as evident from the crushing line in the concrete top fiber at mid-span and from the load vs. mid-span deflection diagram. Another difference with respect to failure of beams B90-5A and B45-5 is that the concrete cover did not spall completely, due to the restraining action of the steel stirrups. Figure 5b shows the load vs. mid-span deflection diagrams of the beams with steel shear reinforcement including beam BV for reference.

Summarizing, two failure mechanisms were observed, namely, debonding of one or more FRP rods and splitting of the concrete cover of the longitudinal reinforcement. Test results seem to indicate that the first mechanism can be prevented by either anchoring the NSM rods in the beam’s flange or using 45-degree rods at a sufficiently close spacing, which provides a larger bond length. Once this failure mode was prevented, splitting of the concrete cover of the longitudinal steel reinforcement became the controlling factor. This mechanism appears to be critical as a result of the difference in configuration between internal stirrups and NSM reinforcement. Unlike internal steel stirrups, NSM rods are not able to exert any restraining action on the longitudinal reinforcement subjected to dowel forces. These forces, in conjunction with the wedging action of the deformed reinforcement, give rise to tensile stresses in the surrounding concrete which may eventually lead to cover delamination and loss of anchorage.

The shear capacity of the strengthened beams can be increased by either decreasing the spacing of the NSM rods, or anchoring the rods into the flange, or changing the inclination of the rods from vertical to 45 degrees. Comparing the amount of FRP material and the gain in capacity in the three cases, it appears that the most efficient way to increase the shear capacity of an RC T-beam is using NSM rods anchored into the flange. Using inclined rods rather than vertical rods is also efficient, while decreasing the spacing between the rods does not produce a remarkable increase in the shear capacity.
CONCLUSIONS

Test results show that the use of NSM FRP rods is an effective technique to enhance flexural and shear capacity of RC beams. The beams strengthened in bending showed an increase in capacity ranging from 25.7% to 44.3% over the control beam. In the beams strengthened in shear, an increase in capacity as high as 105.7% could be obtained. However, it appears that bond is of critical importance for the effectiveness of this technique. The next step in the research will be the analysis of all the deflection and strain data collected. In order to predict the behavior of the strengthened beams, results of bond tests (De Lorenzis, 2000) will be analyzed to understand the mechanics of bond between NSM FRP rods and concrete.

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