EFFECT OF CFRP LAMINATE AND/OR CFRP BARS TO THE SHEAR BEHAVIOR OF DEFICIENT REINFORCED CONCRETE BEAMS

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Abstract- Shear failure is catastrophic and occurs without forewarning. Therefore, there is an urgent need to increase the strength of shear deficient RC beams. There are several strengthening techniques to increase the behavior of deficient structures. CFRP usage is one of the recent method preferred for shear strengthening. It has several advantages according to traditional strengthening techniques. However, one technique has become alternative to this method, embedding CFRP into the precut grooves. The aim of this technique is to overcome the disadvantages of CFRP bonding by embedding it into a groove. Accordingly, an experimental program was fulfilled in order to determine the positive states and comparison of these techniques. The major objective of this experimental work is to investigate the benefits of CFRP bars and strips according to each other. Thus, small strip width (50 mm) was used and equivalent spaces were applied to the beams that were strengthened with bars and strips. The remaining specimen was tested in its virgin condition to serve as a control beam. Tests results indicated that all in all an increase in strength was seen in specimens to which CFRP reinforcements applied.

Index Terms- CFRP, shear strengthening, RC beams.

I. INTRODUCTION

Most of the traditional structures are need of strengthening or retrofitting to resist higher loads and/or earthquake effects. The most common retrofitting technique has been accomplished by the use of conventional materials such as externally bonding steel plates or steel and concrete jacketing [1-2]. On the other hand, the use of modern materials like fiber reinforced polymer (FRP) has come as an alternative to the use of the conventional techniques. Carbon fiber reinforced polymer (CFRP) has been a popular material because of its superior properties such as durability, corrosion resistance, tailorability, ease of handling and installation, high strength to weight ratio etc [3-4].

CFRP is mostly used after gluing it to the concrete surface without additional anchorage usage. However, after gluing the CFRP, a common failure mode, debonding, materializes and decreases the contribution of the technique. Recently, a strengthening technique, in addition to externally bonding FRP laminates, called near-surface mounting (NSM) of CFRP started to be used to increase the capacity of concrete members. In the NSM CFRP technique, laminate strips or CFRP bars are introduced into pre-cut grooves on the concrete cover of the elements to be strengthened that were previously filled with epoxy-adhesive. It is expected that debonding failure can be hindered or delayed after using this technique [5-7]. In addition to that, the advantages of using CFRP bars for structural strengthening installed with the NSM technique include: surface preparation is minimized; grooving is obtained with a single saw cut without any concrete chipping; after installation, the NSM bar is protected from mechanical damage and environmental deterioration and the quality of the concrete inside the groove is typically superior to the surface concrete.

This paper presents the results of an experimental investigation carried out on reinforced concrete beams strengthened in shear by CFRP strips and NSM CFRP bars. As the deficiency of structures principally emerges under earthquakes, the behaviour of CFRP strengthened beams were evaluated under suchlike loading. The major objective of this experimental work is to investigate the benefits CFRP bars and strips according to each other. Thus, small strip width (50 mm) was used and equivalent spaces were applied to the beams for bars and strips. The remaining specimen was tested in its virgin condition to serve as control beam.

II. EXPERIMENTAL TESTS

A.Specimens

All specimens had the same geometry and materials as shown in Fig. 1. Longitudinal reinforcement consists of three 20 mm diameter deformed steel rebars in the bottom and top of the beam section. Beams had no internal shear reinforcement (stirrups) in the shear span. However, stirrups were provided outside the shear span to block local cracks that might occur due to applied load. The measured average cylinder compressive strengths of the concrete were 25 MPa. The yield stress of the longitudinal reinforcing steel bars with a characteristic strength of 414 MPa and elastic modulus of 205 GPa. 6 mm bars with a characteristic strength of 275 MPa and an elastic modulus of 192 GPa were used for the shear reinforcement.

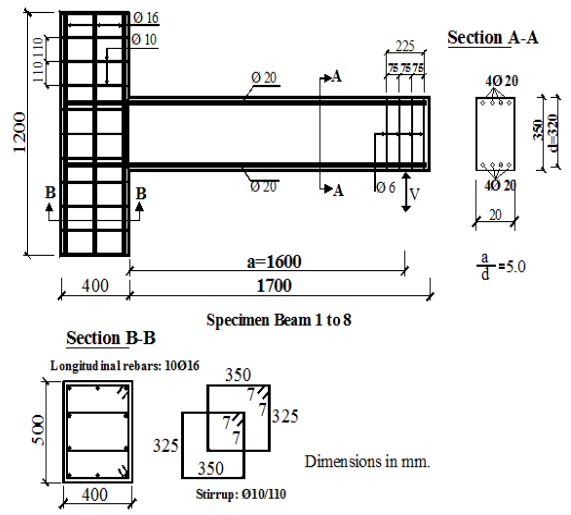


Fig.1. Specimen properties

B. Strengthening material and strengthening procedure

ASLAN 200 CFRP bars and Sikawrap 230c CFRP strips were used for strengthening. The strengthening procedure includes the preparation of the surfaces and the grooves, application of epoxy adhesive and bonding of the CFRP reinforcements. Sikadur-330 epoxy resin was used as adhesive.

Before applying to CFRP strips, some pre-treatment steps for the beams were necessary. First, the beams were sand-blasted to remove outer weak surface of the concrete and then the surfaces were vacuum cleaned to remove loose particles and dust. Epoxy primer was coated at the designated places according to the manufacturer's suggestions. CFRP strips were then placed on the coated epoxy primer and constant pressure was applied on the sheet surface by a roller. Another layer of epoxy was then put on top of the fabric and the extreme resin was cleaned.

Different from the CFRP strip application grooves were cut with the dimensions as function of reinforcement size (one and a half times the diameter of CFRP reinforcement). The vertical length of each groove is 350 mm, which is equal to the depth of the beam. The grooves were half-filled with epoxy adhesive. Afterwards, the CFRP reinforcements (barss) were subsequently inserted and lightly pressed. By applying this force it was aimed to flow around the CFRP reinforcements with adhesive and avoid any pores between CFRP reinforcements and the sides of the groove. Thereafter, grooves were filled with more adhesive and the surface was levelled by removing the residual adhesive. All applications were performed at room temperature.

C. Details of Test Beams

BEAM-1 is the reference of shear deficient beams', is tested without strengthening and used as a baseline for evaluating the effect of strengthening material to shear capacity. The remaining two specimens were strengthened with CFRP reinforcements such as strips and bars.

50 mm wide CFRP strips were bonded on both side of BEAM-2 while strengthening it. CFRP strips were placed with 80mm spacing, which is from the axis of CFRP strips. For BEAM-3, 9 Ø CFRP bars were placed with 80 mm spacing to obtain equivalent spacing with Beam-2.

D. Experimental Setup

All specimens were tested under cyclic loading. To perform cyclic load to the specimen, a loading column was designed with hinges by the beam's free end. Loading column contained two hinges, a load cell and a hydraulic jack. The capacity of the hydraulic jack was 500 kN while the load cell's capacity was 400 kN with 0.06% linearity. Load was applied in cycles of loading and unloading. Load cycles were selected as they will help to evaluate the flexure and shear crack propagations and their affect to behavior. Loading was increased up to yield of flexural reinforcements or until the failure of the specimen. Four linear variable differential transformers (LVDTs) were used to monitor displacements. The LVTD's are located at the end of the beam for maximum displacement, under the rigid support to calculate the undesired displacement and finally on the rigid support to calculate the rotation.

Measurement of strain is crucial for designating the contribution of CFRP reinforcements to shear capacity. Eight strain gauges were used for each specimen. Strain gauges were placed at an interval where shear cracks is expected to be developed, between 80 to 1600 mm apart from the beam's support. A schematic view of experimental set-up and the arrangement of the measurement devices is shown in Fig.2.

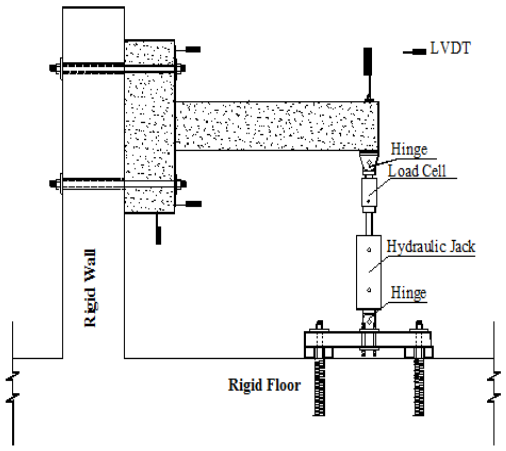


Fig.2. Test setup

III. EXPERIMENTAL RESULTS AND EVALUATIONS

A. Observed Behavior and Failure Modes

Shear force-displacement hysteretic curves of the test specimens are presented in Fig.3 a, b and c. BEAM-1 was failed in shear due to critical shear crack propagation at 45.92 kN (Fig.4 and Fig3-a). It is clear from Fig.3 that all strengthening schemes increased the strength of specimens in different level.

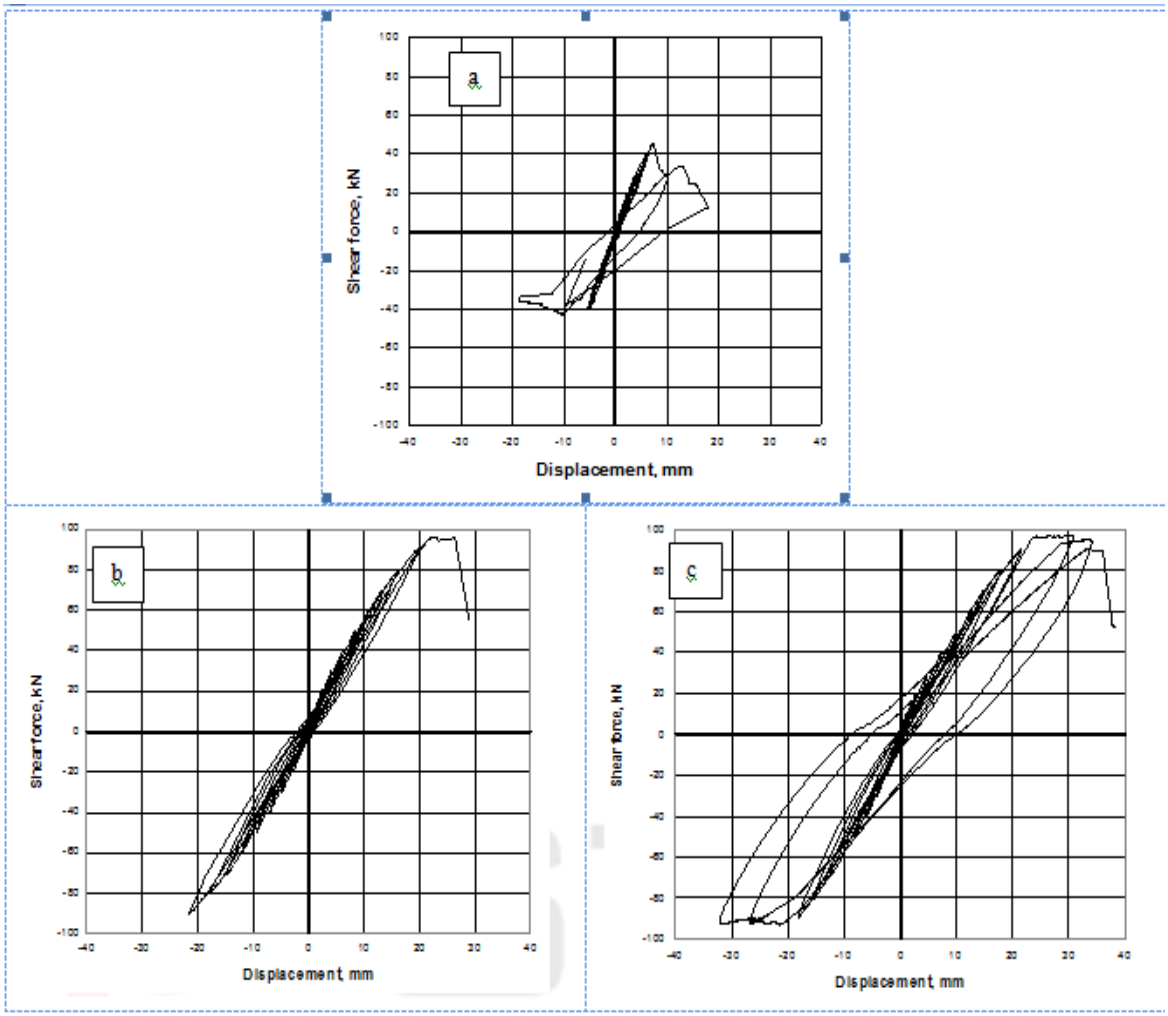


Fig.3. Load-Displacement Curves of the Specimens

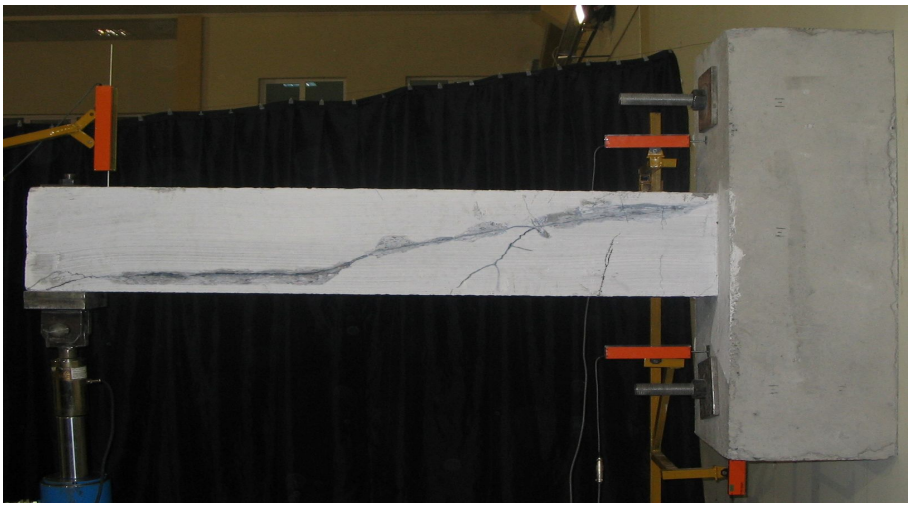


Fig.4. Failure of Control Beam

BEAM-2 was strengthened with side bonded CFRP strips. As the load reached to 15 kN, flexural cracks were occurred at the bending region of BEAM-2. Thereafter, shear crack developments were observed at the unstrengthened part of the specimen, between CFRP strips. After exceeding 70 kN load level, cracks started developing faster, and widen quickly.

However specimen resisted this situation and directed the specimen to ductile flexural behavior. Longitudinal compression reinforcements reached their yield strength at 94.84 kN (Fig.3-b). Right after the yield of the reinforcements, parallel to the propagation of the current cracks, preliminary developed cracks were widened and advanced along the interfacial concrete in a quick manner. Accordingly, specimen was failed right after the yielding of the longitudinal reinforcements as debonding was materialized unexpectedly. Specimen was failed in shear as can be seen from Fig 5.



Fig.5. Failure mode of BEAM-2

CFRP bars were used for strengthening BEAM-3. As a spacing equal to minimum stirrup ratio (ACI-318, 2005) [8] was selected for the specimen, shear cracks were crossed CFRP reinforcements shortly after their propagation. Therefore, crack growing and widening was blocked immediately after the crack propagation without finding the possibility of expansion. Accordingly, specimen was reached at its yield strengths (Fig.3-c).

Virtually no serious shear cracks were visible on the side surfaces of the beam until the yield of the longitudinal reinforcements. When the displacements increased, sudden shear crack propagations all throughout the shear span was observed. As a result, splitting forces were developed by the longitudinal reinforcements and specimen was failed due to concrete cover separation as shown in Fig. 6.

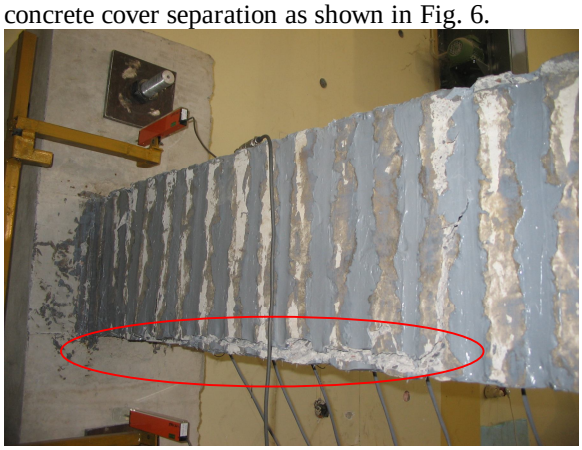


Fig.6. Failure mode of BEAM-3

IV. RESULTS AND DISCUSSION

RC beams strengthened with CFRP strips and CFRP bars were compared with the control beam to interpret the shear strength enhancements. Test results confirmed that the use of CFRP bars and also CFRP strips are both an effective technique for improving the shear capacity of RC beams.

BEAM-2 was strengthened with side bonded CFRP strips without anchorage. This technique is capable of increasing the strength of specimen when compared with control beam. The selected CFRP width and spacing is also effective since a remarkable increase in strength was obtained. But as the load increased CFRP strips were not resisted to increasing loads and debonded. Debonding appears when the maximum shear stress of CFRP reaches the ultimate bond strength. Under these circumstances, the success of CFRP strengthened systems is governed by the bond strength of adhesive and the bonding area of CFRP, not the tensile strength. According to test results, debonding can be materialized when anchorage is not used and if the expected strength increment is too much to reach the yield strength.

Debonding was not occurred for the NSM specimen due to embedding CFRP bars into the slits. As a result, the exact contribution to the shear capacity was obtained from the strengthening technique. However, as the beam exposed to increasing displacement, concrete cover separation failure was observed since this become the weak part of the strengthened specimen. While strengthening, it is almost impracticable to deal with the factors (such as concrete tensile strength, thickness of concrete cover, and the application configuration of longitudinal reinforcements) that cause concrete cover separation. Therefore applying CFRP bars like a conventional stirrup or wrapping CFRP strips could be good

solution to obstruct failure modes such as debonding and also concrete cover separation.

CFRP reinforcements are linearly elastic in nature so it is optimistic to anticipate precise ductile flexural behavior from the specimens that were strengthened with CFRP reinforcements. But limited ductile behavior was obtained for the CFRP embedded specimen. In addition to that longitudinal reinforcements of BEAM-2 have reached their yield strengths. That enabled the specimen to exhibit a slight ductile behavior, even though they ultimately failed in shear right after the reinforcement yielded. This resulted CFRP usage as a reliable strengthening technique whether you use as a strip or a bar.

The measured strain gives essential information for designating the effect of strengthening material on shear capacity. Therefore, strain behavior of strengthened specimens was investigated. Two different strain behavior was observed according to CFRP application. For the NSM usage, strain increments do not occur until the shear force is transferred to the CFRP reinforcements. Once the first shear crack was formed, the strain in the interacted CFRP reinforcement increased with load at a significantly faster rate. Strain increment was continued until failure of specimen For the CFRP strips, initial shear cracks were started to propagate between the CFRP strips. As the load increased, cracks started to develop through the strips and cross them. Right after this propagation causes increment at strains and it started to become faster. When maximum strain are compared, 21% more strain was measured for the specimen in which CFRP strip is applied. That proves CFRP strips have to resist more tension to overcome shear failure, and accordingly that resulted a debonding to be occured.

CONCLUSIONS

The following major conclusions can be drawn from the results of this experimental study;

- Both strengthening techniques are capable of increasing the ultimate strength of shear deficient RC beams.
- Debonding was seen for the side bonded CFRP strengthened specimen. Anchorage usage or wrapping could be good solution for obstructing debonding.
- Embedding CFRP bars in to slits obstructed CFRP bars to be separated from the concrete surface.
- Concrete cover separation was occurred for the NSM specimen as the loads increased. To hinder concrete cover separation applying CFRP bars like a conventional stirrup could be a good solution.
- CFRP reinforcements are linearly elastic in nature so it is optimistic to anticipate precise ductile flexural behavior from the specimens that were strengthened with CFRP reinforcements. However a limited flexural behavior was obtained with CFRP strengthening.

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