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Experimental and Theoretical Investigation on Shear Strengthening of RC Precraced Continuous T-beams Using CFRP Strips

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ABSTRACT

Carbon fiber reinforced polymer (CFRP) sheets are externally bonded to reinforced concrete (RC) members to provide additional strength such as flexural and shear strength. It has been widely accepted that carbon fiber reinforced polymers (CFRPs) can be used effectively to strengthen reinforced concrete (RC) members. This paper is intended to study and use externally bonded CFRP strips to repair and strengthen RC continuous T-beams, as well as investigating the influence of material (CFRP) on repair of shear defect on RC continuous T-beams. This defect will be repaired using different CFRP strips under sustained loading. Total of three RC continuous T-beams with identical sizes of 150x320x3650 mm, flange width of 400 mm and flange thickness of 120 mm were used, and the orientation involved 0/90 degree and 45/135 degree in 3 sides wrap schemes. All beams were tested under sustained loading. Tests result showed the effectiveness and shear capacity of the CFRP strengthened specimens. The shear enhancement of the CFRP strengthened beams varied between 26.57% and 38.56% over the control beam. This study confirms that the CFRP strip technique significantly enhances the shear capacity of reinforced concrete shear beams.

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1. INTRODUCTION

The growing interest in fiber-reinforced polymer (FRP) composite in strengthening and retrofit of structures is becoming apparent in recent years because of the special properties of these composite materials. The most efficient technique for improving the shear strength of deteriorated RC members is to externally bond fiber-reinforced polymer (FRP) plates or sheets [1]. FRP composite materials have experienced a continuous increase of use in structural strengthening and repair applications around the world in the last decade [2]. In addition, the FRP compared with steel materials provides unique opportunities to develop the shapes and forms to facilitate their use in construction. Strengthening of beams and slabs in flexure and confinement of circular columns have been well documented. A review of research studies on shear strengthening, however, revealed that experimental investigations are still needed [3, 4]. There are many methods for shear strengthening option such as: bonded surface configurations, end anchor, shear reinforcement spacing and fiber orientation. While many methods of strengthening structures are available, strengthening structures via external bonding of advanced FRP has become very popular worldwide. Although the materials used in FRP for example, fiber and resins are relatively expensive when compared with traditional materials, the crisis of equipment for the installation of FRP systems are lower in cost. FRP systems can also be used in areas with limited access where traditional techniques would be impractical. Commercially available FRP reinforcing materials are made of continuous aramid (AFRP), carbon (CFRP), and glass (GFRP) fibers. Possible failure modes of FRP strengthened beams are classified into two types: the first type of failure includes the common failure modes such as concrete crushing and FRP rupture based on complete composite action. The second type of failure is a premature failure without

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reaching full composite action at failure. This type of failure includes: end cover separation, end interfacial delamination, flexural crack induced debonding and shear crack induced debonding. Different failure mechanisms in experimental tests were reported in the literature [5-7]. In addition, several studies were conducted to identify methods of preventing premature failure with the aim of improving the load capacity and ductility of RC beams. Researchers studied the use of end anchorage techniques, such as U-straps, L-shape jackets, and steel clamps for preventing premature failure of RC beams strengthened with CFRP [5, 7-17]. Generally, the researches conducted on RC rectangular sections are not representative because most RC beams would have a T-section due to the presence of a top slab. This paper mainly focuses on T-beams strengthened with CFRP on shear.

2. EXPERIMENTAL PROGRAM

2. 1. Test Specimens and Materials

The experimental program consisted of testing five full-scale RC continuous T-beams under four-point loading. All specimens were design according to ACI 318-08 with identical size of 150x320x3650 mm, flange width of 400 mm and flange thickness of 120 mm. All beams have an identical reinforcement detail including longitudinal reinforcement in the form of 14 mm and stirrups reinforcement of 6 mm, at 200 mm spacing center to center. Figure 1 shows specimen details and the place of strain gauge on reinforcement.

All beams were casted using ready mix concrete with compressive strength of 30 N/mm^2. Three bars of main reinforcement with length of 600 mm were tested under uniaxial tension using Universal Testing Machine (UTM) to determine the yield strength (see Table 1). For this study, the used FRP was CFRP bi-directional woven carbon fiber fabric. Mechanical properties of the CFRP are shown in Table 2. The type of adhesive used was Sikadur-330, a two part epoxy impregnating resin A and B. Table 3 shows the mechanical properties of the epoxy.

3.STRENGTHENING SCHEME AND TEST SET-UP

Table 4 summarizes the experimental program. A total of 3 beams of two-span continuous T-beams strengthened with CFRP sheet including orientations of (90°/0°) and (45°/135°) were investigated with shear span to effective depth ratio of 2.5, two beams were cracked and strengthened with CFRP sheets, while the remaining one was kept uncracked as a control. The beams were initially precracked at service load and strengthened with CFRP laminates in the unloaded condition. The test set-up as well as strengthening schemes are shown in Figure 2. Each specimen has different characteristic where for B2.5-C, it was tested with no wrapping and loaded to failure. For B2.5-UA-S and B2.5-LA-S, load was applied until 80% from the ultimate load of control beam or until shear crack was obviously appeared on the beam. After that, the load was released to apply the CFRP on the crack beam and then a load of total 9.5kN was placed on top of the beam and left for one week before loading to failure.

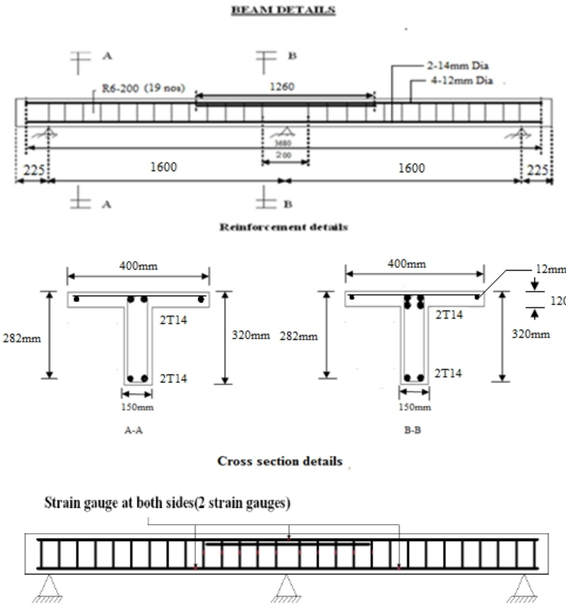

Figure 1. Reinforcement and cross section details

TABLE 1. Material properties of main reinforcement

Type	Diameter of bar (mm)	Yield strength (N/mm²)
High yield steel	12	547.033
High yield steel	14	554.233
High yield steel	6	265.061

TABLE 2. Mechanical properties of CFRP[1]

Density	Tensile strength	Tensile E-modulus	Elongation at break
1.75 g/cm³	3'800 N/ mm² (nominal)	230’000 N/ mm² (nominal)	1.5% (nominal)

TABLE 3. Mechanical properties of Sikadur-330 [2]

Density	Tensile strength	Tensile E-modulus	Elongation at break
1.3 kg/L ± 0.1 kg/L	30N/mm²)	Continuous exposure + 45 °C	0.9 %

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2. [Sika Manufacturer’s Product Data Sheet, Switzerland,(Supplier: Sika Kimia Sdn. Bhd.), Sika Wrap®-330. 2-party epoxy impregnation resin. Edition 0209/1.

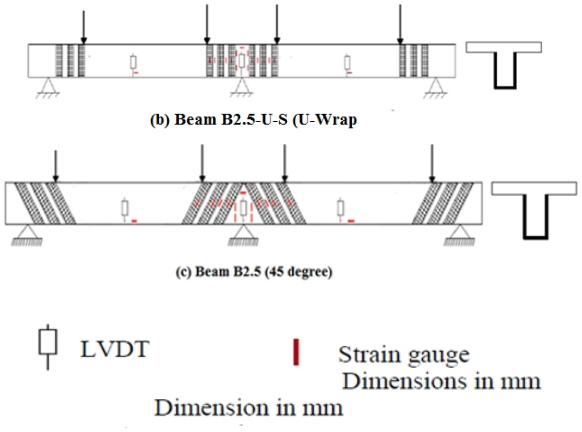

Figure 2. Test set-up and strengthening schemes

Figure 3. Cracking and failure pattern of beam B2.5-B

Figure 4. Cracking and failure pattern of beam B2.5-U-S

Figure 5. Cracking and failure pattern of beam B2.5-L-S

4. EXPERIMENTAL RESULTS AND DISCUSSION

4. 1. Ulyimate Load and Modes of Failure All specimens as shows in Table 5 failed in shear as expected. For control beam, B2.5-C, flexural cracks were started to form at near the mid span at the bottom of the beam at a load approximately 55kN. The shear cracks began to appear at a load of approximately 120 kN and as the load increased, the shear crack widened and propagated up to the final failure at a load level of 180.4 kN. The mode of failure was shear crushing of the concrete as shown in Figure 3. For beam B2.5-U-S, which was strengthened with CFRP strips, three sides (U-wrap) and oriented at 90°/0°, the failure mode of this beam was rupture-shear of CFRP as shown in Figure 4. In this beam, the diagonal shear crack was observed at total load of about 150kN. The first crack was observed total load of 60kN. As the load increased, more shear cracks appeared throughout the shear span. When the total load reached 228kN, the contribution of CFRP to shear capacity was 47.94kN and increased in shear enhancement at 26.57% higher than the control beam. For beam B2.5-L-S, which was three sides (L-wrap) and oriented at 45°/135° with CFRP strips, no cracks were visible on the sides of the beam until 105kN. A diagonal shear crack was observed near the middle of shear spans at a load of 164kN. Finally, the beam failed at a total load of 250.12kN. Test results shows that there was an increase of 38.65% in ultimate load capacity compared to control beam B2.5-C. The failure mode of this beam was rupture-shear of CFRP and the contribution of CFRP to the shear capacity was 69.72kN as shown in Figure 5.

5. LOAD-DISPLACEMENT BEHAVIOR

Figure 6 shows the total applied load versus mid-span deflection relationship for all tested specimens. All beams showed very similar stiffness trend to each other. The smallest deflection was observed for beam B2.5-C. After the occurrence of the first crack, in precracked and repaired phase the specimen B2.5-LA-S had the greatest stiffness because of orientation of CFRP. It was also observed that the stiffness of the beam strengthened with orientation of 90^{o} of CFRP (B2.5-UA-S) was less than the beam strengthened with orientation of 45^{o} (B2.5-LA-S). The ultimate load was greater for specimen B2.5-LA-S compared to specimen B2.5-UA-S. Specimens B2.5-LA-S and B2.5-UA-S had a maximum deflection of 10.4 mm and 9.8 mm at failure load which was greater than the control beam B2.5-C.

6. LONGITUDINAL STEEL STRAIN OF(av/d=2.5)

The applied load versus strain curve for specimens B2.5-C, B2.5-U-S and B2.5-L-S (precracked and repaired phases) are shown in Figure 7. The control specimen B2.5-C has attained maximum strain of 1235 μ_{ε} recorded at the failure.

TABLE 4. Summarizes the experimental program

No.	Specimen	CFRP orientation (˚)	Wrapping schemes	Loading & strengthening condition
1	B2.5-C	-	-	-
2	B2.5- UA-S	0/90	3 sides	0kN→155kN→9.5kN& sustained load apply CFRP→loading to failure
3	B2.5-LA-S	45/135	3 sides	0kN→155kN→9.5kN& sustained load apply CFRP→loading to failure

TABLE 5. Experimental results

Specimen	av/d	CFRP orientation (˚)	First crack	Ultimate load	Shear force s	Contribution of CFRP	Shear enhancement	Mode of failure
B2.5-C		-	55	180.4	59.98	-		Diagonal shear failure
B2.5-U-S	2.5	0/90	60	228.34	75.92	47.94	26.57	Rupture or shear failure
B2.5-L-S		45/135	105	250.12	83.16	69.72	38.65	Rupture or shear failure

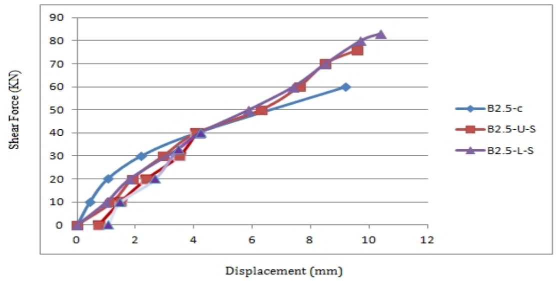

Figure 6. Ultimate load versus mid-span displacement relationship

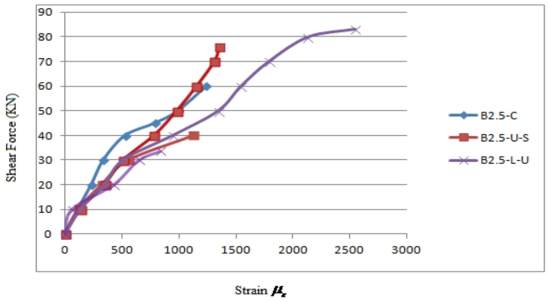

Figure 7. Comparison of load versus strain in tensile steel.

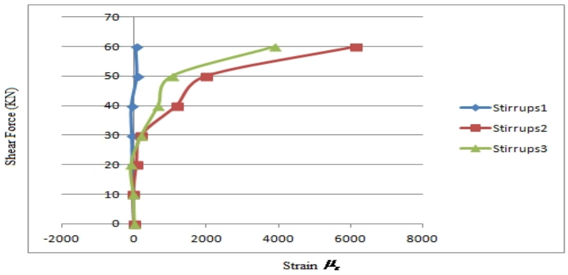

Figure 8. Load versus strain in steel stirrups for control specimen B2.5-C

For specimen B2.5-L-S, less strain was observed in comparison to the specimen B2.5-U-S during the precracked phase. In the repaired phase of B2.5-UA-S, a sudden increase in strain was observed near the support at a load of 36 kN due to the formation of shear cracks over the shear zone. Similarly on specimen B2.5-LA-S, beyond the load 33.75kN, a sudden change in strain was observed near the support. Figure 7 illustrates the comparison of the load versus strain curve. In the precraked and repaired phases, the load strain curve behavior was similar in the CFRP repaired specimens B2.5-U-S and B2.5-L-S. This effect was mainly due to the presence of CFRP reinforcement. At ultimate load, specimens B2.5-U-S and B2.5-L-S measured a maximum strain of 1354 μ_ε and 2545 μ_ε, respectively at the mid span of tensile rebar.

7. STRAIN IN TRANSVERSE STIRRUPS STEEL BAR

This group was reinforced with 6 mm steel stirrups with 200 mm center to center. Figures 8 ,9 and 10 illustrate the applied load versus strain in stirrups for specimens B2.5-C, B2.5-U-S (precracked and repaired) and B2.5-L-S (precracked and repaird), respectively. These strain gauges were placed at the mid height of the steel stirrups. In control specimen B2.5-C, the strain gauge S2 obtained the maximum strain value over S1 and S3 due to the formation of diagonal crack across the stirrup. The maximum stirrup strain observed at strain gauge S3 was 6144 μ_ε. In the precraked phase for specimen B2.5-U-S, the strain recorded was 5 μ_ε at an ultimate load 36 kN in strain gauge S2. For specimen B2.5-L-S, the strain reached 220 μ_ε at an ultimate load 36 kN in strain gauge S2. After strengthening with CFRP strips, the strain for specimens B2.5-U-S and B2.5-L-S increased to maximum stirrup strain of 640 μ_ε (strain gauge S2) and 6321 μ_ε (strain gauge S2), respectively at the ultimate failure load. The specimen B2.5-L-S had higher strain than B2.5-U-S due to the orientation difference of CFRP strip.

8. STRAIN IN CFRP STRIPS AND CONCRETE SURFACE

Figures 11, 12 and 13 illustrate graphs of local strain distribution in CFRP and concrete strain for specimens B2.5-C, , B2.5-U-S and B2.5-L-S. For control beam B2.5-C, the strain at location C4 increased rapidly beyond the applied load 59.8 kN by the initiation of crack near the location of the strain gauge. The recorded maximum strain in concrete surface was 1133 μ_ε. In precracked/repaired phase, specimen B2.5-U-S and B2.5-L-S have recorded maximum strain of 3645 μ_ε (strain gauge F3) and 6231 μ_ε (strain gauge F3), respectively. The CFRP strain increased slowly until the beams reached a load close to 75.92 kN and 83.16 kN, respectively. Beyond this point, the CFRP fabric strain increased significantly until failure occurred due to initiation of diagonal shear crack. The strain value of specimen B2.5-U-S was less than the specimen B2.5- L-S due to the orientation difference of CFRP strip.

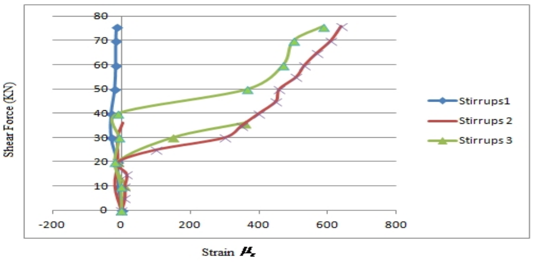

Figure 9. Load versus strain in steel stirrups for precracked/repaired specimen B2.5-U-S.

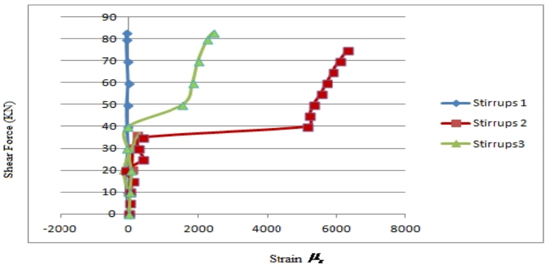

Figure 10. Load versus strain in steel stirrups for precracked/repaired specimen B2.5-L-S.

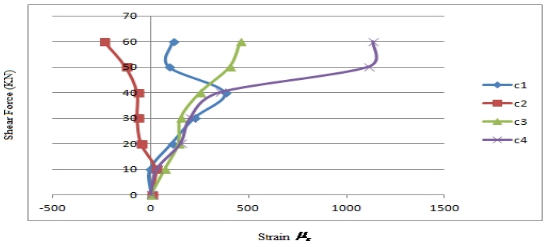

Figure 11. Load versus strain in the concrete surface for control beam C2.5-C.

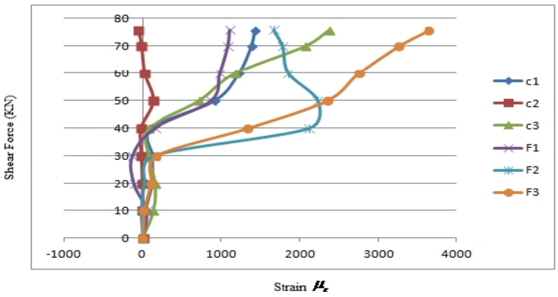

Figure 12. Load versus strain in CFRP strip and concrete surface for precracked/repaired specimen B2.5-U-S

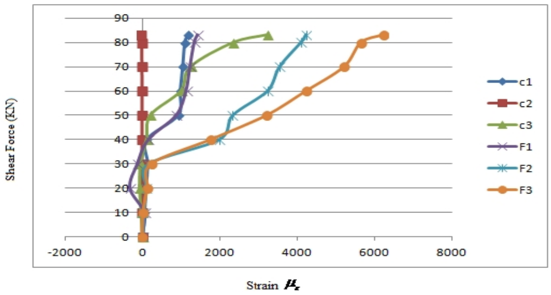

Figure 13. Load versus strain in CFRP strip and concrete surface for precracked/repaired specimen C2.5-LA-S.

9. CONCLUSION

The test results indicated that strengthening of RC continuous beams using externally bonded CFRP strips can be used to enhance the shear capacity of continuous T-beams. For beams tested in the experimental program, the shear capacity increased in a range from 26.57% and 38.56% over the control beam. It was also observed that increasing orientation of CFRP may not result in significant increase of the shear capacity.

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چکیده

ورقهای فیبر کربن تقویت شده پلیمری (CFRP) از بیرون به بتن تقویت شده (RC) متصل می شوند تا استحکام اضافی از قبیل استحکام خمشی و برشی را فراهم کنند. به طور گسترده ای پذیرفته شده است که فیبر کربن پلیمرهای تقویت شده (CFRPs) می تواند به طور موثری برای استحکام بخشیدن به بتن تقویت شده (RC) مورد استفاده قرار گیرند. این مقاله به مطالعه و استفاده از نوار CFRP متصل شده خارجی برای تعمیر و تقویت تیرهای T پیوستهRC و همچنین بررسی تاثیر مواد (CFRP) در تعمیر نقص برشی تیرهای T پیوسته RC پرداخته می شود. این نقص با استفاده از نوارهای CFRP مختلف تحت بار مداوم تعمیر خواهد شد. در مجموع سه تیر T پیوسته RC با اندازه های۳۶۰×۳۲۰×۱۵۰میلی متر، عرض بال ٤۰۰ میلی متر و ضخامت فلنج ۱۲۰ میلی متر و جهت گیری ۰ تا۹۰ درجه و ٤٥ تا ۱۳٥ درجه در ۳ طرف مورد استفاده قرار گرفت. همه تیرها تحت بار مداوم مورد آزمایش قرار گرفتند. نتایج بررسی ها حاکی از اثر بخشی و ظرفیت برشی نمونه تقویت شده CFRP بود. افزایش ظرفیت برشی تیرهای تقویت شده CFRP بین ۲٦/٥۷٪ و ۳۸/٥٦٪ بیش از تیر کنترل متفاوت بود. این مطالعه تایید می کند که روش نوار CFRP به طور قابل توجهی باعث افزایش ظرفیت برشی تیرهای برشی بتن تقویت شده می شود.

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