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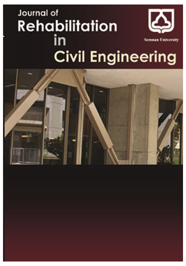

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Pre-Cracked Concrete Shear Strengthened with External CFRP Strips

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ABSTRACT

In reinforced concrete design, there are situations where transfer of shear across a specific plane needs to be considered. Examples of such situation include corbels, bearing shoes, ledger beam bearing, and a host of connection between precast concrete elements. In this study, the shear transfer behavior of reinforced concrete is investigated experimentally by conducting test on 6 precracked push-off specimens. The major parameters considered are the amount of reinforcement and externally bonded fiber reinforced polymer fabrics through the shear plane. External strengthening with Fiber Reinforced Polymer (FRP) fabrics is an effective technique for improving the structural performance and life span of the existing reinforced concrete structures. This paper illustrates the result of shear transfer capacity and modes of failure of the precracked reinforced concrete push-off specimens bonded externally with FRP. An experimental investigation was conducted to study the effectiveness of FRP as an external reinforcement. Based on experimental results, the external FRP reinforcement controls the shear slip along the shear plane and crack width. In the unstrengthened push-off specimens, the pre-existing crack along the shear plane will reduce the ultimate shear transfer capacity and increase of shear slip at all load levels. However in strengthened specimens, the external FRP reinforcement will control the increase of slip and increase the ultimate shear stress transfer capacity along the shear plane.

1. Introduction

The shear friction concept has physical applications in reinforced concrete connections such as corbels, coupled shear walls, wall to foundation connections, and cast-in-place concrete toppings where shear friction forces must be assured at the connection interface. In recent years, repair and new design techniques for strengthening reinforced concrete (RC) structures have been developed using fiber reinforced polymer (FRP) composites. The FRP composite materials are receiving acceptance because of their high strength to weight ratio, environmental resistance, and ease of application over materials such as steel.

Shear tests on uncracked push-off specimens for steel reinforced concrete were used to develop the "shear friction" hypothesis (Birkeland and Birkeland 1966). Initially cracked and uncracked steel reinforced concrete connections have been studied by many researchers including Hofbeck et al. (1969), Mattock and Hawkins (1972), Mattock et al. (1976), Walraven (1981), Hsu et al. (1987), and Hwang et al. (2000). The shear friction concept has also been studied for high-strength reinforced concrete (Mattock 2001; Kahn and Mitchell 2002). Shear connections for wall panels have been studied using push-off specimens, where evaluation of the shear friction coefficient factor was of interest (Foerster et al. 1989; Serrette et al. 1989). Fiber-reinforced concrete, where steel fibers, polypropylene, or other fibers are mixed with concrete, has also been studied and its shear friction properties determined (Allos 1989; Valle and Büyüköztürk 1993).

Dolan et al. (1998) used the Iosipescu test, adopted from *ASTM D5379*, to determine the shear friction strength of RC members with Carbon FRP (CFRP) composites; a design equation was proposed based on shear friction theory. It was found that shear friction is a function of shear plane area, concrete shear capacity, coefficient of friction, area of bonded CFRP laminate, and bond strength of CFRP laminate. Shear friction strength for concrete internally reinforced with glass FRP (GFRP) composite stirrups has been studied by Ibell and Burgoyne (1999); some plasticity was observed because of gradual delamination of the GFRP composite.

The CFRP composite strips are used herein to strengthen concrete externally at a known failure plane to resist shear stresses in shear friction. Six pre-cracked push-off specimens were tested with the following objectives: (1) determine the influence of internal reinforcement ratio; (2) investigate the influence of CFRP reinforcement ratio; and (3) understand the fundamental behavior of CFRP composite connections in shear friction. The shear friction strength of the initially cracked connections was found using experimental results, which combine the shear friction contribution of concrete, reinforcement and that of concrete–CFRP interaction.

2. Materials Properties

The average concrete compressive strength f_c' was 37 MPa. Mild steel reinforcement at the shear failure plane was used with an f_y =360 MPa. CFRP composite with an epoxy–resin matrix was used; the carbon fiber and epoxy–resin properties are described in Table 1.

3. Description of specimens

Push-off specimens were designed to fail in shear at a known plane, shear plane, as shown in Fig. 1.

The push-off specimens were grouped into two series. Group PCR and PCRC had three specimens each. In group PCR there was three specimens PCR1, PCR2 and PCR3 with internal steel reinforcement ratio ρ=1.54%, ρ=1.23% and ρ=0.92%, respectively. The internal reinforcement in series PCRC was same as series PCR. However, these specimens were precracked and strengthened externally with CFRP strips represented as PCRC1, PCRC2 and PCRC3 with CFRP reinforcement ratio ρ=0.35%, ρ=0.35% and ρ=0.35%, respectively (see table 2). Fig. 2. shows the typical push-off specimens in group PCR and PCRC.

The slip of one side of the specimens relative to the other was measured by two LVDTs was mounted vertically and six more LVDTs were mounted horizontally to measure crack width every three seconds during the tests (see Fig. 1(b)). The electrical strain gauges were also_attached on the internal steel stirrups and on the CFRP sheets to measure the strain in the steel bars and CFRP.

The shear stress was deduced from Eq. (1).

$$\tau = \frac{P}{34 \times 13} \tag{1}$$

Where P = axial compressive load; 34×13 = area of shear section.

Two push-off specimens were tested for each of the experiments to investigate repeatability.

Table 1. CFRP properties

Material	Tensile strength(Mpa)	Tensile modulus(GPa)	Tensile strain(mm/m)
carbon fiber	4760	240	15
Epoxy-resin	72	3.2	48
adhesive-epoxy primer	37	2.8	13

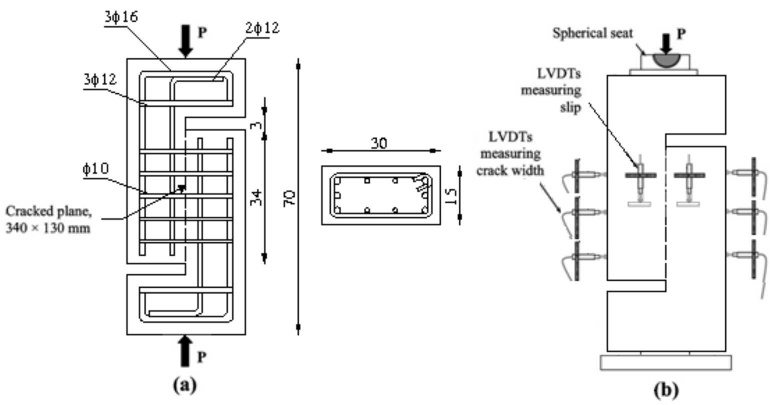

Fig. 1. Test specimens and setup: (a) dimensions and reinforcement details; (b) schematic of test setup.

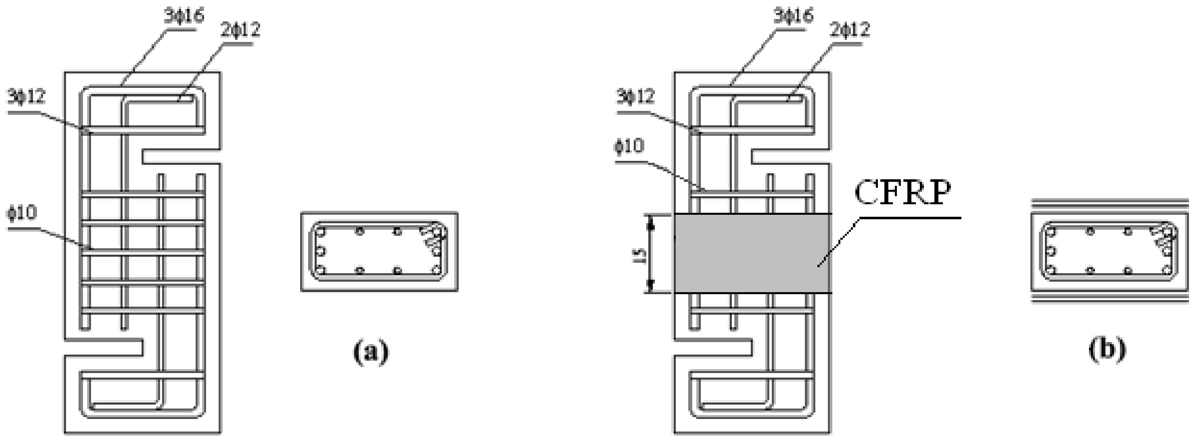

Fig. 2. Typical push-off specimens; (a) group R (b) group RC.

Table 2. Summary of push-off specimens

Push-off specimens	Internal reinforcement (%)	CFRP reinforcement (%)	Wrapping scheme configuration	Number of layers n	CFRP strip width w_f (mm)
PCR3	1.54	------	------	------	------
PCR2	1.23	------	------	------	------
PCR1	0.92	------	------	------	------
PCRC3	1.54	0.19	Two-sided	2	140
PCRC2	1.23	0.19	Two-sided	2	140
PCRC1	0.92	0.19	Two-sided	2	140

4. Test Set-up and Procedure of Push-off Specimens

All of specimens were initially cracked along the shear plane before testing. The experiments were conducted under an axial displacement controlled compressive load P where applied in the rate of 0.1 $^{mm}/_{sec}$, as shown in Fig. 1. To apply an axially concentric load, Steel caps were placed on the top and bottom side of the specimens to center the load as shown in Fig. 1. To prevent local compressive failure, gypsum was used inside the steel caps. The load was increased until failure occurred. Fig. 1(b) and 3 shows the experimental setup of specimens.

5. Discussion of results

5.1. Ultimate Failure Load and Failure Pattern

Specimens PCR1 and PCRC1 had similar amount of internal shear reinforcement ratio of ρ=0.92%, and their area of shear plane was 340 mm x 130 mm. The ultimate failure load of the unstrengthened push-off specimen PCR1 was 216 kN and its corresponding shear stress was 4.88 MPa. The shear failure had occurred along the V-grooves of shear plane. However, in the case of specimen PCRC1 was failed due to debonding of CFRP sheets along the shear plane at a maximum load of 232.2 kN. At ultimate, the achieved shear stress of the strengthened specimen was 5.25MPa. The shear stress increment was 7.15% higher than the unstrengthened specimen PCR1, The reason was due the contributions external CFRP reinforcement. It was also observed that a yielding of reinforcement in the steel stirrups at peak load before the failure of external CFRP reinforcement.

In specimens PCR2 and PCRC2, the amount of internal shear reinforcement ratio was ρ=1.23%. The unstrengthened specimen PCR2 had attained a maximum load of 256 kN with a corresponding shear stress of 5.79 MPa. The strengthened specimen PCRC2 was failed with a CFRP debonding mode of failure along the shear plane at an ultimate load of 271.5 kN; related to a shear stress of 6.14 MPa. The shear stress enhancement was increased 6.05% with respect to the specimen PCR2.

The internal shear reinforcement of specimens PCR3 and PCRC3 were ρ=1.54%. The specimen PCR3 failed at a peak load of 295.5 kN with a shear stress of 6.69 MPa. All the unstrengthened specimens PCR1, PCR2 and PCR3 failed along the shear plane or the V-grooves on the front and rear sides. The externally strengthened specimen PCRC3 was failed at the ultimate load of 311 kN with a corresponding shear stress of 7.04 MPa. There was an enhancement of 5.24% with respect to the unstrengthened push-off specimen PCR3. At ultimate failure, the specimen PCRC3 had yielding of internal steel stirrups similar to specimen PCRC2 and failed in debonding of CFRP sheets. Crushing of concrete was observed at bottom of the shear plane before it reached the failure load. Fig. 4 shows the debonding failure pattern of the strengthened push-off specimen PCRC3. From the investigation, it was found that the increased amount of internal shear reinforcement in the strengthened push-off specimens reduced the contribution of shear enhancement by the external CFRP reinforcement. The ultimate failure load was found to be increased with increase in amount of internal shear reinforcement. Table 3 illustrates the summary of experimental investigation of the unstrengthened and strengthened push-off specimens.

Table 3. Summary of push-off specimens

Push-off specimens	Concrete strength f'_c (Mpa)	Shear stress (Mpa)	Failure load Pu (kN)	Increment(%)
PCR3	37	6.69	295.5	---------
PCR2	37	5.79	256.0	---------
PCR1	37	4.88	216.6	---------
PCRC3	37	7.04	311.0	5.24
PCRC2	37	6.14	271.5	6.05
PCRC1	37	5.25	232.2	7.15

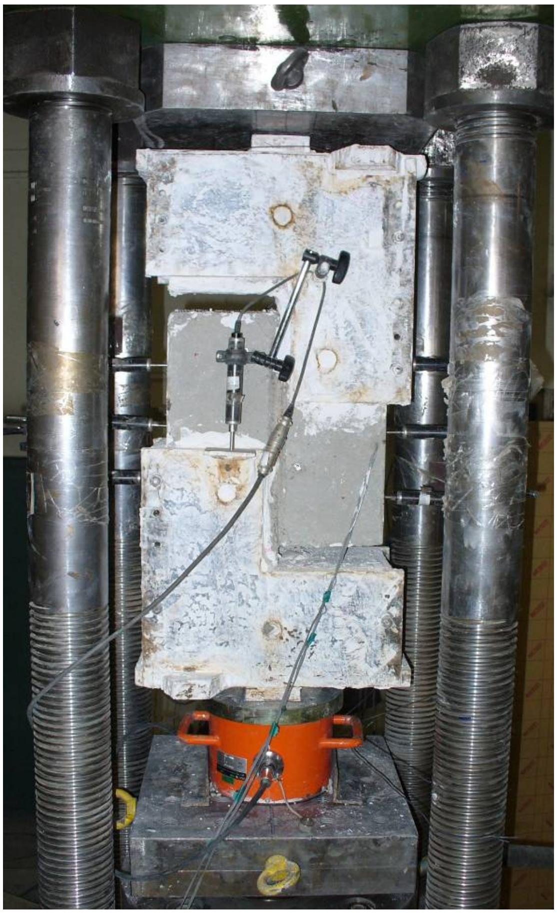

Fig.3. Experimental setup of specimens.

Fig. 4. Debonding failure pattern of the strengthened push-off specimen PCRC3.

5.2. Shear Stress-Shear Displacement and Crack width Relationship

Fig. 5. describes the shear stress related to shear displacement of the strengthened and unstrengthened push-off specimens. The test results indicate that the strengthened push-off specimens have measured significantly lesser shear displacement at each increment of load than the unstrengthened push-off specimens. But there was a sudden increase in shear slip at the peak load in the strengthened push-off specimens as a result of the fact that the FRP composites have brittle manner. The failure of the strengthened push-off specimens occurred with a loud noise. The stiffness of the strengthened push-off specimens was greater than the unstrengthened one. The direct shear test of the unstrengthened push-off specimens shows that shear stress increases with increase of internal shear reinforcement ratio. However in externally bonded push-off specimens, the contribution of CFRP sheet decreases with an increase in the amount of internal shear reinforcement ratio.

The shear stress in contrast to crack width of the strengthened and unstrengthened push-off specimens is shown in Fig. 6. One can see from the Fig. 6, the crack width of the strengthened push-off specimens was relatively less in comparison to the unstrengthened push-off specimens. It was observed that the reinforced concrete specimens with large initial crack width were lower in stiffness than specimens with smaller initial crack width. Increased shear stress increases the shear displacement and crack width in the unstrengthened push-off specimens but in strengthened push-off specimens the increase of displacement level was relatively very less in comparison to the unstrengthened push-off specimens for the same load. It shows that the external bonded CFRP sheets control the slip along the shear plane and it also prevents the widening of crack. It was also remarkable that the strengthened push-off specimens showed greater value of shear displacement and crack width at failure load than unstrengthened push-off specimens. Test results indicate that an increase in reinforcement parameter stiffens the initial straight portion of the curve, raises the linear response to a higher load level, and increases the ultimate strength and deformation. Fig. 5. indicates the ductile nature of the shear deformation due to the combined effect of dowel action by the transverse steel reinforcing bars and the interlocking of aggregates across the crack.

6. Experimental Design Relationship

Experimental results showed that the specimen fails in two successive stages: (1) the shear stress is controlled by the concrete alone until the concrete shear friction capacity is reached; and (2)

the additional imposed shear stress is resisted by the internal reinforcement and CFRP composite acting as a clamping force, which induces additional aggregate interlock until cohesive concrete failure and bond failure of the CFRP strips.

A simple model is proposed to calculate the ultimate shear strength resisted by the specimen

$$v_u = v_{con} + v_{bar} + v_{cfrp} \qquad (2)$$

where v_{con}=concrete shear friction strength; v_{bar}=reinforcement shear friction strength; and v_{cfrp}=shear friction strength contributed by concrete–CFRP interaction.

$$v_u = 0.117 f_c' + 0.8 \rho_{bar} f_y + \mu \rho_f f_{fu}^* \quad (3)$$

The first term in Eq. (3) is the concrete shear friction strength, where 0.117 is the component for bond and asperity shear as proposed by Mattock (2001) and Kahn and Mitchell (2002). The second term in Eq. (3) is the reinforcement shear friction strength, where 0.8 is proposed by ACI. The third term in Eq. (3) is the shear friction strength contributed by concrete–CFRP interaction v_{cfrp}; the shear friction interaction coefficient (μ) must be less than 0.8, and $\rho_f f_{fu}^*$, is the effective CFRP composite tensile stress, which is the clamping stress provided by the CFRP composite.

Eq. (3) is similar to the models by Birkeland and Birkeland (1966), Hofbeck et al. (1969), Mattock and Hawkins (1972), Mattock (2001), and Kahn and Mitchell (2002); however, in those studies shear friction in steel reinforced concrete was studied, which includes the effect of aggregate interlock, shear resistance provided by shear reinforcement, and dowel action. The shear friction expression for steel reinforced concrete proposed by Mattock (2001) is

$$v_u = 0.1 f_c' + 0.8 \rho_{bar} f_y \quad (4)$$

the first term is the component for bond and asperity shear, which is similar to Eq. (3).The second term in Eq. (4) is equivalent to the second term in Eq. (3), which implies that concrete–CFRP reinforcement shear friction interaction depends on the type and amount of reinforcement material; For externally bonded CFRP composite strips, the concrete–CFRP shear friction interaction coefficient of Eq. (3) is lower than that proposed by Mattock et al. (1976) and Mattock (2001) for internal steel reinforcement (0.8) of Eq. (4); when cohesive concrete capacity is exceeded, bond failure of the CFRP occurs. The cohesive concrete capacity cannot increase beyond a certain limit; this is the fundamental difference between internal and adhesively applied external reinforcement, where internal reinforcement can achieve the full tensile strength.

7. Conclusions

Test results of push-off pre-cracked specimens investigating the shear capacity, with variable reinforcement parameter, are reported. The contribution of the CFRP reduces with increased amount of internal shear reinforcement ratio. The external CFRP reinforcement had controlled the shear slip along the shear plane and crack width. In the unstrengthened push-off specimens, the pre-existing crack along the shear plane will reduce the ultimate shear transfer capacity and increase of shear slip at all load levels (Hofbeck et al., 1969). However in strengthened specimens, the external CFRP reinforcement will control the increase of slip and increase the ultimate shear stress transfer capacity along the shear plane. The shear displacement and normal displacement or crack width of the strengthened specimens was less compared to the unstrengthened specimens for the same load, however, the strengthened specimens had achieved greater shear and normal displacement over the unstrengthened push-off specimens at the ultimate failure load. There was a sudden increase of shear displacement and crack width at the peak load. After debonding of CFRP sudden drop of shear stress occurs. The stiffness of the strengthened specimens was greater than the unstrengthened push-off specimens. The shear stress increase of the strengthened push-off specimens varies in the range of 5% to 8% with respect to the unstrengthened push-off specimens.

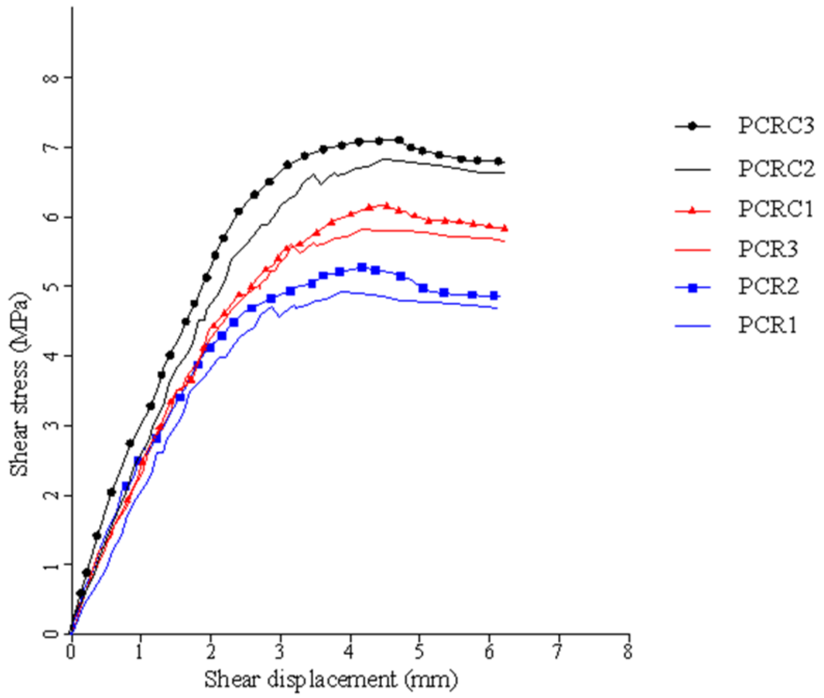

Fig. 5. Shear stress in contrast to shear displacement for series PCR and PCRC

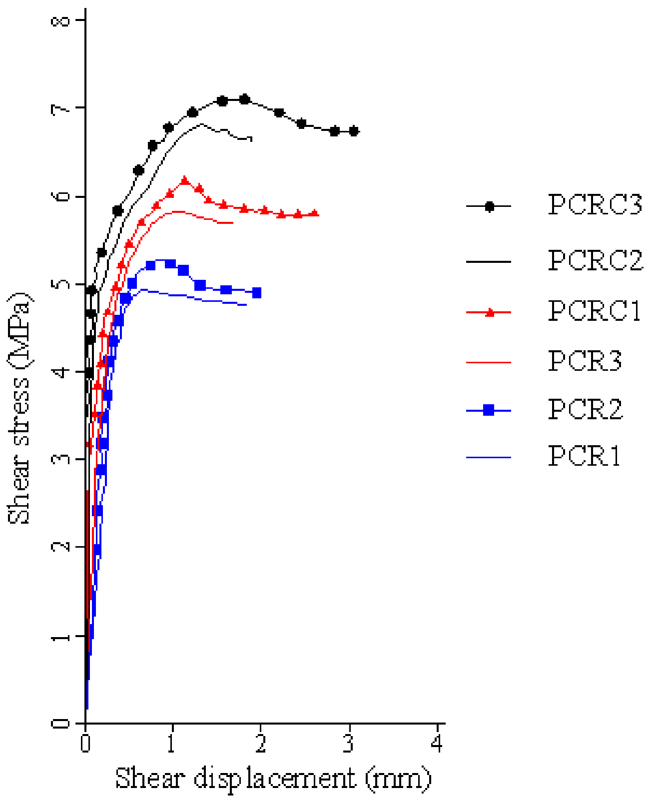

Fig. 6. Shear stress in contrast to crack width for series PCR and PCRC

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