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Assessment of shear transfer capacity of non-cracked concrete strengthened with external GFRP strips

Rahele Naserian [*], Abdollah Hosseini, Mohammad Sadegh Marefat

School of Civil Engineering, College of Engineering, University of Tehran, P.O. Box 1417613131, Tehran, Iran

HIGHLIGHTS

- Shear tests were carried out on 16 non-cracked push-off specimens.
- We investigate the interaction of internal steel reinforcement and external FRP composites.
- Strengthening with FRP strips increases the shear transfer capacity.
- The effectiveness of FRP composites is declined by increasing internal reinforcement.
- We describe the characteristic behavior of strengthened specimens.

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ABSTRACT

To investigate the interaction of internal steel reinforcement and external fiber reinforced polymer (FRP) composites on the behavior of shear transfer, 16 non-cracked push-off specimens were tested. Specimens were internally reinforced with steel reinforcement ratios between zero and 1.54% and externally strengthened with different widths of Glass FRP layers. In strengthened specimens, shear transfer capacity increased from 3% to 38% compared to plain specimens. The contribution of FRP reinforcement in shear transfer capacity, as the percentage of cylindrical concrete strength (f'_c), was between $0.6\%f'_c$ and $3.7\%f'_c$. Based on the results, the characteristic behavior of strengthened specimens is described.

1. Introduction

In many situations the quantity of required external reinforcement has to be determined to transfer a specific shear stress across a known shear plane. This known shear plane can be the interface of two concrete surfaces that is susceptible to cracking, such as the interface between two concrete surfaces cast at different times.

This subject has been studied by many researchers. Birkeland and Birkeland [1] used the non-cracked push-off specimens to develop a shear friction hypothesis. The effect of a pre-existing crack along the shear plane was studied by Hofbeck et al. [2]. This crack reduces the shear transfer capacity and increases shear slip at all load levels. Mattock and Hawkins [3] showed that the shear transfer across a known plane in non-cracked concrete is accompanied by formation of diagonal tension cracks in direction inclined to the shear plane. Increasing shear load makes a truss-like action and the formed struts tend to rotate and consequently stress the shear reinforcement. Finally, the failure occurs with the crushing of the formed concrete struts parallel to the cracks. Also, the shear transfer of the steel reinforced concrete has been studied by researchers [4–7]. The shear strength of concrete could be enhanced by using discrete fibers in the concrete mixture [8–10]. The effect of high strength concrete on the shear transfer capacity has been studied widely [11,12].

External strengthening with FRP composites is an effective technique which improves structural performance of the existing concrete structures. Saenz et al. [13,14] studied the effects of external Carbon FRP (CFRP) strips on the shear friction capacity of non-cracked push-off specimens.

Tests in order to evaluate the effect of the near surface mounted (NSM) steel and CFRP plates on the shear friction capacity were done by Mohamed et al. [15]. Results showed that NSM FRP specimens behave in a ductile fashion, in contrast with externally bonded FRP and steel specimens. Mansur et al. [16] investigated the effects of concrete strength and reinforcement parameter on the shear transfer behavior of pre-cracked concrete with internal

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[*] Corresponding author. Tel.: +98 9134502321.
E-mail addresses: rahi.naserian@gmail.com (R. Naserian), Hossiniaby@ut.ac.ir (A. Hosseini), mmarefat@ut.ac.ir (M.S. Marefat).

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steel reinforcement. Rahal [17] showed that the Simplified Model for Combined Stress (SMCS) is an appropriate method for shear transfer problems.

Due to the relatively lower cost of Glass FRP (GFRP) strips compared to other available FRP materials, the use of GFRP strips in reinforced concrete structures has been recently studied.

In this study, non-cracked push-off specimens were tested to investigate:

(1) The influence of GFRP reinforcement ratios on the shear transfer capacity.
(2) The characteristic behavior of non-cracked push-off specimens with FRP strengthening.
(3) External and internal reinforcement interaction on the shear transfer capacity.

2. Experimental program

In this study, 16 non-cracked push-off specimens were tested. The variables were internal and external reinforcement ratio ρ_v and ρ_f, respectively, to investigate the interaction of internal and external reinforcement. Specimens were divided in two groups as shown in Table 1, internally reinforced (R) and unreinforced (U). The R group was divided into three subgroups, designated by L, M and H, indicating Low (three stirrups crossing the shear plane), Medium (four stirrups crossing the shear plane) and High (five stirrups crossing the shear plane) ranges of internal reinforcement. The U group and each of the R subgroups consist of plain (P) (without external strengthening) and strengthened (S) specimens.

The width of GFRP strips crossing the shear plane were variable, indicating low (l), medium (m) and high (h) ranges of GFRP reinforcement ratio.

Fig. 1 shows dimensions, steel reinforcement and GFRP strengthening of specimens. Dimensions of all specimens were constant and the shear plane was 340 mm × 150 mm.

2.1. Materials

In this study, the specimens were all cast in one batch. Three concrete cylinders were cast from the same batch as the specimens were tested at the time of the push-off test. The average concrete compressive strength (f'_c) was 34.5 MPa. Stirrups crossing the shear plane included 10 mm diameter steel deformed bars with yield strength (f_y) of 360 MPa.

In order to strengthen the specimens with FRP strips, these steps were followed. The epoxy system consisted of resin and hardener mixed in a ratio of 2:1, respectively. This was thoroughly hand-mixed for at least five minutes. The concrete surfaces of specimens were cleaned and completely dried before Nithomortar coating was applied to them. The Nithomortar coating was used to fill blow holes, prevent absorption of resins by concrete and inhibit irregularities prior to the application of subsequent coatings. A thin layer of epoxy was applied to the Nithomortar surface. Then GFRP strips were bonded on the two opposite faces of the specimens.

The properties of GFRP strips and the resin epoxy system are described in Table 2.

2.2. Test setup and instrumentation

The tests on non-cracked specimens were done using a hydraulic jack with a capacity of 3000 kN. The axial compressive load was applied to the specimens with the rate of 1 mm/min. Steel caps, on the top and bottom of the specimens, are shown in Fig. 2. These caps were used to prevent compressive stress concentration and local failure of the specimens. Specimens were subjected to a displacement controlled loading.

The relative slip of the shear plane was measured by two LVDTs installed on each side of the specimens between two points in opposite sides of the shear plane. Six LVDTs were seated horizontally to measure the lateral separation of the shear plane or crack widths after concrete cracking. Two strain gages were bonded to the steel stirrups and two others bonded to FRP strips horizontally at the intersection with the shear plane. The position of LVDTs and strain gages are shown in Fig. 3. The displacements, strains and force were automatically recorded at every three seconds by data logger.

3. Experimental results

3.1. U group

For the plain specimen, maximum shear stress (v_u) was 4.1 MPa at 1 mm slip. The specimen rapidly broke into two pieces and the failure mechanism was very brittle.

For the strengthened specimens, maximum shear stress ranged from 4.5 to 5.0 MPa, an increase of 13–38% compared to the plain specimen. The shear stress- slip curves of the specimens are shown in Fig. 4a. The curve of the UP Specimen was linear up to failure. For the strengthened specimens, the curves were similar to that of the UP Specimen, up to concrete cracking. Also, as shown in Fig. 4b, the strips strain was negligible before cracking. The cracking of concrete was in accordance with change of the slope of the shear stress-slip curve which is due to decreasing of specimens' stiffness. After cracking, the GFRP strips were strained to bond failure. The UP and USl specimens after failure are shown in Fig. 5. The debonding strain of GFRP strips (ε_{fe}) ranged from 6671 to 7260 microstrain which is about 30–33% of the ultimate strain of the GFRP strip (ε_{fu} = 22000 microstrain).

Table 1
Details of push-off specimens.

Push-off specimens	Number of stirrups	Width of strip (mm)	Internal reinforcement ratio ρ_v (%)	FRP ratio ρ_f (%)
U group: Internally unreinforced				
UP	0	0	0	0.0
USl	0	140	0	0.16
USm	0	240	0	0.28
USh[a]	0	240	0	0.57
R group: Internally reinforced				
L subgroup: three stirrups crossing the shear plane				
RLP	3	0	0.92	0.0
RLSl	3	90	0.92	0.1
RLSm	3	140	0.92	0.16
RLSh	3	240	0.92	0.28
M subgroup: four stirrups crossing the shear plane				
RMP	4	0	1.23	0.0
RMSl	4	90	1.23	0.1
RMSm	4	140	1.23	0.16
RMSh	4	240	1.23	0.28
H subgroup: five stirrups crossing the shear plane				
RHP	5	0	1.54	0.0
RHSl	5	90	1.54	0.1
RHSm	5	140	1.54	0.16
RHSh	5	240	1.54	0.28

[a] Two FRP layers bonded on one face of the specimen.