Effect of Cyclic Loading on Punching Shear Strength of Slabs Strengthened with Carbon Fiber Polymer Sheets

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Abstract: *In this paper, the effect of cyclic loading on punching strength of flat slabs strengthened with Carbon Fiber Reinforced Polymer (CFRP) sheets is studied. Experimental results of ten slab specimens under monotonic and cyclic loading are analyzed. Eight specimens were strengthened with CFRP sheets on the tensile face of the slabs and the two other specimens were kept un-strengthened as control specimens. The width of CFRP sheets varied in different specimens. After the tests, the punching shear strength of specimens under cyclic loading was compared with those with monotonic loading. The comparison of results shows that cyclic loading decreases the effect of CFRP sheets on punching shear strengthening. This decrease was more for the specimens with a larger value of reinforcing steel ratio. Therefore, it can be concluded that for specimens with large reinforcing steel ratios, cyclic loading may completely eliminate the effect of CFRP sheets on shear strengthening of slabs.*

Keywords: *cyclic loading, flat slab, CFRP sheet, punching shear, strengthening*

1. Introduction

The slab–column connection of a flat plate is susceptible to punching shear failure. Once punching shear failure occurs, the overall resistance of the structure against gravity load is considerably reduced, which causes the separation of the slab and column, and might even cause progressive collapse of the whole structure.

Currently, there are various existing strength models for slab–column connections including ACI 318 [1], EC 2 [2], CEB-FIP MC 90 [3], and BS 8110 [4]. These existing models were developed for normal concrete slab–column connections, thus they might not be applicable to the strengthened slab–column connections.

The classical strengthening techniques for concrete slab-column connections, in order to prevent sudden punching shear failure, include use of steel plates and bolts, transverse pre-stressed reinforcement, the use of an epoxy bonding steel plate, and thickening of the upper concrete surface or use a large column cross section [5], [6] and [7]. Some of these strengthening methods do provide enough additional strength to the slabs. However, they are elaborate, difficult to install, expensive and aesthetically not pleasing. Strengthening slabs with FRP is simple, does not require excessive labor and does not change the architectural appearance of the slab.

Increasing attention has been placed to the application of advanced composite materials especially carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) in the structural engineering field. There is a wide range of recent, current, and potential applications of these materials that cover both new and existing structures. Some research works dealt with the strengthening of one-way slabs using FRP materials in which slabs were treated in a very similar way to beams [8]. Limited research work has been conducted on the strengthening of concrete two-way slabs using FRP materials. Recently, some experimental and analytical studies have been conducted to propose methods for strengthening flat slabs with FRP sheets against punching failure [9, 10 and11]. It has been shown that a simple and effective method for strengthening of slabs against punching failure is to use FRP sheets as flexural reinforcement [10 and 11]. According to previous studies and BS 8110 Code [4], flexural reinforcing bars increase the punching shear strength. By applying FRP sheets on the tension side of slabs, the flexural strength of slabs and thus the punching shear strength

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increase. Chen and Li [11] used Glass Fiber-Reinforced Polymer Laminates for shear strengthening of slabs. They showed that flexural strengthening of slabs by GFRP laminates can increase the punching strength, significantly. However, GFRP laminated were more effective for the slabs with low steel reinforcement ratios. Based on an analytical method, Chen and Li [11] proposed equations to calculate the punching strength of slabs strengthened with GFRP laminates. In the equations, they introduced two parameters of equivalent reinforcement ratio ρ_{eqv} and equivalent depth d_{eqv} for slabs.

Another problem dealing with punching failure is the effect of cyclic loading. According to the theories of fracture mechanics, cyclic loading causes the progress of cracks and thus reduction of residual strength of a cracked body. For semi-brittle materials such as concrete, different toughening mechanisms in the fracture process zone, ahead of a crack tip, absorb part of the released energy of the cracked body. These toughening mechanisms are vulnerable to cyclic loading. Also, the debonding process between concrete and FRP sheets may be enhanced by cyclic loading. Vertical live and earthquake loads that apply cyclic loading on slabs may decrease the efficiency of punching shear strengthening with FRP sheets. Most previous experimental studies have been carried out using monotonic loading. This research investigates the effect cyclic loading on punching shear strength of slabs.

2. Proposed equations

According to some codes such as BS 8810 [4] and JSCE [12], the tensile reinforcement of slabs increases the punching shear strength. BS 8810 [4] proposes Equation 1 for punching shear strength as follows:

$$V_u = 0.79\sqrt[3]{100\rho_s}\sqrt[4]{\frac{400}{d}}\sqrt[3]{\frac{f_{cu}}{25}}Ud \qquad (1)$$

Where U is the rectangular critical perimeter at distance 1.5d from the face of a column, U = 4(c+3d), f_{cu} is the cube compressive strength of concrete limited to 40 MPa and ρ_s is the reinforcement ratio limited to 0.03. The maximum value of $\sqrt[4]{\frac{400}{d}}$ is 1.0. As seen in Eq.1, the punching strength of slabs increases with the reinforcement ratio of ρ_s. For the case of strengthened slabs, the reinforcement ratio of FRP sheet should be added to ρ_s. To include the value of reinforcement ratio of FRP sheet in Eq.1, Chen and Li [11] proposed an equivalent reinforcement ratio ρ_{eqv}, that should be replaced for ρ_s in Eq.1, as follows:

$$\rho_{eqv} = \frac{T_s + T_f}{bd_{eqv}f_s} \qquad (2)$$

In Eq. 2, the equivalent depth ratio of d_{eqv} is given by:

$$d_{eqv} = \frac{M_{nf}}{T_s + T_f} + \frac{a}{2} \qquad (3)$$

where *a* is the depth of rectangular stress block, T_s and T_f are the tensile forces in the steel reinforcement and FRP sheet, respectively, f_s is the stress in the steel reinforcement and M_{nf} is the flexural strength of strengthened reinforced concrete slabs calculated by:

$$M_{nf} = C_c\left(d - \frac{a}{2}\right) + T_f(h-d) \qquad (4)$$

where C_c is the compressive force in concrete rectangular block and h is the overall thickness of the slab. It should be noted that the proposed equation by ACI 318 Code [1] does not include the reinforcement ratio of tensile reinforcement rs. According to ACI Code, the punching shear strength is taken as the smallest of the following equations:

$$V_u = 0.083\left(2 + \frac{4}{\beta_c}\right)\sqrt{f_c'}b_0 d \qquad (5)$$

$$V_u = 0.083\left(2 + \frac{\alpha_s d}{b_0}\right)\sqrt{f_c'}b_0 d \qquad (6)$$

$$V_u = 0.083 \times 4\sqrt{f_c'}b_0 d \qquad (7)$$

where b_0 is the rectangular critical perimeter at a distance of 0.5d from the face of a column, that is 4(c+d), β_c is the ratio of long side over short side of the column, and α_s is 40, 30 and 20 for interior, edge and corner columns, respectively.

The Iranian Code ABA [13] proposes equations similar to the equations 5-7 for punching shear strength. According to ABA Code [13] punching shear strength is taken as the smallest of the following equations:

$$V_c = \left(1 + \frac{2}{\beta_c}\right) v_c b_0 d \quad (8)$$

$$V_c = \left(1 + \frac{\alpha_s d}{b_0}\right) v_c b_0 d \quad (9)$$

$$V_c = 2 v_c b_0 d \quad (10)$$

In equations 8-10, α_s is 20, 15 and 10 for interior, edge and corner columns, respectively. The shear strength of concrete v_c (in Eq. 10) is given by:

$$v_c = 0.2\phi_c \sqrt{f_c} \quad (11)$$

where $\phi_c = 0.6$ is the strength safety factor of concrete and f_c is the compressive strength of concrete. The load factors used by ABA Code [13] are different with those used by ACI Code. The comparison between the equations 5-7 with the equations 8-11 shows that, in fact, the punching shear strength values predicted by the two codes, ABA [13] and ACI [1], are almost the same.

3. Experimental study

3.1 Materials

For the slab specimens, the design compressive strength of 25 MPa for concrete was used. For each series of casting, the specified compressive strength was measured by testing of five concrete cylinders.

Two sizes of reinforcing bars, 12 and 16 mm were used in specimens. For each bar size, three samples were tested under tension. The yield strengths of the steel bars were 493.7 MPa and 483.4 MPa, respectively.

CFRP sheets were used for strengthening of slabs. Mechanical properties of CFRP sheets were measured according to ASTM D3039 Standard [14]. The carbon fiber sheets were cured saturated in resin for one week. Then, the samples were prepared according to ASTM D3039 and tested in tension. Table 1 presents the mechanical properties of CFRP sheets. The adhesive used for applying the CFRP sheet on the concrete surface was hand-mixed epoxy.

3.2 Test Specimens

Ten slab specimens with the dimensions of 1000×1000 ×100 mm were manufactured. The reinforcing bar ratios rs in slabs were approximately 0.84 and 1.59 percent in different specimens. The test specimens were simply supported along the four edges with corners free to lift and were centrally loaded through the column stub with a 150 mm side length and 150 mm height. The dimensions and the details of reinforcement of specimens are shown in Fig.1. Two un-strengthened specimens were used as reference specimens. These specimens are R0.8-C25-F0 and R1.6-C25-F0 with reinforcement ratio of 0.84% and 1.59%, respectively. Other specimens were tested after strengthening with CFRP sheet. From 8 strengthened specimens, 4 specimens were tested under cyclic loading. Fig.1 shows the position of CFRP sheets on the tension face of a slab specimen. Prior to applying the adhesive, the CFRP sheet was cut to length, and the bottom sides of the slabs were prepared by removing any concrete surface irregularities and loose particles in order to make it a smooth surface. The adhesive was applied evenly on the

Table 1 Mechanical Properties of CFRP sheet

	Layer Thickness	Ultimate Strain	Tensile Strength	Modulus of Elasticity
Test	0.117 mm	0.0120	2845 MPa	237 GPa
According to Manufacturer	0.117 mm	0.0155	3800 MPa	240 GPa

concrete surface using a brush. The CFRP sheet was then smoothly hand-laid to achieve a wrinkle-free surface. The air between concrete surface and CFRP sheet was removed using a plastic roller. Finally, a layer of adhesive was applied on CFRP sheet for better adhesion. The considered adhesive curing time was at least one week, according to the manufacturer's instructions. Testing of the first specimen started after one week. The details of specimens including the width of CFRP sheets are summarized in Table 2.

3.3 Test Setup and test procedure

The test specimens were simply supported along the four edges using a large reaction steel frame and tested using a hydraulic jack. The deflection of the specimens at the center of the tension side of slabs was measured using a LVDT. An electric pressure transducer was used to measure the applied load. The output data were recorded using a computer data acquisition system. Fig.2 shows the test setup.

Specimens under monotonic loading were loaded by the hydraulic jack until failure. The duration time of each of these tests was about 15 minutes. For the case of specimens under cyclic loading, however, an initial of approximately 30% of the predicted ultimate strength of slabs was applied. Then, the specimens were loaded cyclically until failure. Cyclic loading was applied on specimens with increments of about 3000N as seen in figures 3-6. The initial load on these specimens represents the dead load on slabs since it exists before any cyclic loading due to live or earthquake loads.

4. Test results

Figures 3-6 show the load versus displacement relationships for different specimens under cyclic

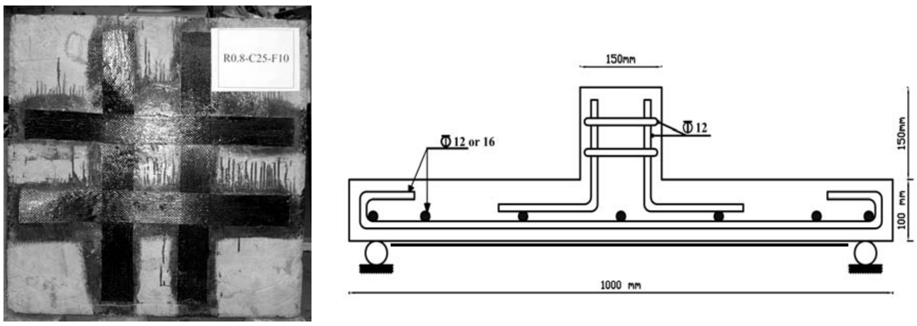


Fig.1 Details of specimens and CFRP position on slab

Table 2 Details of specimens

Specimen*	CFRP width (mm)	$f_c'(MPa)$	ρ_s %	$\frac{\rho_{eqv}}{\rho_s}$ **
R0.8-C25-F0	-	23	0.84	1.00
R0.8-C25-F10	100	23	0.84	1.14
R0.8-C25-F10-CL	100	23	0.84	1.14
R0.8-C25-F15	150	23	0.84	1.17
R0.8-C25-F15-CL	150	23	0.84	1.17
R1.6-C25-F0	-	23	1.59	1.00
R1.6-C25-F15	150	23	1.59	1.05
R1.6-C25-F15-CL	150	23	1.59	1.05
R1.6-C25-F30	300	23	1.59	1.10
R1.6-C25-F30-CL	300	23	1.59	1.10

* R0.8 and R1.6 show the approximate reinforcing steel ratio in percent, C25 stands for design strength of concrete in MPa, F0, F10, F15 and F30 show the width of CFRP sheets in cm, and CL stands for Cyclic Loading.

** ρ_{eqv} is the equivalent reinforcement ratio given by Eq.2.

loading. Peak load envelop of load versus displacement relationship for different tests under cyclic loading are shown in figures 7 and 8. Figures 7 and 8 also show the results of tests under monotonic loading.

5. Analysis of Test Results

As shown in figures 7a and b, cyclic loading decreased the enhancement of punching shear strength of slabs due to strengthening with CFRP sheets. This decrease was approximately 11.5% for specimens R0.8-C25-F10-CL and R0.8-C25-F15-CL compared to the specimens R0.8-C25-F10, R0.8-C25-F15 under monotonic loading. As seen in different load versus displacement relationships, the stiffness of slabs under cyclic loading was also decreased compared to those with monotonic loading. However, even for cyclic loading, strengthening of slabs with CFRP sheets increased the punching shear strength, significantly. In specimens with low reinforcing steel ratio ρ=0.84% (figures 7a, b), the increased values of punching strength due to CFRP strengthening for cyclic loading were 1.25 and 1.36 for specimens R0.8-C25-F10-CL and R0.8-C25-F15-CL, respectively. For monotonic loading, these values were 1.39 and 1.52 for specimens R0.8-C25-F10 and R0.8-C25-F10, respectively.

For the specimens with large reinforcing steel ratio ρ=1.59%, different results were achieved compared to the specimens with low reinforcing steel ratio ρ=0.84%. For these specimens (specimens R1.6-C25-F15-CL and R1.6-C25-F30-CL in figures 8a and b), cyclic loading

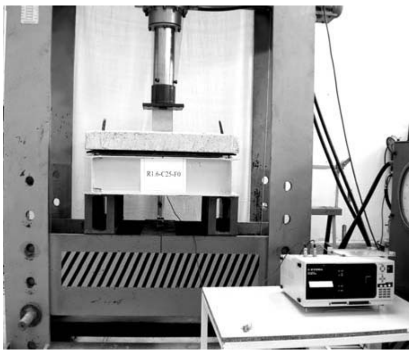


Fig.2 Test setup

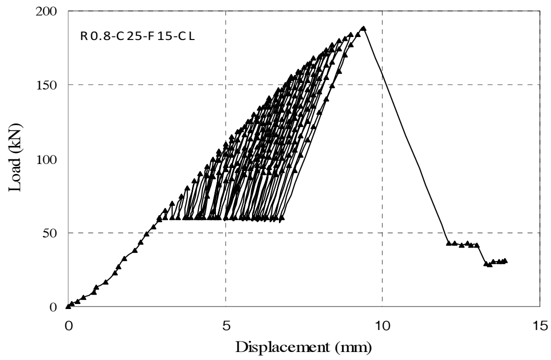


Fig. 4 Load versus Displacement Relationship for specimen R0.8-C25-F15-CL

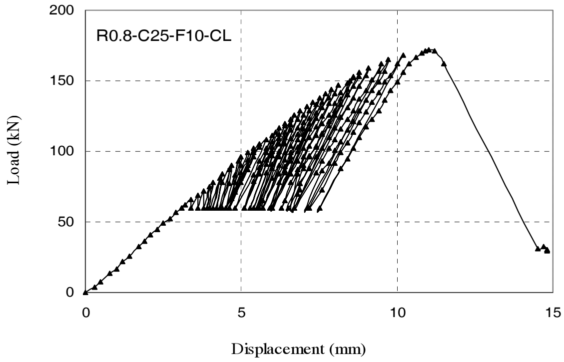


Fig. 3 Load versus Displacement Relationship for specimen R0.8-C25-F10-CL

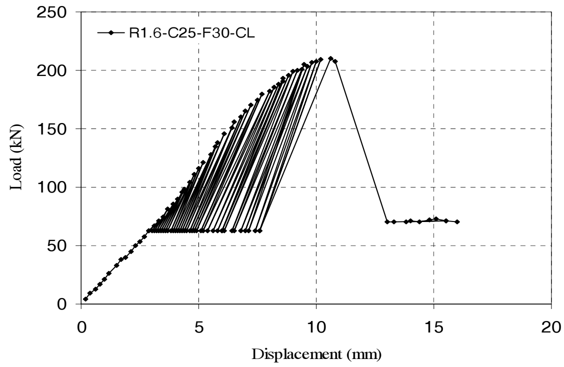


Fig. 5 Load versus Displacement Relationship for specimen R1.6-C25-F15-CL

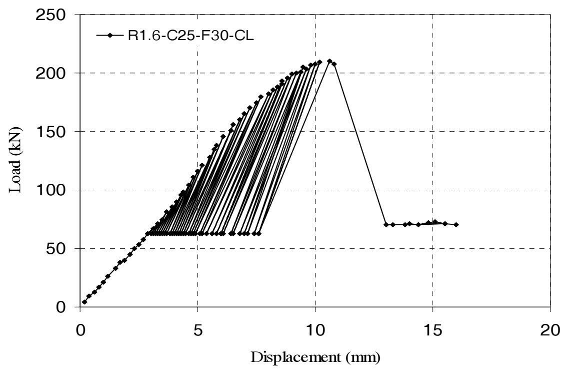
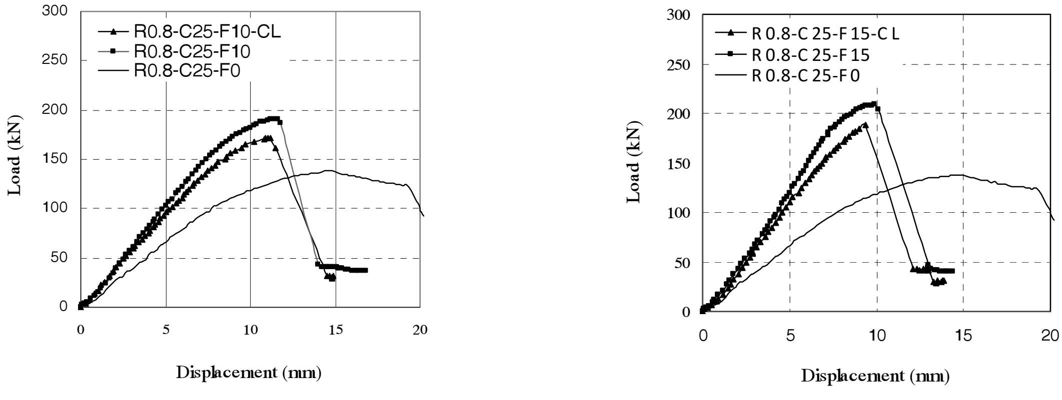
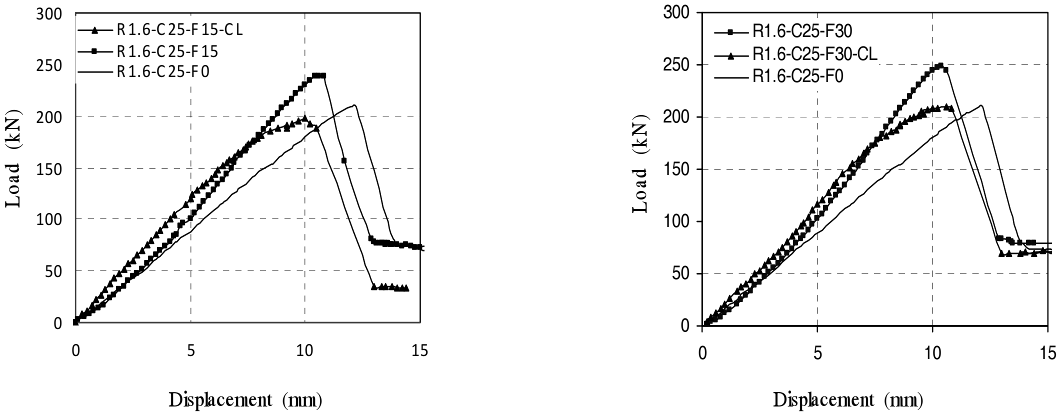


Fig. 6 Load versus Displacement Relationship for specimen R1.6-C25-F30-CL



(a) (b)

Fig.7 Comparison between Load versus Displacement Relationships for R0.8 Specimens under Monotonic and Cyclic Loadings



(a) (b)

Fig.8 Comparison between Load versus Displacement Relationships for R1.6 Specimens under Monotonic and Cyclic Loadings

decreased the punching strength of strengthened specimens down to the values of un-strengthened specimens. Therefore, it seems that for slabs with large reinforcing steel ratio ρ, no improvement may be achieved due to CFRP strengthening. This can be due to the fact that in slabs with large reinforcing bars (like series R1.6), the failure type is mainly punching shear without significant flexural deformation. However, for the case of slabs with small reinforcing bars (like series R0.8), flexural-punching failure occurs after considerable flexural deformation. This can be seen by comparing the load versus displacement relationship of specimens R0.8-C25-F0 and R1.6-C25-F0 in figures 7a and 8a. After strengthening, the failure type of the strengthened specimens with small reinforcing bars changes from flexural-punching to a complete punching. Therefore, strengthening by CFRP sheets in these specimens can be more efficient compared to the specimens with large reinforcing bars. Also, it should be noted that as seen in Table 2, the values of ρ_{eqv}/ρ_s in the slab series of R1.6 are smaller than those in the slab series of R0.8. The stiffness of load versus displacement relationship in slabs with large reinforcing steel ratio ρ was not very different for both types of cyclic and monotonic loadings (figures 8a and b).

Table 3 compares the measured and calculated values of punching shear strength in different specimens using ACI and BS codes. For the case of BS Code, the values of ρ_{eqv} and d_{eqv} calculated by equations 2 and 3, instead of ρ and d, have been used in Eq. 1.

As seen in Table 3, for ACI Code, the mean value of $V_{u,test}/V_{u,ACI}$ for all test results is 1.90 with a standard deviation of 0.33. These values are 1.32 and 0.13 for BS Code, respectively. Therefore, it is concluded that BS Code can predict the punching shear strength of strengthened slabs more accurately with least scatter.

Table 3 comparison between measured and calculated values of punching strength

Specimen	$V_{u,,test}$ (kN)	$V_{u,ACI}$	$V_{u,BS}$	$V_{u,,test}/V_{u,ACI}$	$V_{u,,test}/V_{u,BS}$
R0.8-C25-F0	138.0	103.1	128.3	1.34	1.08
R0.8-C25-F10	191.0	112.1	145.8	1.70	1.31
R0.8-C25-F10-CL	172.0	112.1	145.8	1.53	1.18
R0.8-C25-F15	208.8	113.1	148.2	1.85	1.41
R0.8-C25-F15-CL	188.0	113.1	148.2	1.66	1.27
R1.6-C25-F0	210.0	95.7	147.1	2.19	1.43
R1.6-C25-F15	239.0	100.6	157.6	2.38	1.52
R1.6-C25-F15-CL	198.0	100.6	157.6	1.97	1.26
R1.6-C25-F30	245.0	104.1	165.4	2.35	1.48
R1.6-C25-F30-CL	210.5	104.1	165.4	2.02	1.27
			Mean	1.90	1.32
			SD	0.33	0.13

5. Conclusions

In the paper, the effect of cyclic loading on punching strength of flat slabs strengthened with CFRP sheets was studied. Based on test results of ten specimens, the following conclusions can be drawn.

- Using CFRP sheets as flexural reinforcement can increase the punching shear strength of flat slabs, significantly.

- Comparison between the results shows that cyclic loading decreases the enhancement of punching shear strength due to the slab strengthening by CFRP sheets. This decrease is more for slabs with larger reinforcing steel ratios, ρ. For slabs with large reinforcing steel ratios, cyclic loading may completely eliminate the effect of CFRP sheets on shear strengthening.

- In order to use different code equations to predict the punching shear strength of the strengthened slabs with CFRP sheets, two parameters of the equivalent depth d_{eqv} and equivalent flexural reinforcement ratio ρ_{eqv}, instead of d and ρ, are proposed.

- The average of $V_{u,test}/V_{u,predict}$ ratios for ACI 318 and BS 8110 Codes are 1.90, 1.32 with the coefficient of variations of 0.33, 0.13, respectively. Equations proposed by Iranian Code ABA are similar to the equations presented by ACI Code and result in the same punching shear strength. Among the equations used for punching shear strength prediction, the equation proposed by BS 8110 Code predicted the punching shear strength most accurately with least scatter.

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