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Investigation of CFRP strengthening efficiency experimentally and analytically on reinforced concrete beams

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Abstract

The influence of stirrups, shear span to effective depth ratio, FRP strengthening configuration, and strip width to spacing ratio over the experimental performance of the CFRP-strengthened beams and the estimation accuracy of a total of eleven analytical expressions were evaluated in this study. The main findings obtained in the experimental investigation were as follows. CFRP Strengthening enhanced the load-carrying capacities in all series by an average of 44% with regard to the reference specimens. The use of CFRP for strengthening beams enhanced the maximum deflection and ductility of RC beams across all series. The reduction in stiffness owing to the shear cracks occurring diagonally was more apparent in the reference beams without strengthening. There was no significant difference in the failure loads and CFRP contribution to the strength of both side-bonded and U-wrapped beams when CFRP debonding controlled the failure of the specimens. The failure loads of the strengthened beams and CFRP contribution to strength occur lower as a/d increased. The shear contribution of CFRP was found to be lower in beams with stirrups compared to those without. The investigated equations had more reliable and consistent predictions in beams without stirrups in comparison to the beams with stirrups in both side-bonded and U-wrapped beams. The predictions of the ACI 440.2R, Fib-TG 9.3, CNR-DT200, and CSA-S806 yielded highly inconsistent and unconservative results when the stirrups ratio (ρw) is greater than 0.003.

1. Introduction

Strengthening of deteriorated reinforced concrete (RC) structures with insufficient strength and performance is a critical issue for civil engineers nowadays. Various techniques and methods have been applied to strengthen the deteriorated structures up to now. Strengthening structures with composite materials like Fiber-reinforced polymer (FRP), has been a promising and increasingly common practice. The superior properties of FRP such as corrosion resistance, high strength to weight ratio, and easy of installation, have set it an option to conventional strengthening methods. As the use of FRP in strengthening applications has become widespread in the last two decades, the researchers have paid their attention to the examination of FRP strengthening efficiency. Analytical [1-17] and experimental studies [18-66,88-92] were performed to examine the parameters effective on the performance, behaviour and FRP shear contribution. Chen & Teng [1-2]; Khalifa & Nanni [3]; Triantafillou [4] performed an analytical study on the FRP strengthened beams in shear and proposed equations depending on the effective strains or stresses to predict the contribution of FRP to shear strength. The statistical assessment of the prediction consistency of the equations proposed in the literature to predict FRP shear contribution was carried out by some researchers [67-70]. The behaviour of RC beams strengthened by FRP in a way to enhance the flexural and shear strength were investigated experimentally by a limited number of researchers [47, 50, 53, 61]. The

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effect of some parameters such as stirrups [22-23,25] and the shear span to effective depth ratio (a/d) [33-36] on the experimental behaviour of FRP strengthened specimens in shear has been studied experimentally by various researchers. Grande et al. [18], Bousselham & Chaallal [23], and Khalifa et al. [41] stated that the FRP shear contribution is lower in beams with stirrups compared to the beams without stirrups. Jayaprakash et al. [27], Li & Leung [33], and Khalifa et al. [35] expressed that the a/d possessed a considerable influence on the shear contribution of FRP. Another important parameter is the shear strip width to spacing ratio (w_f/s_f) influencing the behaviour and performance as stated by many researchers [27,46,49,57]. The impact of the various strengthening FRP configurations on the strengthened beams in shear was experimentally investigated by Leung et al. [45] and Diagana et al. [46].

The previous studies have identified several parameters significantly impact the behaviour of FRP strengthened beams, such as a/d, existing stirrups, w_f/s_f, and strengthening configuration. However, it is not well understood how these parameters specifically affect the behaviour of FRP strengthened beams. In addition, most of the experimental studies were carried out on member strengthened with FRP in either flexure or shear. Therefore, it is necessary to evaluate the effect of these parameters on the beams strengthened in both flexure and shear at the same time. Furthermore, many popular models currently in use, proposed by specifications and researchers for U-wrapped and Side-bonded, do not consider these important variables. This lack of consideration poses safety risks for members designed using these models. Therefore, it is necessary to analytically investigate the extent to which these variables influence the calculation of FRP contribution to shear force in order to determine the accuracy of these models. Previous studies have not investigated the effect of these variables on the proposed relations; rather, they have focused on overall assessing the accuracy of the models' predictions. By determining which model consistently provides more reliable predictions in different situations, it is anticipated that more consistent and dependable designs can be achieved.

Within the scope of this study, RC beams with various properties such as two different stirrups spacings (S0 and S20) and three different a/d (a/d=2.5,3.5, and 4.5) were strengthened by CFRP in three strengthening configurations (The U-wrapping, completely wrapping and side-bonding) and tested to investigate the impact of certain parameter such as a/d, stirrups, FRP strengthening configuration, and w_f/s_f under three-point bending tests with the aim of contribution to previous findings. Experimental findings of the tested specimens were examined from the point of the load-carrying capacity, stiffness, ductility, failure modes, and strains of the reinforcement. In addition to the experimental study, the accuracy of the eleven prediction models proposed by researchers and specifications to obtain the FRP contribution to the shear strength in U-wrapped and side-bonded beams were evaluated using the experimental findings of a total of 259 FRP-strengthened beams in shear, which were previously tested by various researchers. The impact of parameters such as stirrups and a/d on the precision of the equations was assessed. In the analytical study, the equation proposed by Sengun & Arslan [88] for calculating the FRP shear contribution in fully wrapped beams was also considered to investigate the feasibility of calculating the FRP shear contribution in U-wrapped and side-bonded beams.

1.1 Research Significance

In the present study, the behaviour of U-wrapped and side-bonded beams was investigated in greater detail and comparatively through experimental analysis. The true novelty of this research lies in examining the extent to which critical parameters, previously shown to be experimentally effective but not considered in analytical models, influence the accuracy of these models. This was achieved using a database of 259 beams. To the best of the authors' knowledge, few studies explicitly explore the impact of these parameters.

2. Experimental Program

The three-point bending test was carried out on RC test specimens with two different stirrups spacing (s=0 and ,200 mm), three different a/d (2.5,3.5, and 4.5), and three different strengthening configurations (Completely Wrapped, U-Wrapped, Side Bonded) to observe FRP strengthening efficiency.

2.1 Features of Test Specimens and Materials

Sixteen RC beams, whose geometric dimensions and reinforcement details were introduced in Fig. 1, were tested. The specimens were separated into four different series based on various *a/d* and stirrup spacing as given in Table 2 so as to make the experimental results easier to interpret and compare. The experimental findings of the reference beams in each series were taken from the study carried out by Sengun & Arslan [88]. The concrete compressive strength was obtained as 43 MPa by compression test on the cube samples with 150 mm side dimensions taken during concrete casting. Two 18 mm steel rebars (2Ø18) were used as tensile reinforcements in all specimens. In the series of K2.5S20 and K3.5S20 (Fig. 1a), 2Ø12 steel bars were placed as compression reinforcements at the top of the beams. The stirrups (Ø8) spaced with 200 mm across the entire beam span in the series of K2.5S20 and K3.5S20 were utilized as shear reinforcements. The mechanical properties of both tensile and shear reinforcements were presented in Table 1.

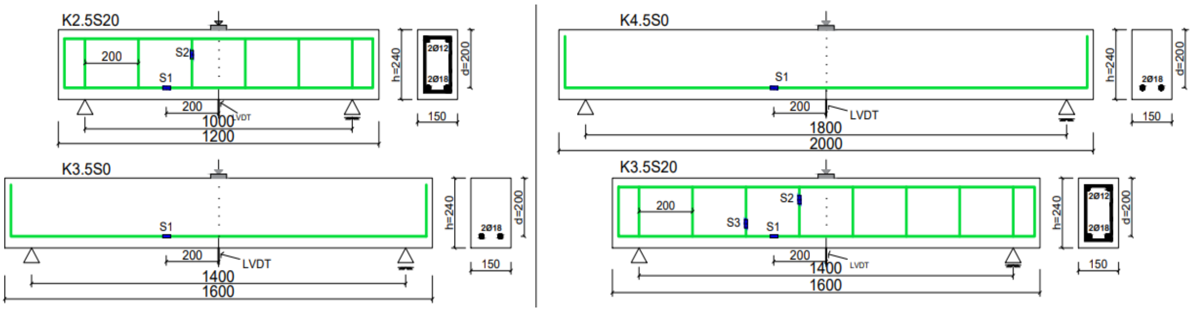
Table 1. Properties of the materials

Materials		Yield strength (MPa)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Thickness(mm)
Steel	D=18 mm	502	654	200	-
	D=12 mm	506	662	200	-
	D=8 mm	610	788	200	-
FRP	CFRP	-	4400	255	0.34

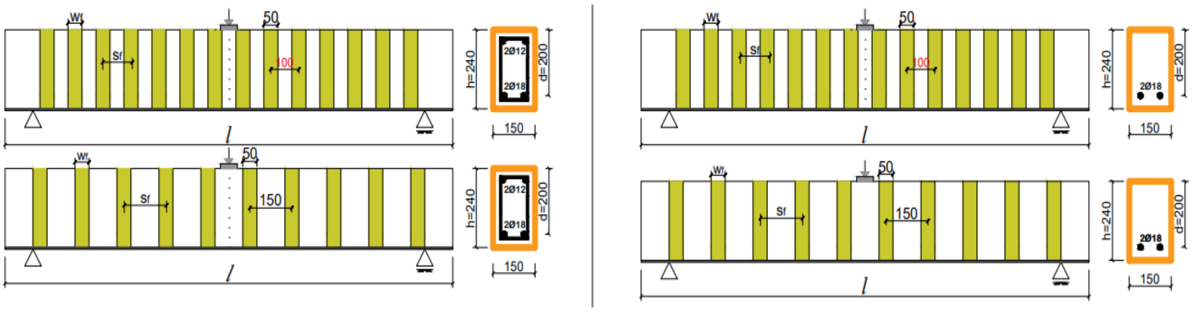
Epoxy obtained by mixing two materials such as hardener and resin in the proportions recommended by the manufacturer was used for bonding CFRP to the beam surface. The mechanical properties of unidirectional CFRP given by the manufacturer were presented in Table 1.

2.2 The Details of The Strengthening Schemes

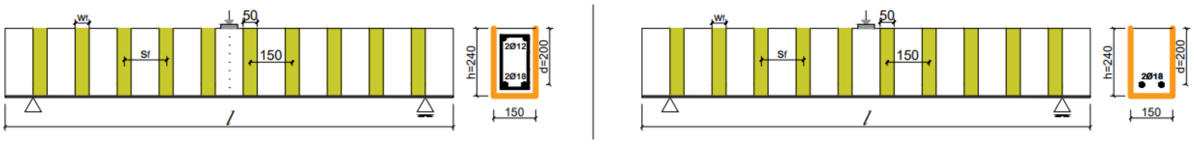
Various configurations, including complete wrapping, U-wrapping, and side bonding, were implemented on the tested beams. In each series, one beam was kept as a reference without CFRP strengthening. The experimental results for these reference beams were sourced from the research conducted by Sengun & Arslan [88]. U-wrapping configurations in shear strengthening as given in Fig. 1c was performed in one-beams of all series tested. In addition, strengthening of the one beam of the K4.5S0, K3.5S20, and K3.5S0 series was conducted by side-bonding CFRP configuration in only shear as given in Fig. 1d. The remaining beams were strengthened for both flexure and shear using CFRP. For shear strengthening, the beams were completely wrapped with CFRP as illustrated in Fig. 1b. To enhance flexural strength, a 150 mm wide CFRP sheet, consisting of two layers, was affixed to the bottom surface of the completely wrapped beams. Additionally, discrete CFRP strips, positioned perpendicular to the beam axis, were applied to all tested beams for shear strengthening. The numerical details of the CFRP strengthening were given in Table 2.



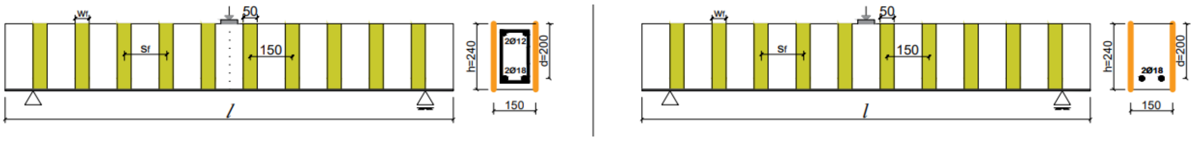
(a)



(b) Completely Wrapped



(c) U-Wrapped



(d) Side-Bonded

Fig. 1. (a) Geometry and test setup of the test beams; (b), (c), (d) Strengthening configurations

The meanings of the numbers and letters utilized in the denotation of the tested beams given in Table 2 were as follows.

Table 2. Properties of FRP strengthening on tested beam

Series	Specimen	FRP	l (mm)	w_f (mm)	n_f	s_f (mm)	n_s	s_n (mm)	ρ_f	w_f/s_f
K3.5S0	K3.5S0-R [88]	-	1600	-	-	-	-	-	-	-
	K3.5S0-C-5-2K	CFRP	1600	50	2	100	2	50	0.0045	0.5
	K3.5S0-C-10-2K		1600			150	2	100	0.003	0.33
	K3.5S0-C-10-U		1600		-	150	1	100	0.0015	0.33
	K3.5S0-C-10-S		1600			150	1	100	0.0015	0.33
K4.5S0	K4.5S0-R [88]	-	2000	-	-	-	-	-	-	-
	K4.5S0-C-10-U	CFRP	2000	50	-	150	1	100	0.0015	0.33
	K4.5S0-C-10-S		2000			150	1	100	0.0015	0.33
K3.5S20	K3.5S20-R [88]	-	1600	-	-	-	-	-	-	-
	K3.5S20-C-5-2K	CFRP	1600	50	2	100	2	50	0.0045	0.5
	K3.5S20-C-10-2K		1600			150	2	100	0.003	0.33
	K3.5S20-C-10-U		1600		-	150	1	100	0.0015	0.33
	K3.5S20-C-10-S		1600			150	1	100	0.0015	0.33
K2.5S20	K2.5S20-R [88]	-	1200	-	-	-	-	-	-	-
	K2.5S20-C-5-2K	CFRP	1200	50	2	100	1	50	0.0045	0.5
	K2.5S20-C-10-U		1200		-	150	1	100	0.0015	0.33

n_s: The number of CFRP layers used for shear strengthening; **n_f**: Flexural strengthening; **w_f:** CFRP shear strips width; **s_n:** the net (clear) distance between two adjacent strips, **w_f/s_f, ρ_f:** CFRP reinforcement ratios (used at shear strengthening; **s_f:** center to center distance of the two adjacent strips; **l:** the length of the beam

KaaSbb-c-dd-ee

- “aa” takes the values of 2.5, 3.5, and 4.5 and represents the a/d.

- "bb" refers to the stirrup spacing (in cm). "0" was used for beams without stirrups. "20" demonstrates the beams with stirrups (center-to-center distance is 20 cm).
- "c" expresses the FRP type used in strengthening. "C" indicates the CFRP.
- "dd" refers to the clear distance between CFRP shear strips (in cm) (s_n).
- "ee" was used to show strengthening configurations. "2K" refers to the strengthened beams with completely wrapped two layers of CFRP in shear and two layers of CFRP in flexure. "U" and "S" indicates the strengthened beams with U wrapped and side-bonded CFRP in only shear, respectively.

2.3 Test Setting and Instrumentation

An experimental investigation was performed utilizing a displacement-controlled three-point bending test with point loading at mid-span. A computer-controlled data acquisition system was employed to capture experimental data, including applied loads, strains on longitudinal and shear reinforcements, and vertical deflections at mid-span. Vertical deflections of all tested beams were measured using linear variable displacement transducers (LVDTs) positioned at mid-span, as depicted in Fig. 1a. Strain gauges were installed on the tensile reinforcements of all specimens at the locations marked S1 in Fig. 1a to measure strains and assess the influence of flexural strengthening on the strain behavior of the longitudinal reinforcement. To evaluate the impact of CFRP shear strengthening on stirrup strains, two strain gauges were affixed at the positions marked S2 and S3 in Fig. 1a, considering potential shear crack locations in the K3.5S20 and K2.5S20 series. In the K2.5S20 series, strain gauges (S2 and S3) were attached to both legs of the third stirrups.

3. Results and Discussions

The overall performance and experimental results of the beams were evaluated in terms of strength, ductility, reinforcement strains, and stiffness using load-deflection curves (Fig. 2) and test results (Table 3). The effects of variables such as shear span to effective depth ratios (a/d), stirrups, strip width to spacing ratio (w_f/s_f), and CFRP strengthening configurations on failure modes, failure load, strain behavior, and cracking patterns were also examined in detail in the subsequent sections.

3.1 The General Behavior of The Tested Specimens

The general behavior of the tested beams was evaluated by means of the load-deflection curves and the test results without considering any specific effect of the investigated parameters.

3.1.1. Strength, Ductility, Stiffness, And Strains

CFRP strengthening enhanced the load-carrying capacities in all series by an average of 44% with regard to the reference specimens due to the contribution of FRP to strength. Based on the ductility index and the area under the load-deflection curves (A) in Table 3, the use of CFRP for strengthening beams enhanced the maximum deflection and ductility of RC beams across all series when compared to reference beams by preventing the propagation and widening of cracks. The CFRP shear strips functioned as anchorage, preventing the complete debonding of CFRP applied for flexural strengthening during the experiments. Additionally, the initial stiffness of CFRP-strengthened beams was generally higher than that of the reference beams in each series. Besides, the reduction in stiffness owing to the shear cracks occurring diagonally was more apparent in the reference beams in comparison to the strengthened beams as seen in the load-deflection curves since the strength of compression struts was enhanced by the confinement effect of CFRP strengthening and CFRP prevented the crack width. It could be concluded considering the load values at which stirrups started to actively contribute to the shear strength that strengthening RC beams with CFRP in shear improved the first diagonal cracking load in the K3.5S20 and K2.5S20 series. The highest strains occurring on the tensile reinforcement were greater on the FRP-strengthened beams due to the higher failure loads and ductility capacities than the reference beams (Table 3). The tensile reinforcement on the reference specimens in K3.5S0 and K4.5S0 series did not yield due to the shear failure mode occurring suddenly (Fig. 3). The horizontal red dashed line ($\varepsilon_{y,longidutional}$, $\varepsilon_{y,stirrups}$) in Fig.3 indicates the yield strain of tensile reinforcement and stirrups, respectively. The longitudinal reinforcement on all the strengthened beams yielded except for beam K4.5S0-C-10-S before the failure occurred. The flexural strengthening by CFRP postponed the yielding of the tensile reinforcement and slowed the flexural cracks to be widen.

Table 3. Experimental results

Series	Specimens	P_n (kN)	Increase at P_n	δ_u (mm)	δ_y (mm)	δ_u/δ_y	A (kNmm)	ε_1 (S1)	ε_2 (S2)	ε_3 (S3)
K3.5S20	K3.5S20-R [88]	133.07	-	11.82	6.16	1.92	1054.43	0.0056	0.0015	0.0019
	K3.5S20-C-5-2K	198.59	49%	56.26	3.60	15.63	8660.79	0.0096	0.0030	0.0023
	K3.5S20-C-10-2K	199.45	50%	14.28	4.24	3.37	1842.31	0.0107	0.0014	0.0030
	K3.5S20-C-10-U	150.25	13%	13.98	3.82	3.66	1469.19	0.0117	0.0015	0.0023
	K3.5S20-C-10-S	149.72	13%	36.48	15.58	2.34	4406.70	0.0033	0.0023	0.0036
K2.5S20	K2.5S20-R [88]	165.17	-	8.06	5.80	1.39	866.35	0.0025	0.0009	-
	K2.5S20-C-5-2K	294.53	78%	12.86	3.62	3.55	2296.32	0.0208	0.0009	-
	K2.5S20-C-10-U	195.04	18%	10.12	2.48	4.08	1757.45	0.0047	0.0027	-
K3.5S0	K3.5S0-R [88]	99.13	-	6.00	-	-	336.38	0.0021	-	-
	K3.5S0-C-5-2K	194.71	96%	93.74	15.26	6.14	16134.90	0.0029	-	-
	K3.5S0-C-10-2K	174.50	76%	82.20	-	-	12570.07	-	-	-
	K3.5S0-C-10-U	138.86	40%	11.84	4.78	2.48	1068.41	0.0143	-	-
	K3.5S0-C-10-S	142.25	43%	18.72	2.56	7.31	2158.71	0.0079	-	-
K4.5S0	K4.5S0-R [88]	85.45	-	7.06	-	-	330.58	0.0024	-	-
	K4.5S0-C-10-U	105.40	23%	13.32	5.62	2.37	936.73	0.0036	-	-
	K4.5S0-C-10-S	109.56	28%	12.64	-	-	922.54	0.0018	-	-

P_n: Maximum load
δ_u: Maximum deflection
δ_y: Deflection at yielding point
A: Area under the load-deflection curves
ε_1: Maximum strain on the longitudinal reinforcement
ε_2,ε_3: Maximum strain on the stirrups

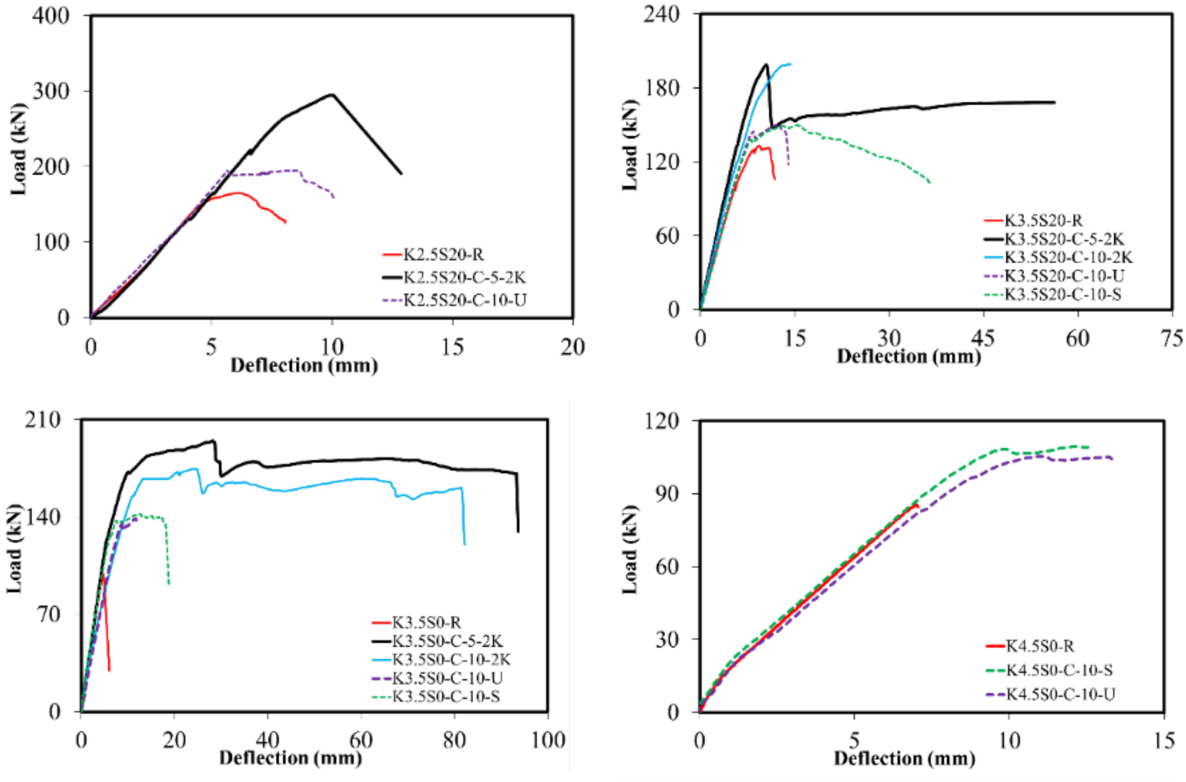
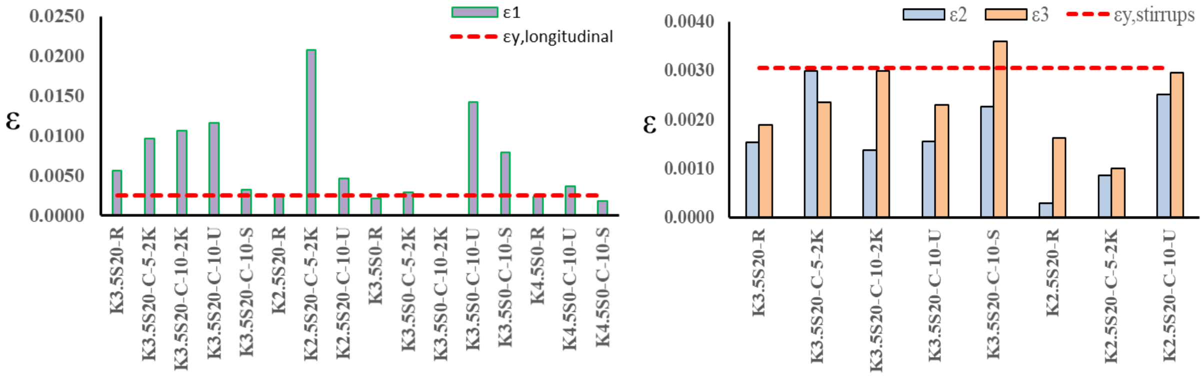


Fig. 2. Load-deflection curves of the tested beams

Due to the wider shear cracks at the intersection points with the third stirrup (ε_3), the third stirrup experienced greater strains compared to the fourth stirrup (ε_2) in the K3.5S20 series, as shown in Fig. 3. Because the strains in the stirrups remained minimal until the formation of shear cracks, the contribution of the stirrups to the shear strength was limited. After the shear cracks formed, the strains on the stirrups increased and the stirrups actively contributed to the shear strength. The loads were distributed between CFRP and stirrups in the strengthened beams, resulting in strain values on the third stirrup (ε_3) of the strengthened beams in K3.5S20 series that were less than the reference specimens (K3.5S20-R) at the same load levels. As a result of the sudden collapse of U-wrapped and side-bonded beams in the K2.5S20 and K3.5S20 series due to the debonding of CFRP shear strips, it was observed that the stirrups (S2 and S3) except for the third stirrups of K3.5S20-C-10-S did not yield before the fracture occurred. Therefore, it could be concluded that it is not suitable to assume that stirrups intersecting the shear cracks yielded as accepted in the specifications to calculate the stirrups' contribution to shear strength, when shear failure with CFRP debonding in the U-wrapping and side bonding configurations occurred. The experimental study indicated that the performance of the strengthened beams related to, ductility, deflection, and load-carrying capacities were dependent on the parameters such as FRP strengthening configurations, a/d, stirrups, and w_f/s_f. The influence of investigated variables on performance and behavior were examined separately in the subsequent sections.

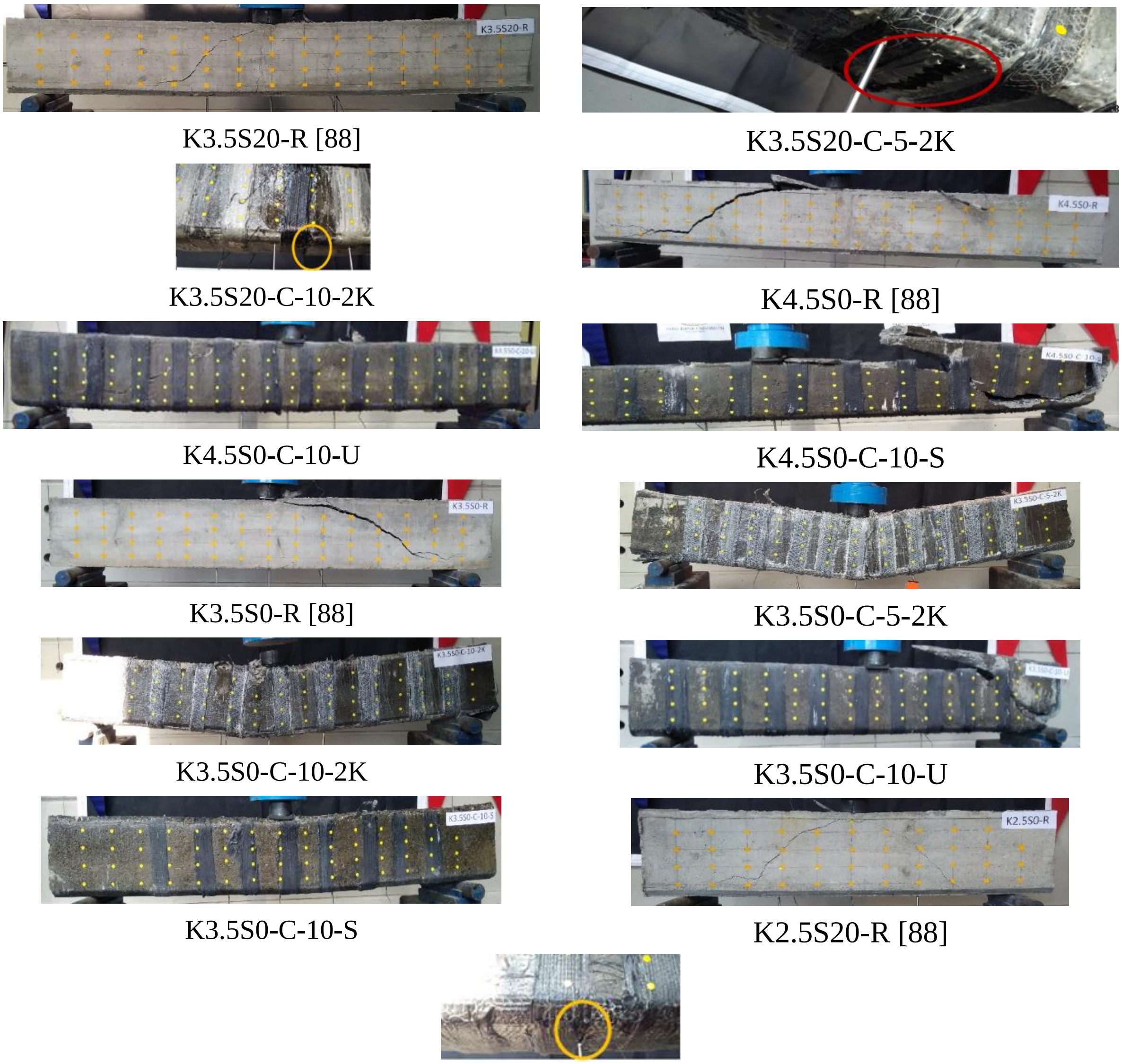


(a) (b)

Fig. 3. The highest strains on the reinforcements a) Longitudinal reinforcements, b) Stirrups

3.1.2 Failure Modes and Cracking Structures

The brittle shear failure due to the shear cracks in the shear spans of the reference beams occurred as noticed in Fig. 4. As the *a/d* increased, the flexural cracks at the middle region were more apparent in the reference (K2.5S20-R, K3.5S20-R) beams with stirrups due to the higher effect of bending moments around mid-span with higher a/d. The shear cracks occurring in the reference beams without stirrups (K3.5S0-R, K4.5S0-R) were more noticeable than in the reference specimens including stirrups (K2.5S20-R, K3.5S20-R). K3.5S20-C-5-2K, K3.5S20-C-10-2K, and K2.5S20-C-5-2K failed abruptly in consequence of the CFRP rupture bonded to the bottom of these beams in flexural strengthening as seen in Fig. 4. The shear strengthening with CFRP applied to these beams limited the development of the shear cracks and retarded their propagation compared to the reference beams. K3.5S0-C-10-2K and K3.5S0-C-5-2K had a flexural failure with concrete crushing occurring under the load application point (Fig. 4). The shear cracks were less obvious on these beams than the flexural cracks due to the failure types of concrete crushing and the presence of stirrups. In addition, the flexural cracks width on K3.5S0-C-10-2K and K3.5S0-C-5-2K was wider in comparison to the reference beams, and the beams failing with the rupture of CFRP used in flexural strengthening. The side-bonded and U-wrapped beams in each series experienced shear failure due to the debonding of CFRP shear strips intersecting with diagonal shear cracks. The failure modes and cracking patterns of the U-wrapped and side-bonded beams differed from those of the reference beams and the beams strengthened in both flexure and shear with complete wrapping (Fig. 4) since the characteristic of debonding failure, suddenly occurring, is completely different from the rupture failure of FRP. This observation suggests that stirrups limit the width of shear cracks, that FRP strengthening can alter failure modes compared to reference beams, and that the configuration of FRP strengthening significantly influences failure modes and cracking patterns.



K3.5S20-R [88]

K3.5S20-C-5-2K

K3.5S20-C-10-2K

K4.5S0-R [88]

K4.5S0-C-10-U

K4.5S0-C-10-S

K3.5S0-R [88]

K3.5S0-C-5-2K

K3.5S0-C-10-2K

K3.5S0-C-10-U

K3.5S0-C-10-S

K2.5S20-R [88]

K2.5S20-C-5-2K

Fig. 4. The condition of the tested beams after the experiment

3.2 Investigated Parameters

3.2.1 Shear Span to Effective Depth Ratios (a/d)

Providing that the RC beams possessed the same geometric dimensions and CFRP reinforcement ratio in shear (ρ_f), the failure loads of the strengthened beams and CFRP contribution to strength became lower in all series as a/d increased as seen in Fig. 5. In this study, the load carrying capacity of the beams and the FRP contribution to the shear strength were found to be higher in beams with a/d equal to 2.5. Similar findings were also reported by Li & Leung [33]. Li & Leung [33] stated that the highest contribution of FRP to the shear strength in U-wrapped beams was obtained at values of a/d between 2 and 2.5. However, contrary to the results obtained in this study, Khalifa & Nanni [3] and Bousselham & Chaallal [23] have stated that the contribution of FRP to the shear strength increases as the a/d ratio increases. In addition, as the a/d increased, the initial stiffness of the tested specimens decreased since the slender beams effect started to govern the behavior of the beams. The deflection capacities of the U-wrapped beams and completely wrapped in shear improved contrary to the side bonded beam as a/d increased. The ductility on U-wrapped and side-bonded beams decreased as a/d increased as seen in load-deflection curves given in Fig. 2. The increase in the initial stiffness occurred due to the FRP strengthening compared to reference beams in each series was higher for all strengthening configurations as *a/d* increased. Therefore, it could be concluded that the *a/d* possessed significant impacts the performance and behavior of the strengthened beams differently based on the CFRP strengthening configurations. The maximum strains on longitudinal reinforcement of the reference beams become higher as the *a/d* ratio increases. The strain values on stirrups of U-wrapped beams declined as the *a/d* ratio enhanced contrary to completely wrapped beams.

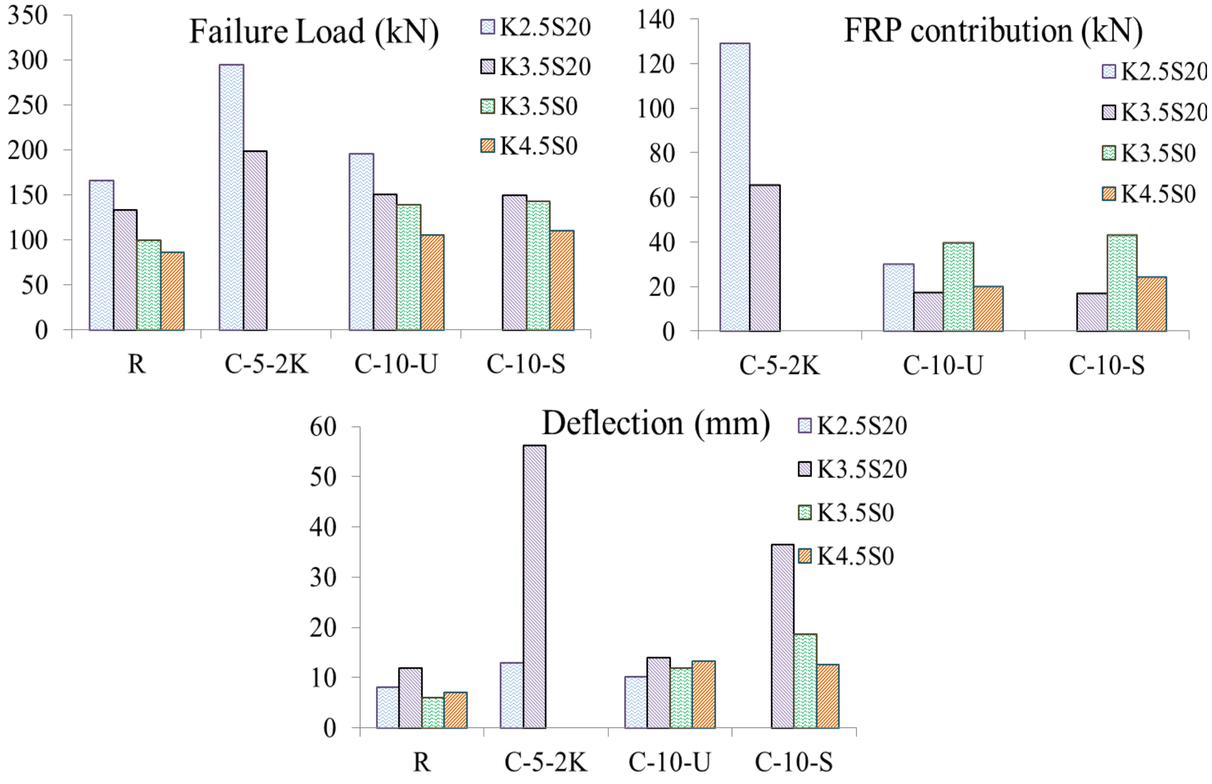


Fig. 5. The effect of a/d on the behavior of tested beams

3.2.2 The Effect of Stirrups

Given that the RC beams had identical geometric dimensions, CFRP reinforcement ratios in shear (ρ_f), and a/d ratios, the strengthened specimens with stirrups exhibited higher failure loads compared to those without stirrups, due to the additional strength provided by the stirrups. The presence of stirrups altered the crack pattern and limited crack widths, resulting in reduced strain values in the CFRP. Therefore, the shear contribution of CFRP was less in beams including stirrups compared to beams without stirrups. Based on this experimental result, it can be evaluated that there could be a possible interaction between the stirrups and CFRP negatively influence the shear contribution of each other. The ductility and deflection capacities in the U-wrapped and side-bonded beams improved as the stirrup ratio increased on account of the confinement effect of stirrups on concrete causing higher failure strains. The beams in K3.5S20 series (K3.5S20-C-5-2K, K3.5S20-C-10-2K) collapsed suddenly due to the rupture of CFRP used in flexure; therefore, the deflection and ductility capacities of these beams become lower compared to the counterpart in K3.5S0 series as demonstrated in Fig. 6. Therefore, it could be evaluated that the presence of the stirrups affects the deflection and ductility behavior of the tested specimens differently based on the CFRP strengthening schemes. As the stirrup ratios increased, the highest-recorded strain on the tensile reinforcement of the side-bonded and U-wrapped beams decreased compared to completely wrapped beams.

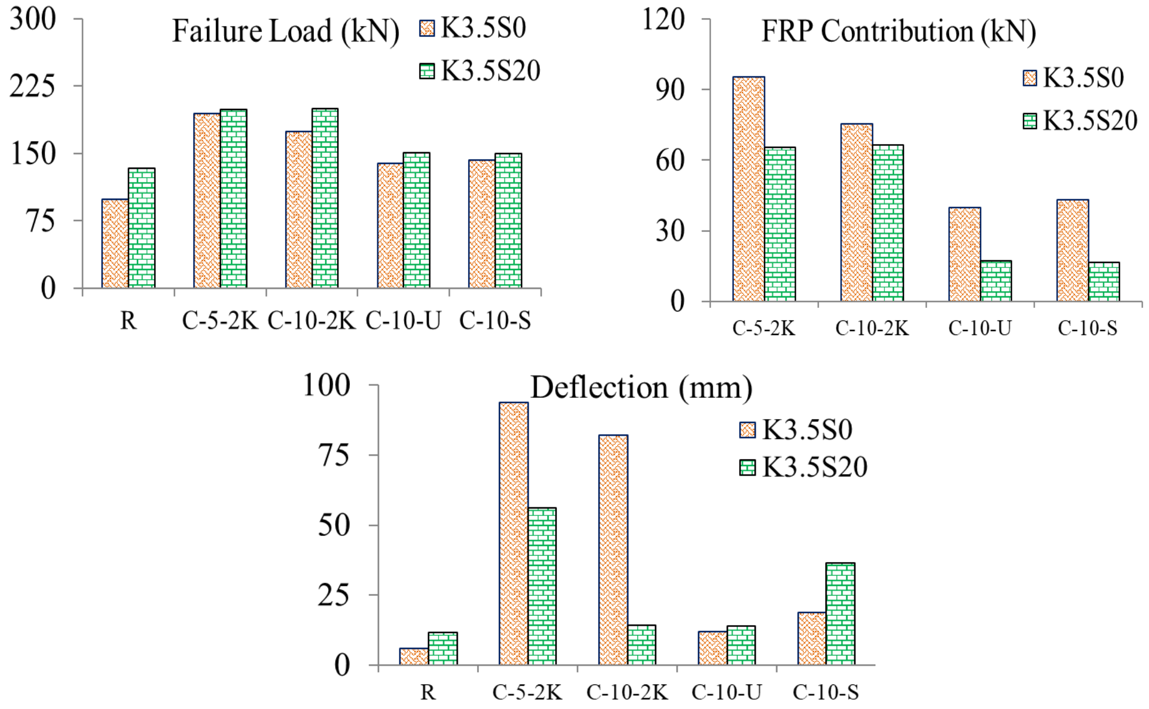


Fig. 6. The effect of stirrups ratios

3.2.3 The Strip Width to Spacing Ratios (w_f/s_f)

The w_f/s_f affected the outcome of the experimental results of tested beams differently depending on whether the beams have stirrups in the shear span. As w_f/s_f enhanced, the CFRP contribution to strength and load-carrying capacity obtained greater on beams without stirrups (K3.5S0 series) since the narrower spacing between CFRP strips was more successful at catching flexural/shear cracks and limiting their expansion.

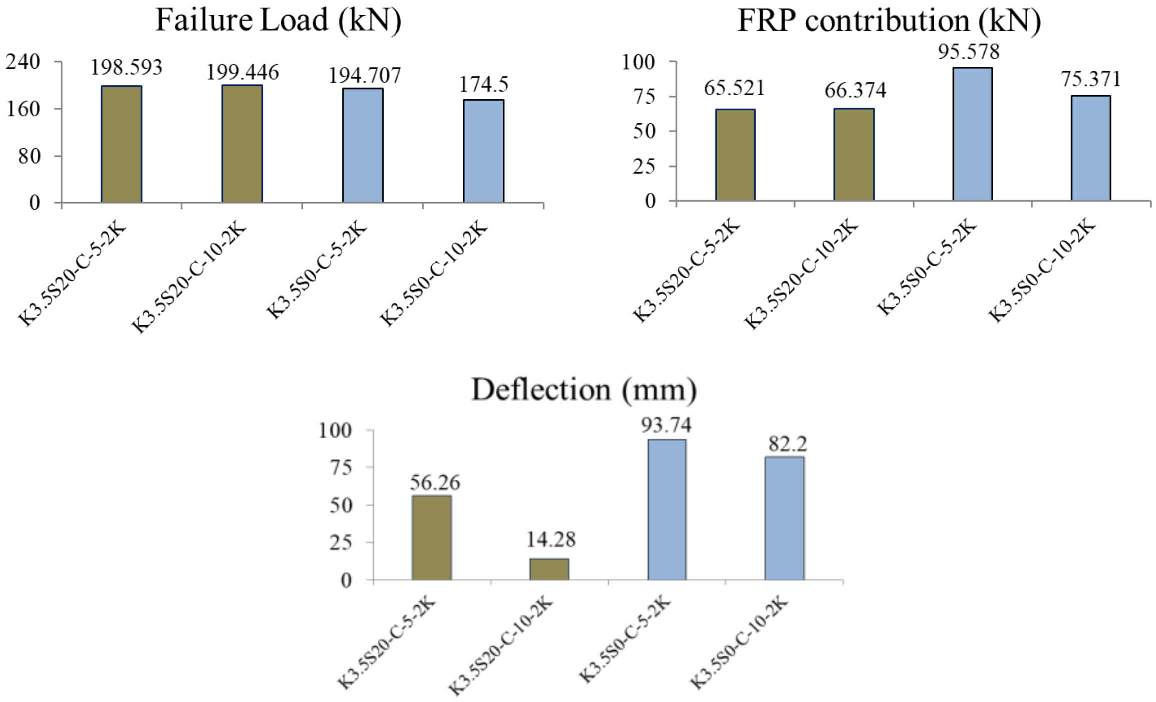


Fig. 7. wf/sf effect on the strengthened beams

However, as w_f/s_f decreased there was no considerable change in the CFRP contribution and load-carrying capacity for beams with stirrups since the beams (K3.5S20-C-10-2K and K3.5S20-C-5-2K) suddenly failed in flexure and the number and also the width of the diagonal cracks was limited due to the existing stirrups on beams as seen in Figs. 4 and 7. Furthermore, the ductility and deflection capacities of the strengthened specimens decreased as w_f/s_f decreased. The development in the initial stiffness compared to reference beams become lower as w_f/s_f decreases in K3.5S0 and K3.5S20 series. Similarly, Jayaprakash et al. [27] indicated the enhancement of stiffness by increasing in w_f/s_f.

3.2.4 Strengthening Configurations

The failure loads and CFRP contribution in beams strengthened for both flexure and shear were higher than those with U-wrapping and side-bonding CFRP configurations in shear, as shown in Fig. 2 and Table 3. When CFRP debonding dictated the failure modes, there was no significant difference in load-carrying capacity and CFRP contribution between the side-bonding and U-wrapping configurations. This can be explained as follows. Since the FRP debonding occurred at lower strain values as a result of the cracks formed, the contribution of FRP, the failure loads, in short, the strengthening efficiency of FRP was found to be limited in both U-wrapped and side-bonded beams. The ductility and deflection capacities of beams strengthened with complete wrapping in both flexure and shear were superior to those of side-bonded and U-wrapped beams in shear. This is attributable to the higher capacity of completely wrapped FRP at catching occurred cracks. In the K3.5S0 and K3.5S20 series, unlike the K4.5S0 series, side-bonded beams exhibited higher deflection and ductility capacities compared to U-wrapped beams. CFRP strengthening in both flexure and shear resulted in a greater increase in initial stiffness than in side-bonded and U-wrapped beams in shear relative to the reference beams due to the higher confinement effect on concrete. While side-bonded beams in the K4.5S0 series showed a larger increase in initial stiffness compared to U-wrapped beams, U-wrapped beams in the K3.5S20 series displayed a higher increase in initial stiffness than side-bonded beams. Thus, CFRP strengthening enhanced initial stiffness differently based on the strengthening configuration.

4. Analytical Study

This study examined the impact of key experimental parameters, such as a/d ratio and stirrups, on the prediction accuracy of equations proposed by specifications (ACI 440.2R [84], Fib-TG 9.3 [85], CNR-DT200 [86], and CSA-S806 [87]) and various researchers (Chen and Teng [1-2], Khalifa & Nanni [3], Triantafillou [4], Bukhari et al. [10], Khalifa et al. [15], Mofidi & Chaallal [16]) for calculating the FRP shear contribution in both U-wrapped and side-bonded beams. The study utilized data from 259 beams collected from the literature, including the specimens tested in this research (Leung et al. [45], Taerwe et al. [71], Diagana et al. [46], Grande et al.[18], Khalifa [41], Khalifa & Nanni [72], Khalifa & Nanni [3], Panda et al. [48], Panda et al. [73], Pellegrino & Modena [6], Pellegrino & Modena [11], Bousselham & Chaallal [23], Bousselham & Chaallal [22], Sundarraja et al. [57], Lee et al. [90], Baggio et al. [54], Abass & Hassan [25], Benzeguir et al. [37], Ozden et al.[56], Li & Leung [36], Sato et al. [74], Wu et al. [75], Tan & Ye [76], Feng & Chen [77], Allam & Ebeido [42], Rizzo & De Lorenzis [78], Mofidi & Chaallal [79], Micelli et al. [80], Adhikary & Mutsuyoshi [43], Bousselham & Chaallal [34], Mostofinejad et al. [44], Panigrahi et al. [91], Sato el al. [81], Panda et al. [8], Pellegrino & Modena [7], Damnoo & Kumar [21], Chaallal et al. [30], Bukhari et al. [10], Li et al. [39], Saafan [61], Triantafillou [4], Uji [82], Antonopoulos [83]). The compatibility of the equation previously proposed by Sengun & Arslan [88] for the calculation of FRP shear contribution in the FRP-strengthened beams in the form of completely wrapping was also investigated within the analytical study to examine whether it might be used in beams strengthened by CFRP of U-wrapping and side-bonding configurations. The influence of *a/d* and stirrups on the statistical performance of the proposed equations was evaluated separately for both side-bonded (96 beams) and U-wrapped (163 beams) beams in shear. The necessary variables to calculate FRP shear contribution in each equation were taken from the database provided by Li & Leung [36] and original research papers. The collected database contained the CFRP/GFRP strengthened beams with/without stirrups. The database included rectangular and T-sections FRP-strengthened beams in shear were included in the collected beams. The analytical evaluation of the predictions obtained by the equations was performed as follows. The effect of *a/d* on estimation accuracy of the strengthened beams by U-wrapping and side-bonding was evaluated in three different *a/d* ranges (*a/d<2.5, 2.5≤a/d<3.5, a/d≥3.5*). The number of the beams investigated was different for each equation since some of them were valid for only certain cases. The FRP contribution ($V_{f,exp}$) obtained experimentally was figured out by subtracting the shear strength of reference specimens from the FRP-strengthened specimens. The partial safety factors were excluded from each equation to determine the FRP contribution to shear strength, and were assumed to be one. The ratio of the experimental FRP contribution to the predicted FRP contribution ($V_{f,exp}/V_{f,pre}$) was calculated for each beam using various equations. Statistical measures, including mean values (MV), standard deviation (STD), and coefficient of variation (COV) of these ratios ($V_{f,exp}/V_{f,pre}$), were computed and incorporated into the statistical analysis to evaluate the prediction accuracy of the equations.The FRP shear contribution predicted negatively especially in ACI 440.2R [84] were excluded from the statistical evaluation of the database. Since there were three beams with *a/d* higher than 3.5 (*a/d≥3.5*) in side-bonded beams, no statistical evaluation had been made to evaluate the influence of *a/d* in that range of a/*d* higher than 3.5 (*a/d≥3.5*). The STD and COV are indicators used to assess the accuracy of the equations. The prediction accuracy increases as the COV gets smaller. MV may be used to evaluate whether the predicted FRP contribution is conservative or unconservative. The MV, STD, and COV values of each equation for each strengthening configuration (U-wrapping and side-bonding) according to the investigated parameters (*a/d* and stirrups) were given in Tables 4-9.

4.1 Side Bonded Beams

All equations except for Triantafillou [4], Fib-TG 9.3 [85], Mofidi & Chaallal [16], and Sengun & Arslan [88] had conservative results with the MV greater than one in side-bonded beams. Triantafillou [4] and Sengun & Arslan [88] gave the least conservative results due to the lowest MV values compared to other investigated equations (Table 4). Mofidi & Chaallal [16] gave more consistent and reliable prediction with lower COV compared to other equations. ACI 440.2R [84], CNR-DT200 [86], and CSA-S806 [87] yielded inconsistent predictions with the experimental results owing to the higher COV's. In addition, even though the equation proposed by Sengun & Arslan [88] were derived from test carried out on the completely wrapped beams, it also yielded consistent results with a lower COV in side-bonded beams.

Table 4. Statistical results of all side-bonded beams

Equations	Side-bonded all beams				
	Specimen Number	MV	STD	COV	Conservative (%)
ACI 440.2R [84]	67	1.091	1.081	0.991	33
Triantafillou [4]	95	0.615	0.315	0.513	11
Fib-TG 9.3 [85]	91	0.843	0.478	0.567	36
Khalifa et al. [15]	57	1.681	1.705	1.014	42
Khalifa & Nanni [3]	32	1.347	1.118	0.830	44
Mofidi & Chaallal [16]	90	0.977	0.424	0.434	46
Bukhari et al. [10]	91	1.515	0.907	0.598	66
Chen & Teng [1-2]	88	1.415	0.726	0.513	66
CNR-DT200 [86]	90	2.317	2.618	1.130	64
Sengun & Arslan [88]	96	0.675	0.331	0.490	14
CSA-S806 [87]	96	1.857	2.097	1.129	56

4.1.1 The Effect of The Stirrups

Triantafillou [4] gave the least conservative results in both beams with stirrups and beams without stirrups on account of the lowest MV values compared to other investigated equations (Figs. 8-9 and Table 5). Points above the inclined line indicate that the predictions are unconservative, while points below the inclined line imply that the predictions are conservative in Figs. 8-9. The equations proposed by Chen and Teng [1-2] and Mofidi & Chaallal [16] had more reliable predictions than other examined equations in beams with stirrups due to the better statistical results such as lower

COV's. Mofidi & Chaallal [16], Chen and Teng [1-2], and Sengun & Arslan [88] gave more consistent and reliable predictions with lower COV's than other equations in beams without stirrups. With the exception of Chen and Teng [1-2], Khalifa & Nanni [3], and CNR-DT200 [86], the coefficient of variation (COV) values for the evaluated equations were generally higher in beams with stirrups than in those without. Furthermore, apart from Mofidi & Chaallal [16], beams without stirrups exhibited a higher percentage of conservative results for each equation compared to beams with stirrups. Thus, when considering the mean value (MV), standard deviation (STD), and COV for side-bonded beams, it is evident that the equations examined generally yielded more reliable and consistent predictions in beams without stirrups. This is evidenced by MVs exceeding one, lower COVs, and a higher percentage of conservative results.

Table 5. Statistical findings related to stirrups effect

Equations	Side-bonded beams									
	Beams with stirrups					Beams without stirrups				
	Specimen Number	MV	STD	COV	Conservative (%)	Specimen Number	MV	STD	COV	Conservative (%)
ACI 440.2R [84]	28	0.743	1.022	1.377	14	34	1.212	1.060	0.874	38
Triantafillou [4]	39	0.485	0.272	0.560	3	47	0.682	0.329	0.482	15
Fib-TG 9.3 [85]	40	0.650	0.406	0.624	20	42	0.936	0.492	0.526	40
Khalifa et al. [15]	21	0.726	0.819	1.128	10	31	2.112	1.910	0.904	55
Khalifa & Nanni [3]	12	0.645	0.347	0.537	8	16	1.416	0.973	0.687	56
Mofidi & Chaallal [16]	40	0.922	0.466	0.505	48	42	1.001	0.411	0.411	40
Bukhari et al. [10]	40	1.215	0.864	0.711	48	42	1.707	0.935	0.548	76
Chen & Teng [1-2]	38	0.976	0.429	0.440	42	42	1.716	0.766	0.446	81
CNR-DT200 [86]	40	1.046	0.585	0.559	43	42	3.333	3.380	1.014	79
Sengun & Arslan [88]	40	0.490	0.266	0.544	3	47	0.790	0.330	0.418	21
CSA-S806 [87]	40	1.712	2.023	1.182	40	47	1.951	2.302	1.180	62

4.1.2 The Effect of the a/d

The results of the beams without stirrups (*wost)*, and with stirrups *(wst)* were presented in Fig. 10. Since the equation proposed by Triantafillou [4] delivered predictions resulting in the lowest MV of the ratio of experimental results to predictions for all considered ranges of the *a/d*, it yielded the most unconservative results among the considered equations (Fig. 10 and Table 6).

Table 6. Statistical results in terms of a/d effect

Equations	Side-bonded beams									
	a/d<2.5					2.5≤a/d<3.5				
	Specimen Number	MV	STD	COV	Conservative (%)	Specimen Number	MV	STD	COV	Conservative (%)
ACI 440.2R [84]	18	0.678	0.549	0.810	22	37	1.107	1.134	1.025	30
Triantafillou [4]	17	0.460	0.301	0.654	6	62	0.656	0.305	0.465	11
Fib-TG 9.3 [85]	15	0.591	0.424	0.717	13	60	0.879	0.462	0.526	37
Khalifa et al. [15]	14	1.271	0.984	0.774	43	31	1.564	1.628	1.041	35
Khalifa & Nanni [3]	13	1.420	1.080	0.761	46	12	0.741	0.448	0.605	25
Mofidi & Chaallal [16]	15	0.739	0.482	0.652	27	60	1.057	0.400	0.379	52
Bukhari et al. [10]	15	1.116	0.818	0.733	47	60	1.629	0.931	0.572	72
Chen & Teng [1-2]	13	1.302	0.797	0.612	54	60	1.433	0.714	0.498	68
CNR-DT200 [86]	15	1.233	0.843	0.683	60	60	2.538	3.055	1.204	60
Sengun & Arslan [88]	18	0.604	0.461	0.763	11	62	0.693	0.281	0.405	13
CSA-S806 [87]	18	1.424	1.353	0.950	50	62	2.085	2.416	1.159	56

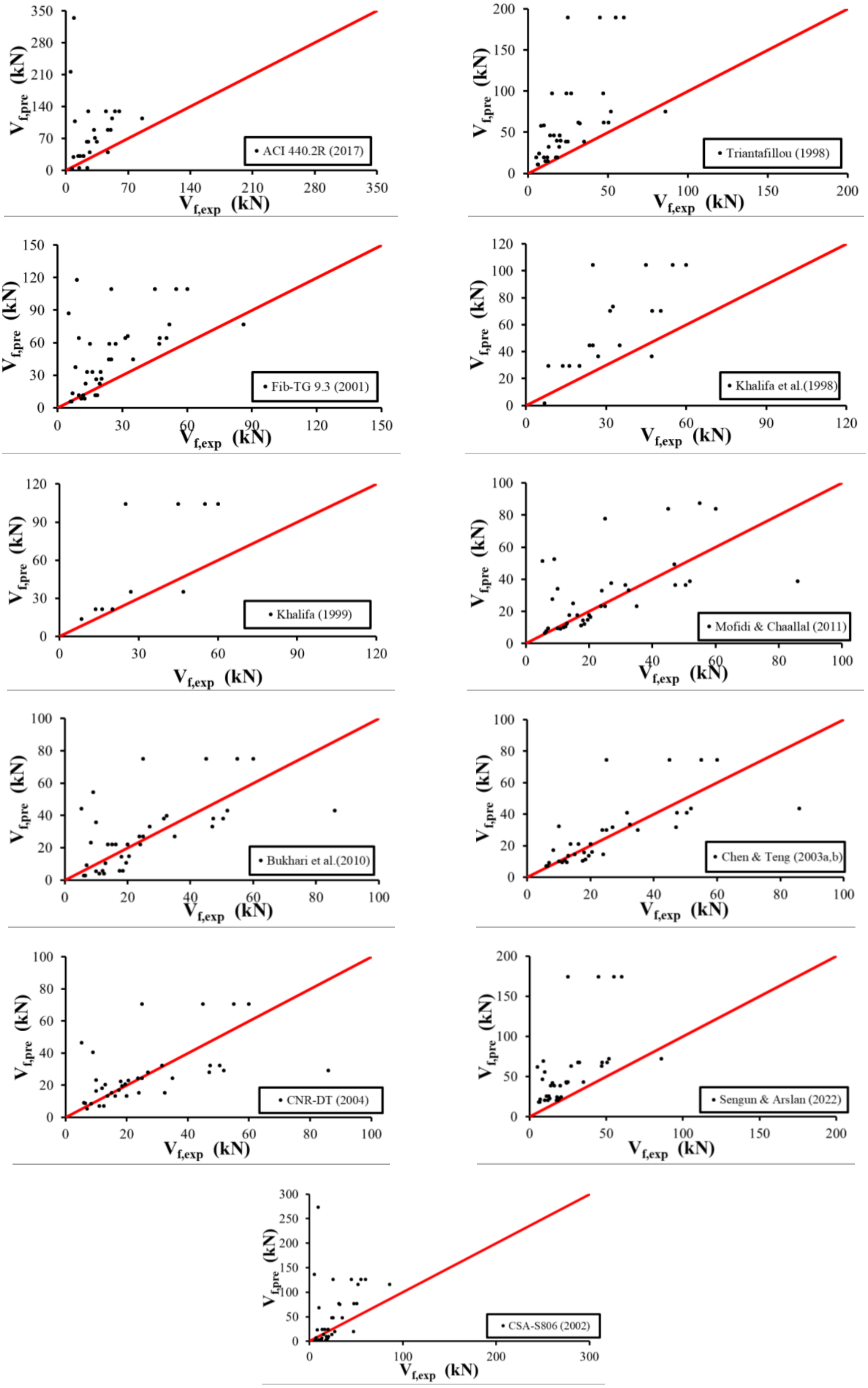


Fig. 8. The distribution of Vf,exp and Vf,pre on side bonded beams with stirrups

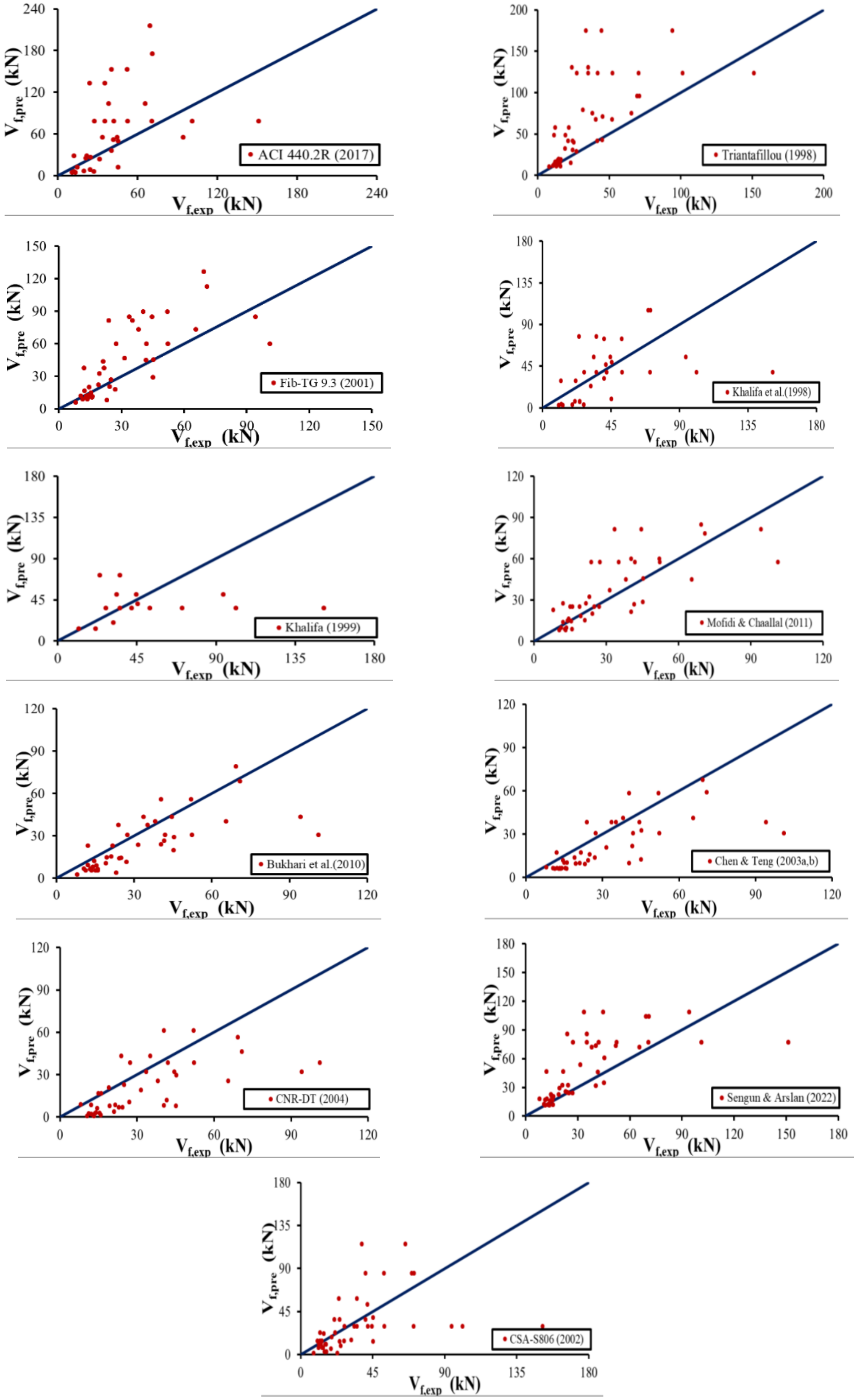
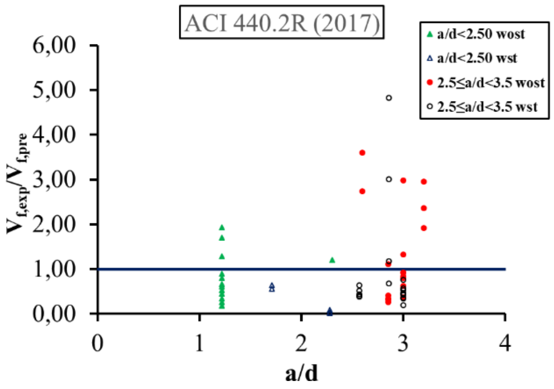
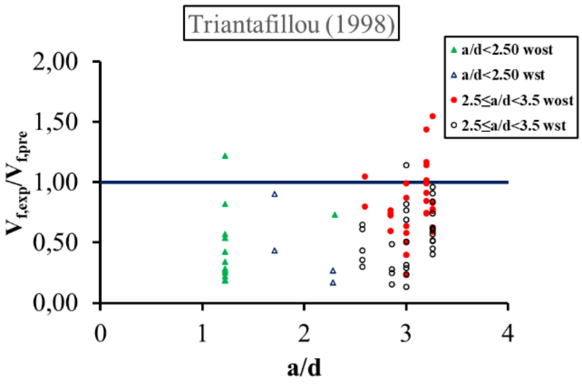
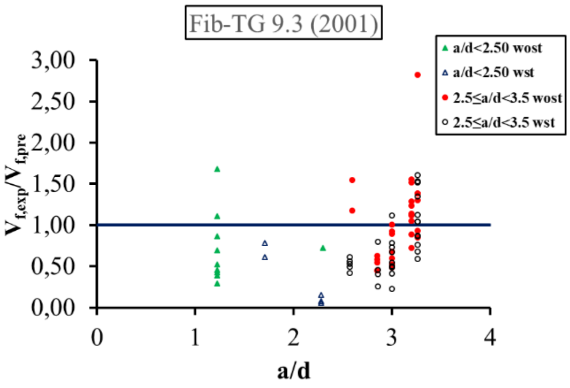


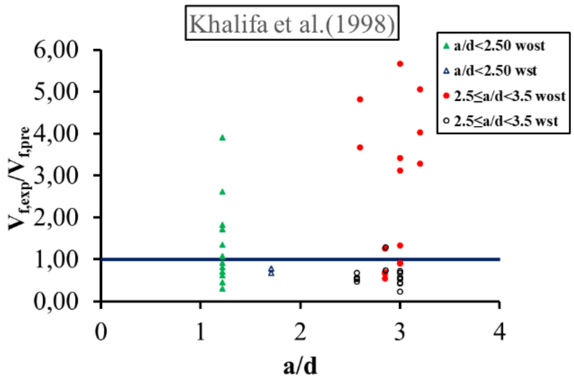
Fig. 9. The distribution of Vf,exp and Vf,pre on side bonded beams without stirrups

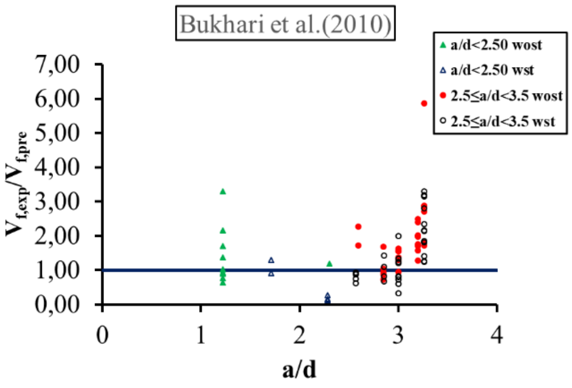
Considering the statistical results, the equation of Chen and Teng [1-2] yielded the most consistent predictions for the beams with *a/d* less than 2.5 (*a/d<2.5*), while the equation of Mofidi & Chaallal [16] returned the most reliable results when *a/d* is between 2.5 and 3.5 (*2.5≤a/d<3.5*). Hence, when the values of MV, COV and conservative results percentage were evaluated, it might be expressed that the equations considered in this study generally yielded more consistent predictions for side-bonded beams with *a/d* between 2.5 and 3.5 (*2.5≤a/d<3.5*) compared to those with *a/d* less than 2.5(*a/d<2.5*).

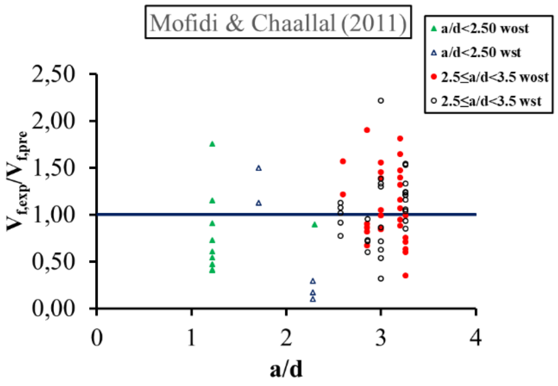


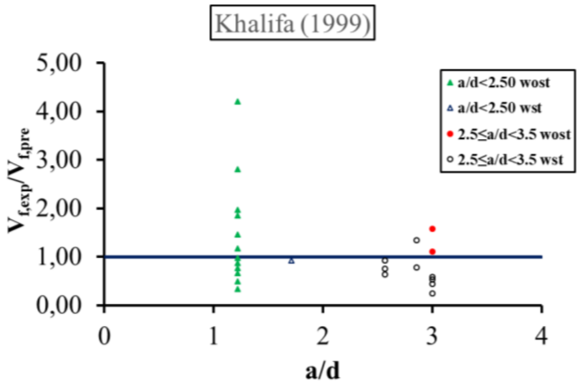


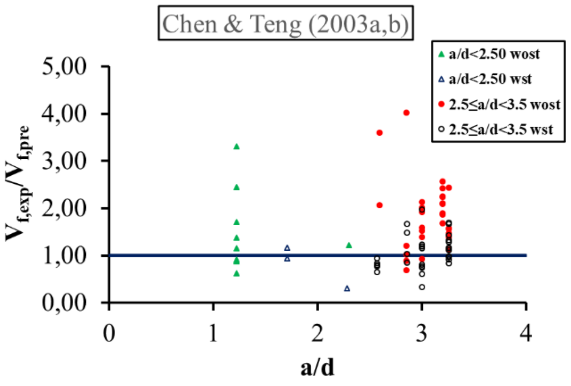












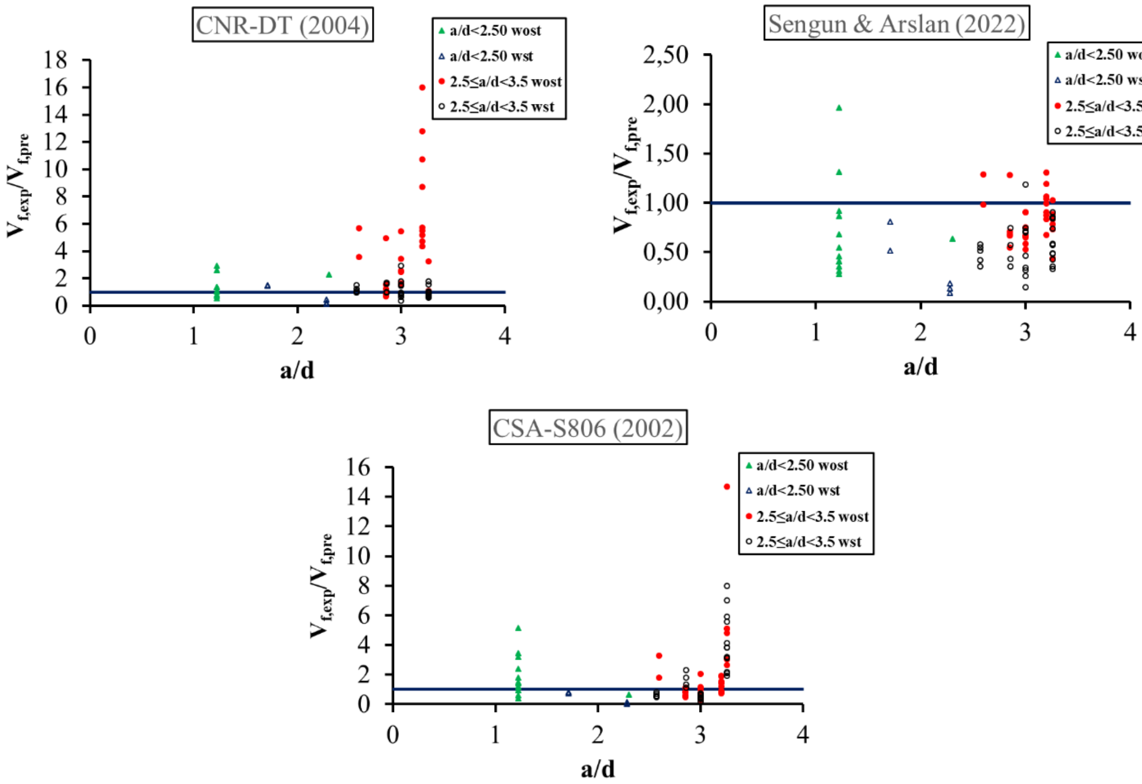


Fig. 10. The distribution of Vf,exp/Vf,pre according to a/d on side-bonded beams

When the results obtained are evaluated collectively, it could be stated that the predictions of the proposed models in side-bonded beams are inconsistent with the experimental results in beams containing stirrups and with a/d ratio less than 2.5 (*a/d<2.5*), and therefore special care should be taken when using these models in such elements.

4.2. U-Wrapped Beams

All equations except for Chen and Teng [1-2], Bukhari et al. [10], Khalifa et al. [15], ACI 440.2R [84], and CSA-S806 [87] gave unconservative results with MV's less than one. Since Triantafillou [4] had the lowest MV, this equation had the most unconservative results among investigated equations. The equations proposed by Sengun & Arslan [88] produced more reliable and consistent predictions due to the lower COV in U-wrapped beams (Table 7).

Table 7. Statistical results of all U-wrapped beams

Equations	U-wrapped all beams				
	Specimen Number	MV	STD	COV	Conservative (%)
ACI 440.2R [84]	157	1.102	0.883	0.802	41
Triantafillou [4]	163	0.598	0.377	0.631	15
Fib-TG 9.3 [85]	163	0.955	0.629	0.658	45
Khalifa et al. [15]	156	1.061	0.835	0.787	42
Khalifa & Nanni [3]	103	0.944	0.720	0.762	39
Mofidi & Chaallal [16]	163	0.947	0.612	0.646	42
Bukhari et al. [10]	163	1.223	1.014	0.829	45
Chen & Teng [1-2]	163	1.354	0.883	0.652	62
CNR-DT200 [86]	163	0.986	0.715	0.725	40
Sengun & Arslan [88]	163	0.693	0.430	0.621	19
CSA-S806 [87]	163	1.037	0.981	0.946	37

4.2.1 The Effect of The Stirrups

Except for Bukhari et al. [10] and Chen and Teng [1-2], the other equations gave unconservative results for the beams with stirrups with MV's less than one. In the beams without stirrups, all the equations other than Triantafillou [4], Mofidi & Chaallal [16], and Sengun & Arslan [88] had conservative results due to having MV's greater than one. The equations proposed by Sengun & Arslan [88] produced more reliable results due to the lower COV in beams with stirrups as seen in Table 8 and Figs. 11-12. Points above the inclined line indicate that the predictions are unconservative, while points below the inclined line imply that the predictions are conservative in Figs. 11-12. Triantafillou [4] and Sengun & Arslan [88] yielded the lower COV's in beams without stirrups. The investigated equations have commonly lower COV's in beams without stirrups with regard to the beams with stirrups. The ratio of the beams having conservative results in beams without stirrups was generally greater than the beam including stirrups. Thus, this result can be obtained for U-wrapped beams that the equations proposed in the calculation of FRP shear contribution have more reliable and consistent results in beams without stirrups.

Furthermore, collected beams contained a total of 102 U-wrapped beams with stirrups ratios (ρ_w) ranging from 0.071 to 0.838%. In beams with stirrups ratio (ρ_w) greater than 0.003, the percentage of unconservative results of ACI 440.2R [84], Fib-TG 9.3 [85], CNR-DT200 [86], and CSA-S806 [87] is 90%, 83%, 90%, and 94%, respectively. The stirrup ratio (ρ_w) is one of the key variables on the FRP contribution and the accuracy of the proposed equations. It could be concluded by means of the distribution of $V_{f,exp}/V_{f,pre}$ and ρ_w as seen in Fig. 13, the predictions of the ACI 440.2R [84], Fib-TG 9.3 [85], CNR-DT200 [86], and CSA-S806 [87] yielded highly inconsistent and unconservative results when the stirrups ratio (ρ_w) is greater than 0.003.

Table 8. Statistical results in terms of stirrups effect

Equations	U-wrapped beams									
	Beams with stirrups					Beams without stirrups				
	Specimen Number	MV	STD	COV	Conservative (%)	Specimen Number	MV	STD	COV	Conservative (%)
ACI 440.2R [84]	98	0.947	0.816	0.862	36	57	1.298	0.867	0.668	47
Triantafillou [4]	102	0.535	0.372	0.695	12	59	0.674	0.326	0.483	17
Fib-TG 9.3 [85]	102	0.848	0.623	0.734	38	59	1.084	0.541	0.499	54
Khalifa et al. [15]	98	0.848	0.633	0.747	36	56	1.393	0.998	0.717	52
Khalifa & Nanni [3]	63	0.770	0.631	0.819	32	38	1.161	0.726	0.626	47
Mofidi & Chaallal [16]	102	0.957	0.687	0.718	43	59	0.909	0.455	0.501	39
Bukhari et al. [10]	102	1.089	1.019	0.935	38	59	1.378	0.886	0.643	54
Chen & Teng [1-2]	102	1.104	0.754	0.683	51	59	1.715	0.879	0.513	80
CNR-DT200 [86]	102	0.914	0.702	0.768	36	59	1.032	0.605	0.586	46
Sengun & Arslan [88]	102	0.538	0.327	0.607	5	59	0.933	0.455	0.488	41
CSA-S806 [87]	102	0.930	1.011	1.086	30	59	1.151	0.829	0.721	46

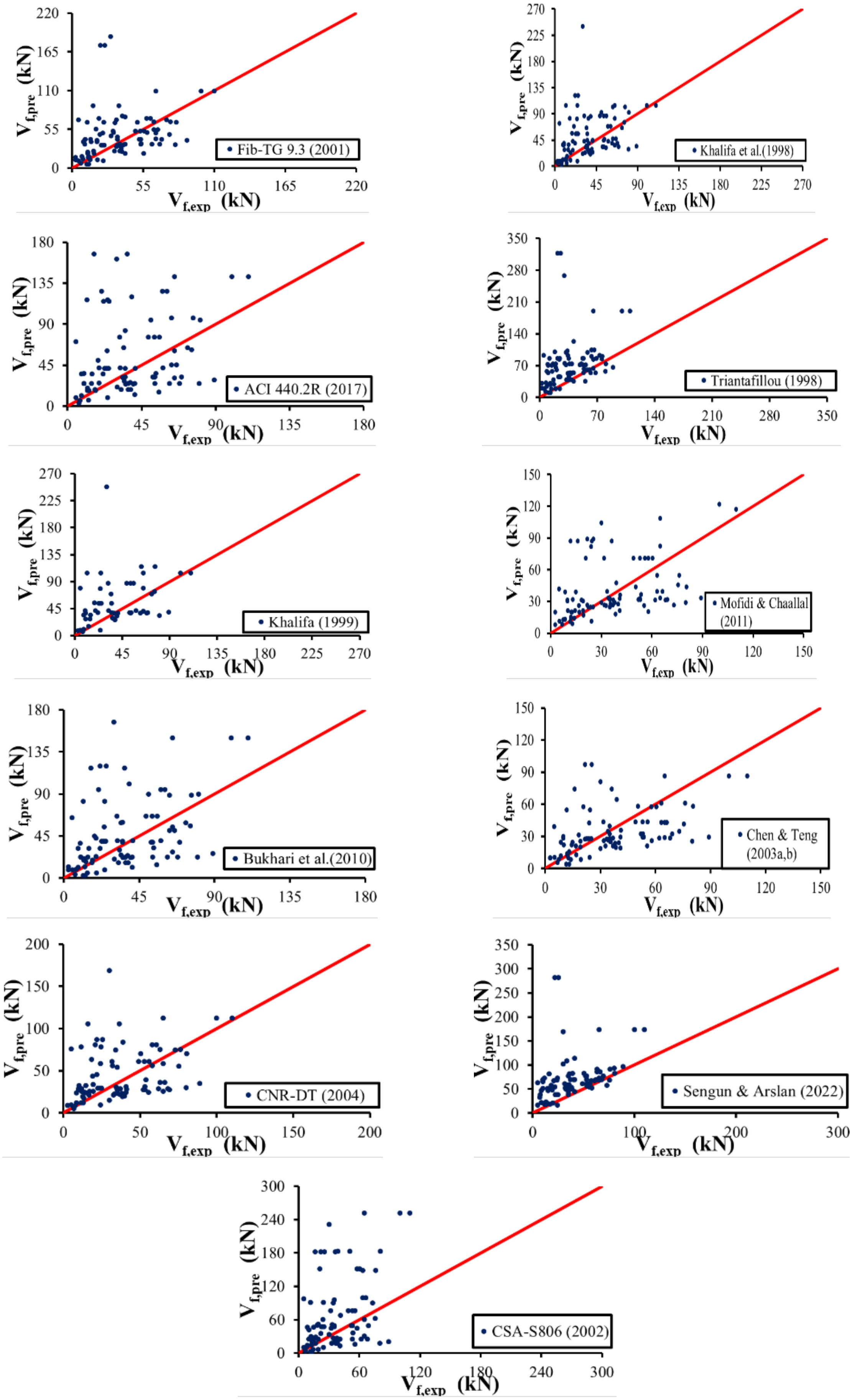


Fig. 11. The distribution of Vf,exp and Vf,pre on U-wrapped beams with stirrups

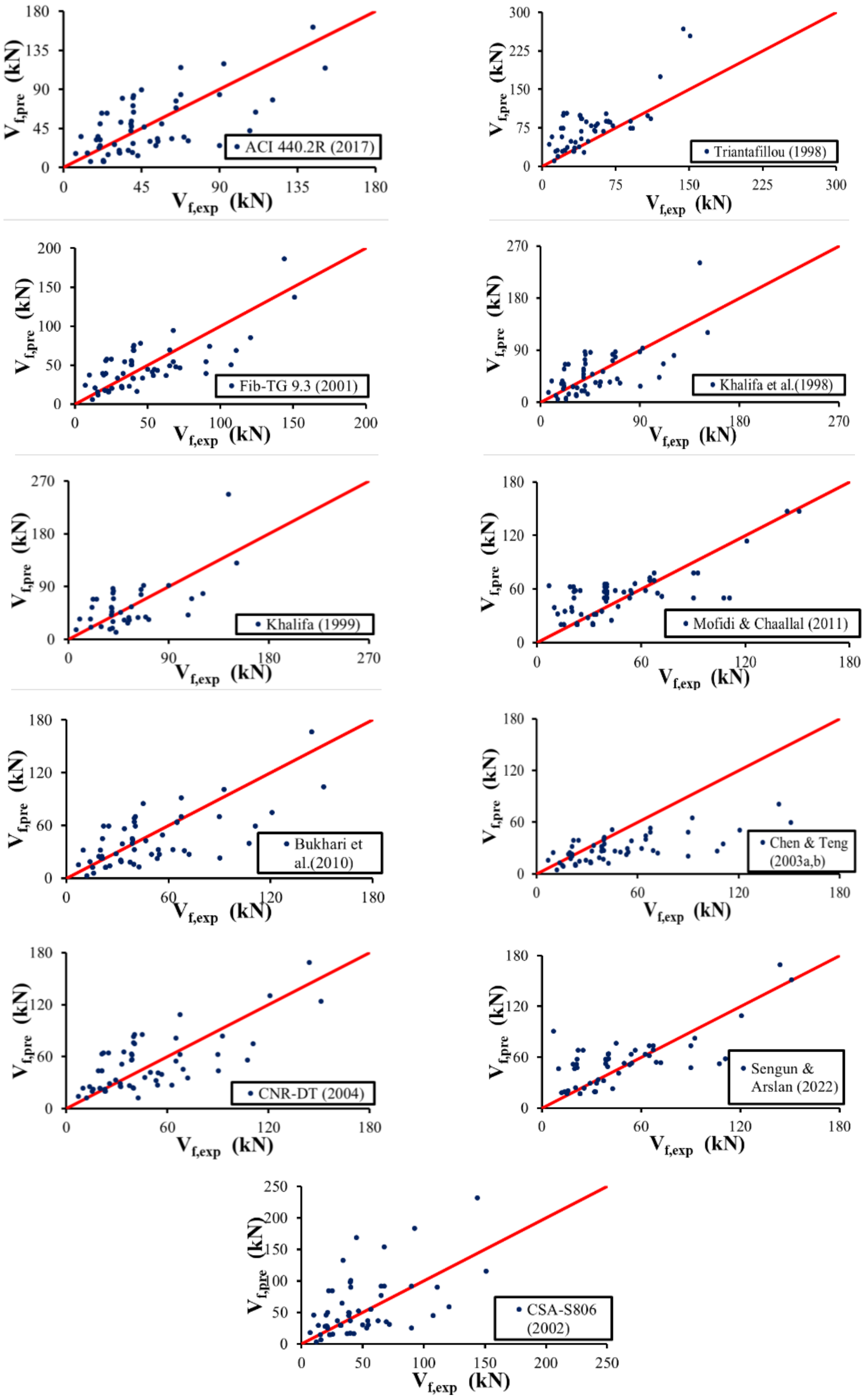


Fig. 12. The distribution of Vf,exp and Vf,pre on U-wrapped beams without stirrups

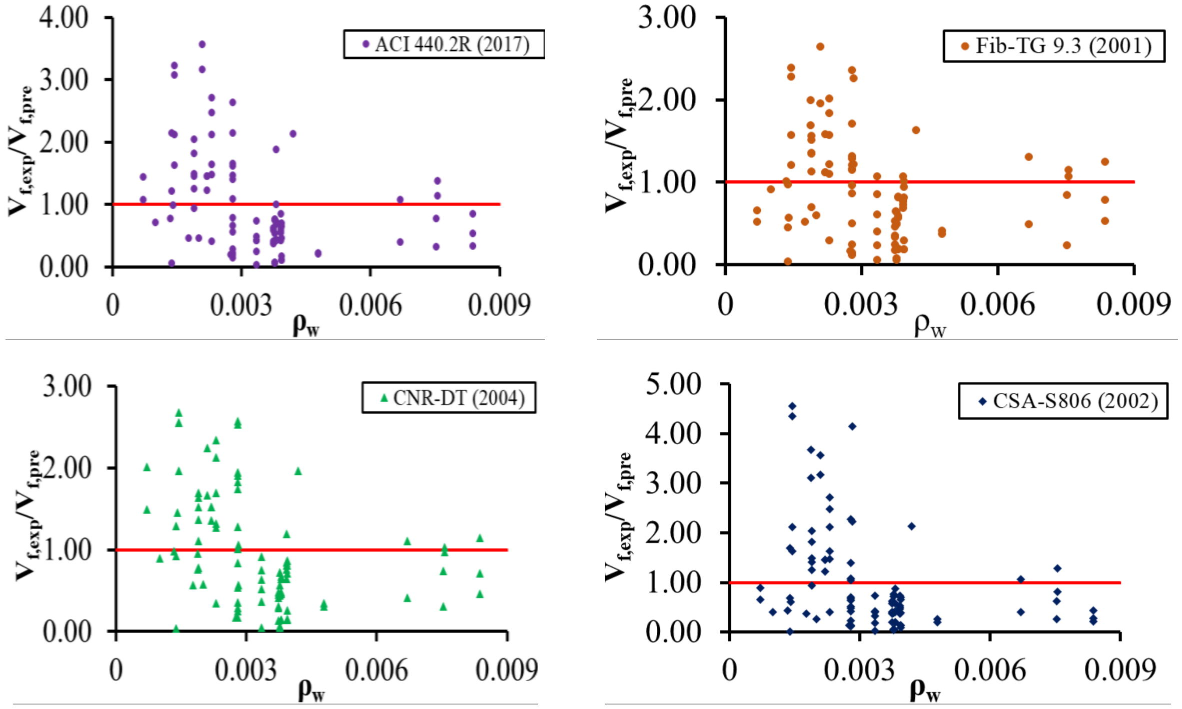


Fig. 13. The distribution of Vf,exp/Vf,pre according to a/d on U-wrapped beams

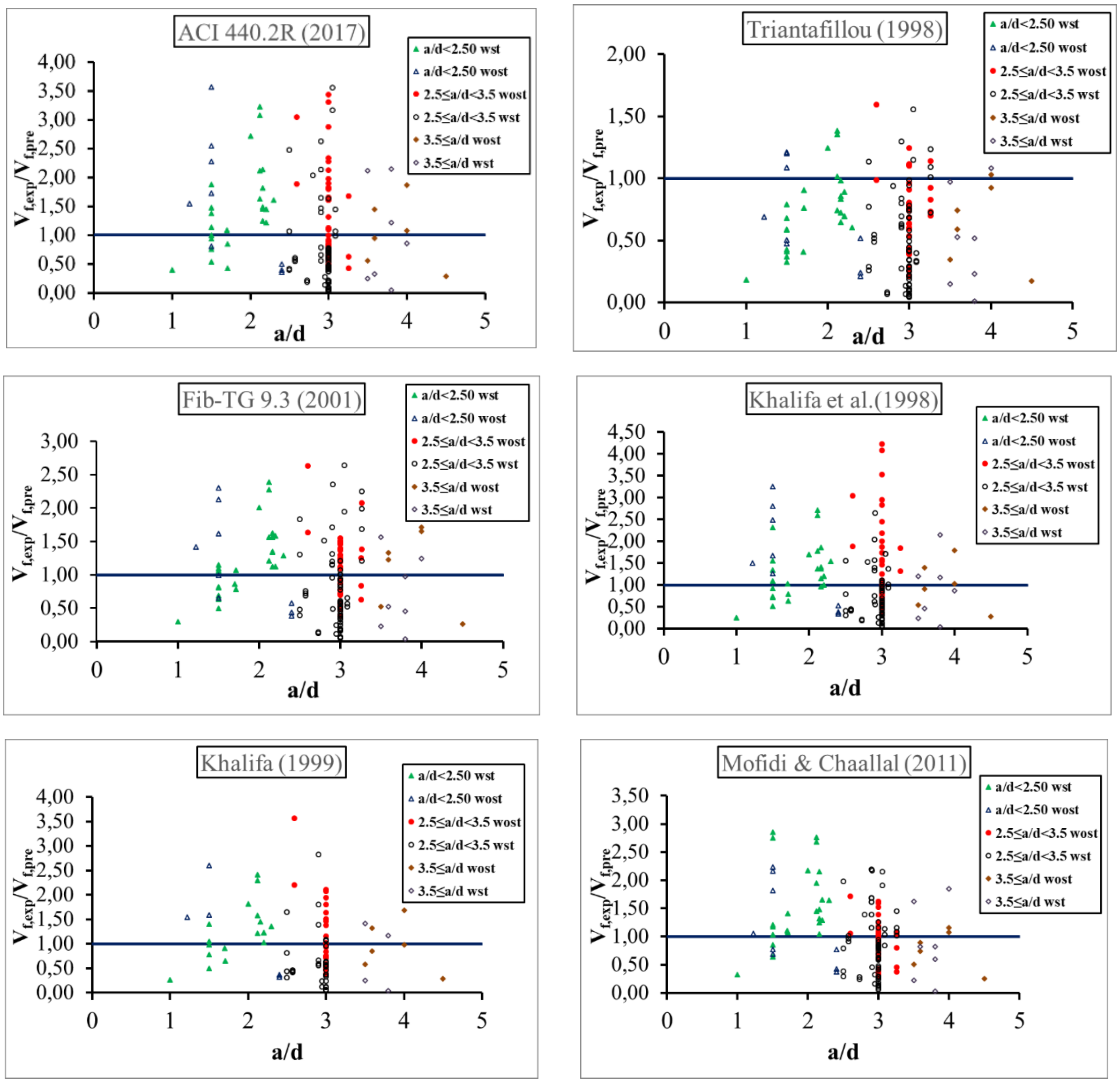
4.2.1 The Effect of a/d

"wost" represents the beams without stirrups, *"wst"* indicates the beams with stirrups in Fig. 14. Since the equation of Triantafillou [4] delivered predictions resulting in the lowest MV of the ratio of experimental results to predictions for all considered ranges of the *a/d*, it produced the most unconservative results among the considered equations (Table 9 and Fig. 14). The equations of Triantafillou [4], Mofidi & Chaallal [16] and Chen and Teng [1-2] yielded more reliable results for the beams with *a/d* less than 2.5 (*a/d<2.5*), between 2.5 and 3.5 (*2.5≤a/d<3.5*), and greater than 3.5 (*a/d≥3.5*), respectively, as they resulted in the lowest COV's.

Table 9. Statistical results in terms of a/d effect

Equations	U-wrapped beams														
	a/d<2.5					2.5≤a/d<3.5					a/d≥3.5				
	Specimen Number	MV	STD	COV	Conservative (%)	Specimen Number	MV	STD	COV	Conservative (%)	Specimen Number	MV	STD	COV	Conservative (%)
ACI 440.2R [84]	36	1.450	0.853	0.589	67	101	0.974	0.849	0.872	32	13	1.008	0.720	0.714	46
Triantafillou [4]	36	0.701	0.340	0.484	19	107	0.561	0.365	0.652	12	13	0.561	0.366	0.653	15
Fib-TG 9.3 [85]	36	1.163	0.587	0.505	61	107	0.876	0.604	0.690	39	13	0.904	0.589	0.652	46
Khalifa et al. [15]	36	1.332	0.772	0.580	67	100	0.979	0.865	0.883	34	13	0.925	0.623	0.673	46
Khalifa & Nanni [3]	23	1.242	0.640	0.515	65	63	0.827	0.724	0.875	30	10	0.857	0.552	0.644	40
Mofidi & Chaallal [16]	36	1.376	0.737	0.536	72	107	0.831	0.511	0.614	35	13	0.815	0.527	0.648	31
Bukhari et al. [10]	36	1.504	0.942	0.626	67	107	1.141	1.021	0.895	38	13	1.002	0.708	0.706	46
Chen & Teng [1-2]	36	1.682	0.967	0.575	78	107	1.264	0.814	0.644	59	13	1.112	0.650	0.585	54
CNR-DT200 [86]	36	1.244	0.706	0.567	58	107	0.864	0.647	0.749	34	13	1.061	0.637	0.601	54
Sengun & Arslan [88]	36	0.811	0.442	0.545	19	107	0.669	0.416	0.622	20	13	0.551	0.385	0.699	8
CSA-S806 [87]	36	1.373	1.079	0.786	58	107	0.937	0.929	0.991	31	13	0.805	0.672	0.834	31

Even though the equation proposed by Sengun & Arslan [88] is valid for the beams completely wrapped with FRP, it returned consistent results for the U-wrapped beams, especially those with *a/d* between 2.5 and 3.5 (*2.5≤a/d<3.5*), with a relatively low COV compared to the other equations. The *a/d* had substantial effect on both the experimental performance and prediction accuracy of the tested U-wrapped beams. All the considered equations except those proposed by Triantafillou [4], Mofidi & Chaallal [16] and Sengun & Arslan [88] produced predictions resulting higher COV's for the beams with *a/d* between 2.5 and 3.5 (*2.5≤a/d<3.5*) compared to the other considered ranges of *a/d*. Hence, their accuracies are lower for this range of *a/d* (*2.5≤a/d<3.5*). In case of the beams with *a/d* between 2.5 and 3.5 (*2.5≤a/d<3.5*), the percentages of the beams with conservative results for most of the considered equations are lower compared to the other considered ranges of *a/d*. In addition, the number of equations resulting in a MV of the ratio of experimental results to predictions less than one in this range of *a/d* (*2.5≤a/d<3.5*) is greater than those for the other considered ranges of *a/d*. The considered equations delivered more inconsistent results for U-wrapped beams, especially for the beams with *a/d* between 2.5 and 3.5 (*2.5≤a/d<3.5*). The *a/d* affects the accuracy of the equations. However, more experimental research is needed to understand better the impact of *a/d* on the FRP shear contribution and the accuracy of the proposed equations.



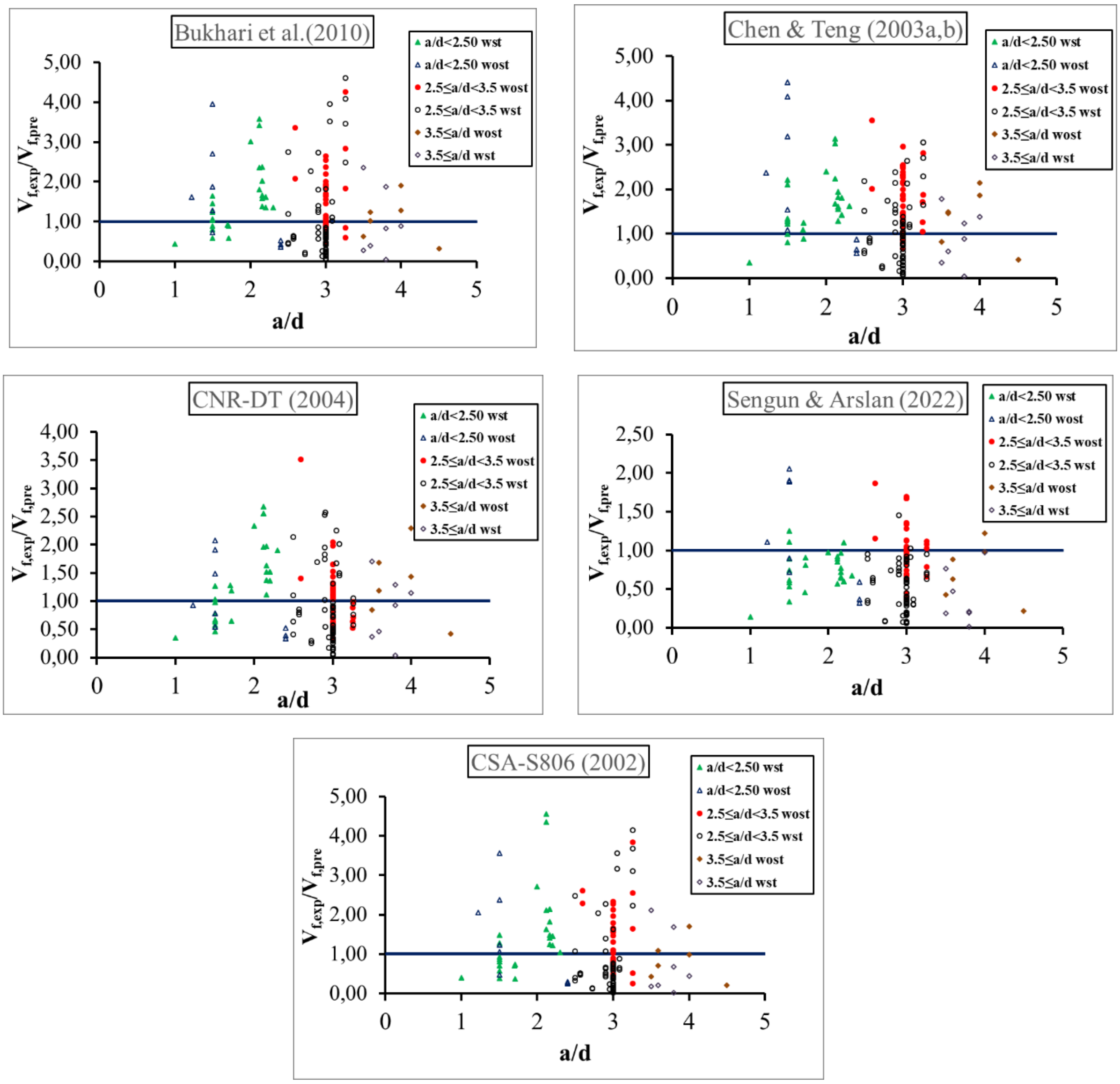


Fig. 14. The distribution of Vf,exp/Vf,pre according to a/d on U-wrapped beams

When the results obtained are evaluated collectively, it could be stated that the predictions of the proposed models in U-wrapped beams are highly inconsistent with the experimental results in beams with stirrups ratio (ρ_w) greater than 0.003 and with a/d between 2.5 and 3.5 (*2.5≤a/d<3.5*). Therefore, more experimental and analytical research are needed to derive analytical expressions including some important parameter such as stirrups and a/d for U-wrapped and side-bonded beams.

5. Conclusions

This study investigated CFRP-strengthened beams through both experimental and analytical methods. The experimental behavior was evaluated based on parameters such as strength, ductility, stiffness, failure modes, and strains. Furthermore, the influence of critical variables, including the a/d ratio and the presence of stirrups, on the experimental behavior of FRP-strengthened beams and the prediction accuracy of commonly used equations for calculating FRP shear contribution were analyzed. The principal findings from these analyses are summarized as follows:

- Strength, deflection, and ductility capacities of the beams were improved by strengthening with CFRP in comprasion to the unstrengthened beams.

- Since CFRP strengthening prevented the expansion and propagation of the cracks, the loss in stiffness subsequent to the diagonal shear cracks was less in the strengthened beams in comparison to the reference beams. In addition, CFRP-strengthening enhanced the load at which the first shear cracks occurred in K3.5S20 and K2.5S20 series compared to the reference beams.
- The yielding of the longitudinal reinforcement was delayed by the flexural strengthening by CFRP and slowed the flexural cracks to be widen. In addition, it could not be suitable to suppose that stirrups intersecting the shear cracks yielded in the case of shear failure in U-wrapping and side-bonding configurations due to the CFRP debonding as accepted in the specifications to figure out the stirrups' contribution to shear strength on CFRP strengthened beams.
- The cracking pattern and failure modes of the strengthened beams, compared to the reference beams, may be influenced by the CFRP strengthening configurations and the a/d ratio.
- As the a/d ratio increased, the failure loads of the strengthened beams and CFRP's contribution to load-carrying capacity decreased across all series. Changing the a/d ratio from 2.5 to 3.5 resulted in an average 25% decrease in strength for the reference beams with stirrups, as well as the completely wrapped and U-wrapped beams. Conversely, when the a/d ratio increased from 3.5 to 4.5, there was an average 20% decrease in the load-carrying capacities of the reference beams without stirrups, as well as the side-bonded and U-wrapped beams.
- The deflection capacities of the strengthened beams in flexure and shear with completely wrapped and the beams with U-wrapped CFRP in shear improved as *a/d* increased contrary to beams with side-bonded CFRP. It could be concluded that the *a/d* had substantial effect on the behavior and experimental performance of the strengthened beams differently based on the strengthening configurations.
- The failure loads of the strengthened beams with stirrups were higher than those without stirrups due to the added strength provided by the stirrups. However, the CFRP shear contribution was lower in beams with stirrups compared to those without. This experimental result suggests a potential interaction between the stirrups and CFRP that may negatively affect their individual contributions to shear strength.
- The w_f/s_f influenced the behavior of the strengthened beams differently depending on whether the beams have stirrups in the shear span. As w_f/s_f increased, the load-carrying capacity and CFRP contribution obtained higher on beams having no stirrups (K3.5S0 series) contrary to the beams with stirrups (K3.5S20 series). In beams strengthened with the same configuration of FRP, the reduction of w_f/s_f by increasing the center-to-center distance (s_f) between FRP shear strips resulted in an average of 45% decrease in deflection capacity.
- The CFRP contribution to strength and load-carrying capacity was higher in completely wrapped beams compared to U-wrapped and side-bonded beams in shear. However, if CFRP debonding was the failure mode, there was no significant difference in load-carrying capacity and CFRP contribution between U-wrapped and side-bonded configurations.
- The investigated equations produced more reliable results in beams without stirrups compared to those with stirrups in U-wrapped and side-bonded beams. For U-wrapped beams, the equations provided by Fib-TG 9.3 (2001), CSA-S806 (2002), ACI 440.2R (2017), and CNR-DT200 (2004) for the FRP shear contribution resulted in highly inconsistent and unconservative outcomes when the stirrup ratio exceeded 0.003
- Since Sengun & Arslan (2022) provided more reliable results for U-wrapped beams, their equation may be used to calculate the CFRP contribution in U-wrapped beams. Mofidi & Chaallal (2011) presented more reliable results for side-bonded beams. However, the accuracy of these equations should be verified with additional beams, and if necessary, the proposed equations should be refined.
- *a/d* affected the accuracy of the equations on both The accuracy of the predictions of the equations was affected by *a/d* in U-wrapped and side-bonded beams. In side-bonded beams, the investigated equations generally gave more consistent prediction with experimental results when *a/d* is between 2.5 and 3.5 ($2.5 \leq a/d < 3.5$) compared to the values where *a/d* is

less than 2.5(*a/d<2.5*). The equations had more inconsistent results, especially for the values of *a/d* between 2.5 and 3.5 (*2.5≤a/d<3.5*) in U-wrapped beams. Therefore, stirrups ratio and *a/d* need to be considered in the calculation of FRP shear contribution.

When the findings obtained in the previous and the present study are evaluated, it is concluded that the efficiency of completely-wrapped is superior to other strengthening configurations. Therefore, this configuration should be prioritized for retrofitting applications whenever feasible. In addition to its effect on experimental behavior, the stirrups have been demonstrated to influence the accuracy of prediction models. It is noteworthy that the majority of models do not incorporate this critical parameter explicitly. Consequently, there is a need to develop enhanced design models capable of producing more precise predictions for strengthened beams with stirrups. The integration of machine learning techniques in this field holds promise. Finally, it is observed that the U-wrapped and side-bonded specimens demonstrate similar behavior. The strengthening efficiency is found to be low due to the debonding problem. In these strengthening methods, it is hypothesized that anchors recommended in the literature should be employed to overcome the debonding problem. Additionally, the analytical findings from this study are applicable only to U-wrapped and side-bonded beams with an a/d ratio below 4.5. Further research is needed to determine the applicability of these results to completely-wrapped beams.

Data availability

A comprehensive paper that includes both experimental and analytical study.

References

[1] Chen JF, Teng JG. Shear capacity of FRP-strengthened RC beams: FRP debonding. Constr Build Mater. 2003;17(1):27-41. https://doi.org/10.1016/S0950-0618(02)00091-0

[2] Chen JF, Teng JG. Shear Capacity of Fiber-Reinforced Polymer-Strengthened Reinforced Concrete Beams: Fiber Reinforced Polymer Rupture. J Struct Eng. 2003;129(5):615-625. https://doi.org/10.1061/(ASCE)0733-9445(2003)129:5(615)

[3] Khalifa A, Nanni A. Rehabilitation of rectangular simply supported RC beams with shear deficiencies using CFRP composites. Constr Build Mater. 2002;16(3):135-146. https://doi.org/10.1016/S0950-0618(02)00002-8

[4] Triantafillou TC. Shear strengthening of reinforced concrete beams using epoxy-bonded FRP composites. ACI Struct J. 1998;95:107-115. https://doi.org/10.14359/531

[5] Triantafillou TC, Antonopoulos CP. Design of Concrete Flexural Members Strengthened in Shear with FRP. J Compos Constr. 2000;4(4):198-205. https://doi.org/10.1061/(ASCE)1090-0268(2000)4:4(198)

[6] Pellegrino C, Modena C. An experimentally based analytical model for the shear capacity of FRP-strengthened reinforced concrete beams. Mech Compos Mater. 2008;44(3):231-244. https://doi.org/10.1007/s11029-008-9016-y

[7] Pellegrino C, Modena C. Fiber Reinforced Polymer Shear Strengthening of Reinforced Concrete Beams with Transverse Steel Reinforcement. J Compos Constr. 2002;6(2):104-111. https://doi.org/10.1061/(ASCE)1090-0268(2002)6:2(104)

[8] Panda KC, Bhattacharyya SK, Barai SV. Shear strengthening of RC T-beams with externally side bonded GFRP sheet. J Reinf Plast Compos. 2011;30(13):1139-1154. https://doi.org/10.1177/0731684411417202

[9] Cao SY, Chen JF, Teng JG, Hao Z, Chen J. Debonding in RC Beams Shear Strengthened with Complete FRP Wraps. J Compos Constr. 2005;9(5):417-428. https://doi.org/10.1061/(ASCE)1090-0268(2005)9:5(417)

[10] Bukhari IA, Vollum RL, Ahmad S, Sagaseta J. Shear strengthening of reinforced concrete beams with CFRP. Mag Concr Res. 2010;62(1):65-77. https://doi.org/10.1680/macr.2008.62.1.65

[11] Pellegrino C, Modena C. Fiber-reinforced polymer shear strengthening of reinforced concrete beams: Experimental study and analytical modeling. ACI Struct J. 2006;103(5):720. https://doi.org/10.14359/16924

[12] Adhikary BB, Mutsuyoshi H, Ashraf M. Effective shear strengthening of concrete beams using FRP sheets with bonded anchorage. In: Fibre-Reinforced Polymer Reinforcement for Concrete Structures. 2003:457-466. https://doi.org/10.1142/9789812704863_0042

[13] Iannіruberto U, Imbimbo M. Role of Fiber Reinforced Plastic Sheets in Shear Response of Reinforced Concrete Beams: Experimental and Analytical Results. J Compos Constr. 2004;8(5):415-424. https://doi.org/10.1061/(ASCE)1090-0268(2004)8:5(415)

[14] Mostofinejad D, Tabatabaei Kashani A, Hosseini A. Design model for shear capacity of RC beams strengthened with two-side CFRP wraps based on effective FRP strain concept. Eur J Environ Civ Eng. 2016;20(2):161-179. https://doi.org/10.1080/19648189.2015.1021382

[15] Khalifa A, Gold WJ, Nanni A, MIA AA. Contribution of Externally Bonded FRP to Shear Capacity of RC Flexural Members. J Compos Constr. 1998;2(4):195-202. https://doi.org/10.1061/(ASCE)1090-0268(1998)2:4(195)

[16] Mofidi A, Chaallal O. Shear Strengthening of RC Beams with EB FRP: Influencing Factors and Conceptual Debonding Model. J Compos Constr. 2011;15(1):62-74. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000153

[17] Al-Rousan R. Predicting the Optimum Shear Capacity of Reinforced Concrete Beams Externally Strengthened With CFRP Composites. Procedia Manuf. 2020;44:631-638. https://doi.org/10.1016/j.promfg.2020.02.246

[18] Grande E, Imbimbo M, Rasulo A. Effect of Transverse Steel on the Response of RC Beams Strengthened in Shear by FRP: Experimental Study. J Compos Constr. 2009;13(5):405-414. https://doi.org/10.1061/(ASCE)1090-0268(2009)13:5(405)

[19] Ozturk M, Sengun K, Arslan G. CFRP contribution to load-carrying capacity of retrofitted geopolymer concrete beams. Struct. 2023;48:1391-1402. https://doi.org/10.1016/j.istruc.2023.01.028

[20] Kim G, Sim J, Oh H. Shear strength of strengthened RC beams with FRPs in shear. Constr Build Mater. 2008;22(6):1261-1270. https://doi.org/10.1016/j.conbuildmat.2007.01.021

[21] Damnoo DJ, Kumar S. Experimental study on post repair performance of reinforced concrete beams rehabilitated and strengthened with CFRP sheets. Res J Eng Technol. 2016;7(3):103. https://doi.org/10.5958/2321-581X.2016.00022.2

[22] Bousselham A, Chaallal O. Mechanisms of shear resistance of concrete beams strengthened in shear with externally bonded FRP. J Compos Constr. 2008;12(5):499-512. https://doi.org/10.1061/(ASCE)1090-0268(2008)12:5(499)

[23] Bousselham A, Chaallal O. Effect of transverse steel and shear span on the performance of RC beams strengthened in shear with CFRP. Compos Part B Eng. 2006;37(1):37-46. https://doi.org/10.1016/j.compositesb.2005.05.012

[24] Bencardino F, Spadea G, Swamy RN. The problem of shear in RC beams strengthened with CFRP laminates. Constr Build Mater. 2007;21(11):1997-2006. https://doi.org/10.1016/j.conbuildmat.2006.05.056

[25] Abass AL, Hassan YR. Shear behavior of reinforced concrete wide beams strengthened with CFRP sheet without stirrups. 2019;12(1):19. https://doi.org/10.24237/djes.2019.12110

[26] Benzeguir ZEA, El-Saikaly G, Chaallal O. Influence of size on the behavior of RC T-beams strengthened in shear with externally bonded CFRP.

[27] Jayaprakash J, Abdul Samad AA, Anvar Abbasovich A, Abang Ali AA. Shear capacity of precracked and non-precracked reinforced concrete shear beams with externally bonded bi-directional CFRP strips. Constr Build Mater. 2008;22(6):1148-1165. https://doi.org/10.1016/j.conbuildmat.2007.02.008

[28] Galal K, Mofidi A. Shear strengthening of RC T-beams using mechanically anchored unbonded dry carbon fiber sheets. J Perform Constr Facil. 2010;24(1):31-39. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000067

[29] Carolin A, Täljsten B. Experimental study of strengthening for increased shear bearing capacity. J Compos Constr. 2005;9(6):488-496. https://doi.org/10.1061/(ASCE)1090-0268(2005)9:6(488)

[30] Chaallal O, Nollet MJ, Perraton D. Shear strengthening of RC beams by externally bonded side CFRP strips. J Compos Constr. 1998;2(2):111-113. https://doi.org/10.1061/(ASCE)1090-0268(1998)2:2(111)

[31] Haddad RH, Marji CS. Composite strips with U-shaped CFRP wrap anchor systems for strengthening reinforced concrete beams. Int J Civ Eng. 2019;17(11):1799-1811. https://doi.org/10.1007/s40999-019-00447-w

[32] Teng JG, Chen GM, Chen JF, Rosenboom OA, Lam L. Behavior of RC beams shear strengthened with bonded or unbonded FRP wraps. J Compos Constr. 2009;13(5):394-404. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000040

[33] Li W, Leung CKY. Shear span-depth ratio effect on behavior of RC beam shear strengthened with full-wrapping FRP strip. J Compos Constr. 2016;20(3):04015067. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000627

[34] Bousselham A, Chaallal O. Behavior of reinforced concrete T-beams strengthened in shear with carbon fiber-reinforced polymer-an experimental study. ACI Struct J. 2006;103(3):339. https://doi.org/10.14359/15311

[35] Khalifa A, Belarbi A, Nanni A. Shear performance of RC members strengthened with externally bonded FRP wraps. New Zealand. 2000;9.

[36] Li W, Leung CKY. Effect of shear span-depth ratio on mechanical performance of RC beams strengthened in shear with U-wrapping FRP strips. Compos Struct. 2017;177:141-157. https://doi.org/10.1016/j.compstruct.2017.06.059

[37] Benzeguir ZEA, El-Saikaly G, Chaallal O. Size effect in RC T-beams strengthened in shear with externally bonded CFRP sheets: Experimental study. J Compos Constr. 2019;23(6):04019048. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000975

[38] Benzeguir ZEA, El-Saikaly G, Chaallal O. Size effect of RC T-beams strengthened in shear with externally bonded CFRP L-shaped laminates. J Compos Constr. 2020;24(4):04020031. https://doi.org/10.1061/(ASCE)CC.1943-5614.0001045

[39] Li A, Diagana C, Delmas Y. CRFP contribution to shear capacity of strengthened RC beams. Eng Struct. 2001;23(10):1212-1220. https://doi.org/10.1016/S0141-0296(01)00035-9

[40] Li A, Diagana C, Delmas Y. Shear strengthening effect by bonded composite fabrics on RC beams. Compos Part B Eng. 2002;33(3):225-239. https://doi.org/10.1016/S1359-8368(02)00003-3

[41] Khalifa A, Tumialan G, Nanni A, Belarbi A. Shear strengthening of continuous RC beams using externally bonded CFRP sheets. In: Proc., 4th Int. Symp. on FRP for Reinforcement of Concrete Structures (FRPRCS4); Baltimore, MD: American Concrete Institute; 1999; 995-1008.

[42] Allam SM, Ebeido TI. Retrofitting of RC beams predamaged in shear using CFRP sheets. Alexandria Eng J. 2003;42(1):16.

[43] Adhikary BB, Mutsuyoshi H. Behavior of concrete beams strengthened in shear with carbon-fiber sheets. J Compos Constr. 2004;8(3):258-64. https://doi.org/10.1061/(ASCE)1090-0268(2004)8:3(258)

[44] Mostofinejad D, Hosseini SA, Razavi SB. Influence of different bonding and wrapping techniques on performance of beams strengthened in shear using CFRP reinforcement. Constr Build Mater. 2016;116:310-20. https://doi.org/10.1016/j.conbuildmat.2016.04.113

[45] Leung CKY, Chen Z, Lee S, Ng M, Xu M, Tang J. Effect of size on the failure of geometrically similar concrete beams strengthened in shear with FRP strips. J Compos Constr. 2007;11(5):487-96. https://doi.org/10.1061/(ASCE)1090-0268(2007)11:5(487)

[46] Diagana C, Li A, Gedalia B, Delmas Y. Shear strengthening effectiveness with CFF strips. Eng Struct. 2003;25(4):507-16. https://doi.org/10.1016/S0141-0296(02)00208-0

[47] Mostofinejad D, Tabatabaei Kashani A. Experimental study on effect of EBR and EBROG methods on debonding of FRP sheets used for shear strengthening of RC beams. Compos Part B Eng. 2013;45(1):1704-13. https://doi.org/10.1016/j.compositesb.2012.09.081

[48] Panda KC, Bhattacharyya SK, Barai SV. Effect of transverse steel on the performance of RC T-beams strengthened in shear zone with GFRP sheet. Constr Build Mater. 2013;41:79-90. https://doi.org/10.1016/j.conbuildmat.2012.11.098

[49] Sundarraja MC, Rajamohan S. Strengthening of RC beams in shear using GFRP inclined strips - an experimental study. Constr Build Mater. 2009;23(2):856-64. https://doi.org/10.1016/j.conbuildmat.2008.04.008

[50] Sharkawi AEDM, Etman E. Effect of shear strengthening on the flexural behavior of RC simple beams strengthened externally with FRP laminates. In: Twelfth International Colloquium on Structural and Geotechnical Engineering. Ain Shams University, Faculty of Engineering, Department of Structural Engineering; 2007; 10-12.

[51] Rashidi M, Takhtfirouzeh H. An experimental study on shear and flexural strengthening of concrete beams using GFRP composites. 2018;3(1):7. https://doi.org/10.37516/global.j.civ.eng.2019.0047

[52] Nanda RP, Behera B, Majumder S, Khan HA. RC beam strengthening by glass fibre reinforced polymer. Int J Eng Technol Sci Res. 2018;5:21-6.

[53] Dong J, Wang Q, Guan Z. Structural behaviour of RC beams with external flexural and flexural-shear strengthening by FRP sheets. Compos Part B Eng. 2013;44(1):604-12. https://doi.org/10.1016/j.compositesb.2012.02.018

[54] Baggio D, Soudki K, Noël M. Strengthening of shear critical RC beams with various FRP systems. Constr Build Mater. 2014;66:634-44. https://doi.org/10.1016/j.conbuildmat.2014.05.097

[55] Grace NF, Sayed GA, Soliman AK, Saleh KR. Strengthening reinforced concrete beams using fiber reinforced polymer (FRP) laminates. ACI Struct J. 1999;96(5):865-74. https://doi.org/10.14359/741

[56] Ozden S, Atalay HM, Akpinar E, Erdogan H, Vulaş YZ. Shear strengthening of reinforced concrete T-beams with fully or partially bonded fibre-reinforced polymer composites. Struct Concr. 2014;15(2):229-39. https://doi.org/10.1002/suco.201300031

[57] Sundarraja MC, Rajamohan S, Bhaskar D. Shear strengthening of RC beams using GFRP vertical strips-an experimental study. J Reinf Plast Compos. 2008;27(14):1477-95. https://doi.org/10.1177/0731684407081772

[58] Nanda RP, Behera B. Experimental study of shear-deficient RC beam wrapped with GFRP. Int J Civ Eng. 2020;18(6):655-64. https://doi.org/10.1007/s40999-020-00498-4

[59] Van Cao V, Pham SQ. Comparison of CFRP and GFRP wraps on reducing seismic damage of deficient reinforced concrete structures. Int J Civ Eng. 2019;17(11):1667-81. https://doi.org/10.1007/s40999-019-00429-y

[60] Alacali S, Akkaya HC, Sengun K, Arslan G. Proposal and evaluation of new models for predicting the FRP contribution to shear strength in reinforced concrete beams using gene expression programming. Neural Comput Appl. 2024;36(25):15515-44. https://doi.org/10.1007/s00521-024-09892-8

[61] Saafan MAA. Shear strengthening of reinforced concrete beams using GFRP wraps. Acta Polytech. 2006;46(1). https://doi.org/10.14311/800

[62] Sengun K, Arslan G. Performance of RC beams strengthened in flexure and shear with CFRP and GFRP. Iran J Sci Technol Trans Civ Eng. 2024;48:117-30. https://doi.org/10.1007/s40996-023-01305-5

[63] Hawileh RA, Rasheed HA, Abdalla JA, Al-Tamimi AK. Behavior of reinforced concrete beams strengthened with externally bonded hybrid fiber reinforced polymer systems. Mater Des. 2014;53:972-82. https://doi.org/10.1016/j.matdes.2013.07.087

[64] Keskin RSO, Arslan G, Sengun K. Influence of CFRP on the shear strength of RC and SFRC beams. Constr Build Mater. 2017;153:16-24. https://doi.org/10.1016/j.conbuildmat.2017.06.170

[65] Sengun K, Arslan G. Parameters affecting the behaviour of RC beams strengthened in shear and flexure with various FRP systems. Structures. 2022;40:202-12. https://doi.org/10.1016/j.istruc.2022.04.024

[66] Sengun K, Arslan G. Influence of CFRP on the strength of retrofitted RC beams without stirrups. Sigma J Eng Nat Sci. 2017;35(1):77-85.

[67] Kar S, Biswal KC. Shear strengthening of reinforced concrete T-beams by using fiber-reinforced polymer composites: a data analysis. Arab J Sci Eng. 2020;45(5):4203-34. https://doi.org/10.1007/s13369-020-04412-x

[68] Kotynia R, Oller E, Marí A, Kaszubska M. Efficiency of shear strengthening of RC beams with externally bonded FRP materials - State-of-the-art in the experimental tests. Composite Structures. 2021;18. https://doi.org/10.1016/j.compstruct.2021.113891

[69] Lima JL, Barros JA. Reliability analysis of shear strengthening externally bonded FRP models. Proc Inst Civ Eng Struct Build. 2011;164(1):43-56. https://doi.org/10.1680/stbu.9.00042

[70] Pellegrino C, Vasic M. Assessment of design procedures for the use of externally bonded FRP composites in shear strengthening of reinforced concrete beams. Compos Part B Eng. 2013;45(1):727-41. https://doi.org/10.1016/j.compositesb.2012.07.039

[71] Taerwe L, Khalil H, Matthys S. Behaviour of RC beams strengthened in shear by external CFRP sheets. In: Proc 3rd Int Symp Nonmetallic (FRP) Reinforcement for Concrete Structures. Tokyo: Japan Concrete Institute; 1997. p. 483-90.

[72] Khalifa A, Nanni A. Improving shear capacity of existing RC T-section beams using CFRP composites. Cem Concr Compos. 2000;22(3):165-74. https://doi.org/10.1016/S0958-9465(99)00051-7

[73] Panda KC, Bhattacharyya SK, Barai SV. Shear strengthening effect by bonded GFRP strips and transverse steel on RC T-beams. Struct Eng Mech. 2013;47(1):75-98. https://doi.org/10.12989/sem.2013.47.1.075

[74] Sato Y, Ueda T, Kakuta Y, Ono S. Ultimate shear capacity of reinforced concrete beams with carbon fiber sheet. In: Proc 3rd Symp Non-Metallic (FRP) Reinforcement for Concrete Structures (FRPRCS-3). Sapporo, Japan; 1997; 1: 499-505.

[75] Wu G, An L, Lv ZT. Experimental research on RC beam strengthened in shear with CFRP sheet. J Build Struct. 2000;30(7):16-20, 51. (in Chinese).

[76] Tan Z, Ye LP. Experimental research on shear capacity of RC beam strengthened with externally bonded FRP sheets. China Civ Eng J. 2003;36(11):12-8. (in Chinese).

[77] Feng XS, Chen ZF. Experimental research on shear strengthening of reinforced concrete beams with externally bonded CFRP sheets. Ind Constr. 2004;Supplement:89-93. (in Chinese).

[78] Rizzo A, De Lorenzis L. Behavior and capacity of RC beams strengthened in shear with NSM FRP reinforcement. Constr Build Mater. 2009;23(4):1555-67. https://doi.org/10.1016/j.conbuildmat.2007.08.014

[79] Mofidi A, Chaallal O. Shear strengthening of RC beams with externally bonded FRP composites: Effect of strip-width-to-strip-spacing ratio. J Compos Constr. 2011;15(5):732-42. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000219

[80] Micelli F, Annaiah RH, Nanni A. Strengthening of short shear span reinforced concrete T joists with fiber-reinforced plastic composites. J Compos Constr. 2002;6(4):264-71. https://doi.org/10.1061/(ASCE)1090-0268(2002)6:4(264)

[81] Sato Y, Veda T, Kakuta Y, Tanaka T. Shear reinforcing effect of carbon fiber sheet attached to side of reinforced concrete beams. In: El-Badry MM, editor. Adv Compos Mater Bridges Struct. 1996. p. 621-7.

[82] Uji K. Improving shear capacity of existing reinforced concrete members by applying carbon fiber sheets. Trans Jpn Concr Inst. 1992;14:253-66.

[83] Antonopoulos CP. Shear strengthening of reinforced concrete structures using composite materials [Diploma thesis]. Patras, Greece: University of Patras, Department of Civil Engineering; 2000.

[84] American Concrete Institute. Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures (ACI 440.2R-17). Farmington Hills, MI, USA; 2017.

[85] Fédération internationale du béton. Externally bonded FRP reinforcement for RC structures. Task Group 9.3, Bulletin No. 14. Lausanne, Switzerland; 2001.

[86] CNR-Italian Research Council, Advisory Committee on Technical Recommendations for Construction. Guide for the design and construction of externally bonded FRP systems for strengthening existing structures. Rome, Italy; 2004.

[87] CAN/CSA. Design and construction of building components with fiber-reinforced polymer. S806-02. Canadian Standards Association, Rexdale, Canada; 2002.

[88] Sengun K, Arslan G. Investigation of the parameters affecting the behavior of RC beams strengthened with FRP. Front Struct Civ Eng. 2022. https://doi.org/10.1016/j.istruc.2022.04.024

[89] Guadagnini M, Pilakoutas K, Waldron P. Shear resistance of FRP RC beams: Experimental study. J Compos Constr. 2006;10(6):464-73. https://doi.org/10.1061/(ASCE)1090-0268(2006)10:6(464)

[90] Lee HK, Cheong SH, Ha SK, Lee CG. Behavior and performance of RC T-section deep beams externally strengthened in shear with CFRP sheets. Compos Struct. 2011;93(2):911-22. https://doi.org/10.1016/j.compstruct.2010.07.002

[91] Panigrahi SK, Deb A, Bhattacharyya SK. Modes of failure in shear deficient RC T-beams strengthened with FRP. J Compos Constr. 2016;20(1):04015029. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000586

[92] Akkaya HC, Aydemir C, Arslan G. Evaluation of shear behavior of short-span reinforced concrete deep beams strengthened with fiber reinforced polymer strips. Eng Struct. 2024;299:117145. https://doi.org/10.1016/j.engstruct.2023.117145