

Effect of confining FRP overlays on bond strength enhancement

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Abstract

In this study, changes in the bond strength of reinforcing bars due to external confinement, through FRP overlays, was investigated. Eccentric pullout specimens with insufficient bond length and with two different normal strength concrete levels were reinforced with single deformed bars placed with a small cover thickness. Three reinforcing bar sizes and two FRP types, each having two different number of layers, were used in the experiments. Significant enhancement in bond strength due to FRP confinement was observed in all specimens. Although the increase in bond strength was closely related to the clamping force developed by the FRP overlays, the effectiveness of the invoked clamping force reduces beyond a limiting value. The orientation of the splitting cracks was also affected by the existence of the FRP overlays.

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1. Introduction

The bond mechanism and the parameters affecting the bond strength between reinforcing bars and the concrete are commonly defined and cataloged by the researchers of the recent century [1–6]. Parameters affecting the bond strength may be summarized into three major groups as follows. Components of the concrete mix, such as the types of aggregates, binding minerals, fibers, admixtures, and the level of concrete strength, both compressive and tensile, may be accounted as the first group of parameters [1,5,7–20]. The second group, which is mainly associated with the reinforcing bar itself, may be listed as reinforcing bar diameter, rib geometry and reinforcing bar surface specifications, splice length, position of the reinforcing bars with respect to each other and to concrete surface, and the reinforcing bar surface coating [1,2,4,9,16–18,21–26]. The rest of the influencing parameters may be classified in the third group and may be listed as the existence and amount of transverse rein-

forcement, lateral pressure, temperature, corrosion level, environmental conditions, and the loading history, etc. [4,8,14,18,24,25,27–30].

Bond stress that leads the concrete and reinforcing steel to work together is the result of an interaction between the reinforcing bar and the concrete placed around it. The main part of this interaction may be defined as the mechanical bond stresses in the case of deformed reinforcing bars. The pseudo-concrete-cylinder (PCC) which is placed around the reinforcing bar, with a diameter bordered with the minimum of concrete cover or half of the bar spacing, controls the bond action and the bond failure basically. The mechanical bond stresses developed in case of deformed reinforcing bars yields radial stress components, depending on the rib geometry and rib angle, that causes tensile stresses in the so called PCC and tries to split it to failure [2–4,6]. Delaying the tensile splitting of PCC or totally preventing it enhances the bond strength and may well be succeeded by using transverse steel around the reinforcing bars, or by increasing the tensile strength of the concrete matrix by using higher strength concrete. On the other hand, it should be noted that, the shearing of con-

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Notation

C	concrete cover thickness (mm)	P	tension force on the reinforcing bar applied by the hydraulic jack
C_s	rib spacing (mm)	t_{FRP}	thickness of FRP overlay (one ply) (mm)
D_b	reinforcing bar diameter (mm)	u_c	calculated average bond stress at failure (MPa)
E_{Comp}	modulus of elasticity of composite (FRP and epoxy) (MPa)	u_e	measured average bond stress at failure (MPa)
E_{Epoxy}	modulus of elasticity of epoxy resin (MPa)	u_{eo}	measured average bond stress at failure in virgin specimens (MPa)
E_{FRP}	modulus of elasticity of FRP overlay (MPa)	V	vertical support forces (kN)
E_s	modulus of elasticity of reinforcing bar (MPa)	VP_{Epoxy}	volume percent of epoxy resin in epoxy–FRP composite (%)
f'_c	compressive strength of concrete (150×300 mm cylinder) (MPa)	VP_{FRP}	volume percent of FRP in epoxy–FRP composite (%)
f'_{cn}	nominal compressive strength of concrete (MPa)	w	cross-sectional width of the specimen (mm)
f'_{cs}	split cylinder strength of concrete (150 × 300 mm cylinder) (MPa)	σ_{CSCc}	calculated clamping stress on PCC (MPa)
F_R	rib area (mm ²)	$\sigma_{CSCc-lim}$	limit value for the calculated clamping stress on PCC (MPa)
f_y	yield strength of reinforcing bar (MPa)	σ_{CSCe}	measured clamping stress on PCC (MPa)
h	cross-sectional height of the specimen (mm)	σ_{FRPe}	measured average stress in FRP at the time of bond failure (MPa)
k	number of ribs at cross-section of the bar	$\Delta(u_c/f'_c)^{(1/2)}$	normalized bond strength enhancement
k_1	aspect coefficient for bond effectiveness (considers perimeter/area relation)	α	rib inclination to bar axis (°)
l_b	bond length (mm)	β	rib face angle (°)
L_{SR}	gauge length of strain readings on FRP parallel to fiber orientation (mm)	ϵ_{co}	concrete tensile strain at the time of bond failure
m_1	initial slope of the idealized effectiveness of FRP clamping on bond strength	ϵ_{FRPe}	calculated FRP strain at the time of bond failure
m_2	secondary slope of the idealized effectiveness of FRP clamping on bond strength	ϵ_{FRPc}	measured FRP strain at the time of bond failure
n	number of FRP layer	PCC	pseudo-concrete-cylinder
		RRA	relative rib area

crete lugs between the ribs of reinforcement along the reinforcing bar axis is another limit for the bond failure.

Available literature on the subject reveals that higher strength concrete classes provide higher tensile strength, hence resulting improvement in bond strength. On the other hand, the increase in tensile strength of concrete beyond a certain compressive strength level is so small that the bond strength may not be improved further [10,16,18,26]. In addition, the bond stress distribution along the reinforcing bar axis becomes more non-uniform and fewer lugs participate in the stress transform in the case of higher concrete strength classes [15,18]. The use of steel fibers in the concrete matrix is reported to increase the tensile strength and toughness of concrete, resulting in a higher bond strength and leading to a considerable improvement in ductility of bond slip behavior especially for the cases of splitting predominant failures; through delaying the splitting failures [6,12–14,19]. Higher bond strengths may be obtained for higher ratios of steel fibers in concrete.

The ratio of wall thickness of the PCC surrounding the reinforcing bar, to the reinforcing bar diameter (C/D_b) is observed as another parameter affecting the

bond strength. It was reported that, lower C/D_b values results in lower bond strength values [21]. On the other hand, sustained increases in C/D_b beyond a certain limit does not result in bond strength increase since the failure mechanism changes from splitting of PCC towards the pullout of reinforcing bar. This limiting value is reported between 2.5 and 3 in the available literature [4,25].

Confinement on the concrete section, either active or passive, has significant positive contribution on the bond strength [6,25]. It can be concluded from the results of many researchers that the use of transverse reinforcement in reinforced concrete members causes higher bond strength levels and more ductile bond behavior; leading to sufficient bond strength with a relatively shorter anchorage length [4,6,8,18,27,29,30]. Likely the effects of concrete cover thickness, sustained increases in confinement may not result in further bond strength increases since the failure mode is changed from splitting to pullout. Some of the recent investigations indicated that FRP wrapped concrete beams were upgraded by means of not only significant improvements in load capacity and ductility but also considerable enhancement on bond performance [31–33].

2. Experimental procedure

Insufficient anchorage length in flexural members generally results in brittle and premature failures triggered by inadequate bond strength. The anchorage length may be considered as insufficient due either to a lower concrete strength, higher reinforcing steel yield strength, small concrete cover thickness, or small anchorage length relative to the design specified values, and the external FRP confining overlays may well be a solution in the case of such deficiencies. This study highlights the effectiveness of bond strength improvement and attainable level of bond strength increase by the use of FRP confining overlays.

2.1. Test specimens

Seventy H-shaped eccentric pullout specimens (Fig. 1) with insufficient bond length, l_b were designed and constructed in this study [34]. The H-shaped specimens which have rectangular cross-section at the testing region ($w = 240$ mm; $h = 300$ mm) were intended to simulate the bond in a reinforced concrete member under combined flexure and shear forces (Fig. 1). In order not to trigger a shear failure before reaching the bond strength of the sub-assembly, the length of the member was designed longer than the bond length. No longitudinal or transverse reinforcement, except the specific reinforcing bar for the bond test, was used in any of the H-shaped specimens.

Two different concrete nominal compressive strength levels, namely $f'_{cn} = 20$ MPa and $f'_{cn} = 40$ MPa, were used in the test specimens. It was intended to obtain data for the normal strength concrete (NSC) range which is common in the existing building and bridge stock. Three different bar diameters (D_b) were used in each concrete strength level. The cross-sectional area over perimeter ratio for the $D_b = 12$ mm, $D_b = 16$ mm and $D_b = 26$ mm reinforcing bars were 3.0, 4.0 and 6.5, respectively. The reinforcing bars were placed at the bottom of the cross-section (bottom cast bars) during casting. For each combination of concrete quality and reinforcing bar diameter, two different FRP

types, namely CFRP and GFRP, were used with two different number of layers. The FRP overlays were used only over the bonded length, l_b and the fiber orientation of the FRP layers were perpendicular to the reinforcing bar axis. In each set, two specimens were tested without FRP overlay. The concrete cover thickness over reinforcing bar diameter ratio (C/D_b) was kept at unity in all specimens.

The specimens were named in a way to recognize the variables tested in this specific specimen. The first four letters in the specimen names give the nominal concrete strength in MPa. The next three letters show the diameter of reinforcing bar in millimeters. The third info block with three letters shows the polymer type and the number of layer of the confining FRP overlay. And the last variable block was used to distinguish the replicas of the specimens with the same variable list. The first specimen with 20 MPa concrete strength and 26 mm bar diameter, confined with 4 layers of CFRP was named as EC20D26-FC4-A while the second specimen of the same set was called as EC20D26-FC4-B.

2.2. Material properties

Portland cement, river sand and crushed limestone were used in the concrete mix. The water cement ratios for $f'_{cn} = 20$ MPa and $f'_{cn} = 40$ MPa concrete classes were 0.8 and 0.48, respectively. A commercially available superplasticizer conforming to ASTM C494-81-F specifications was used in the $f'_{cn} = 40$ MPa concrete at an amount equal to 2% of the cement weight. Vibration was applied to all specimens for regular compaction of concrete. The development of concrete compressive strength over time was monitored by compression tests on 150×300 mm cylinders. Concrete compressive strength values (f'_{cn}) at the time of sub-assembly testing varied between 19.3 and 24.6 MPa for the $f'_{cn} = 20$ MPa specimen set and between 40.6 and 45.5 MPa for the $f'_{cn} = 40$ MPa specimen set.

The reinforcing bars with 12, 16, and 26 mm nominal diameters (D_b) were tested in a 600 kN capacity universal testing machine, with fully electronic data acquisition, in

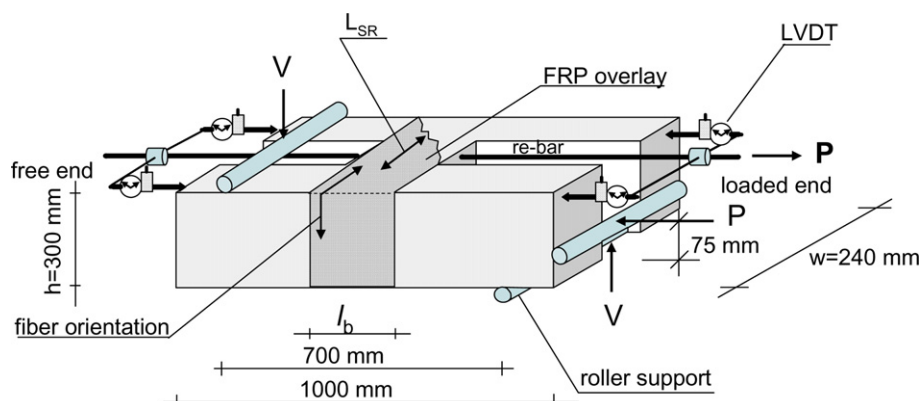
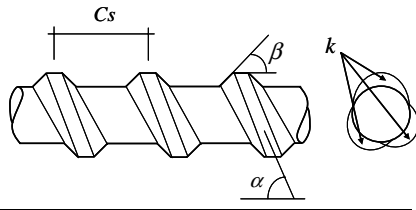


Fig. 1. Specimen dimensions.

Table 1
FRP, epoxy and reinforcing bar properties

Property	FRP and Epoxy		
	CFRP	GFRP	Epoxy
Thickness (mm)	0.117	0.157	N/A
Modules of Elasticity (MPa)	240,000	73,000	6000
Tensile strength (MPa)	3800	3400	17
Fiber density (g/m ³)	1.70	2.54	N/A
Fiber area weight (g/m ²)	200	400	N/A
Ultimate elongation (%)	1.58	4.66	N/A
Adhesion to concrete (MPa)	N/A	N/A	4
	Reinforcing bar		
	$D_b = 12$ mm	$D_b = 16$ mm	$D_b = 26$ mm
Nominal bar diameter (mm)	12	16	26
Modules of Elasticity (MPa)	195,000	194,400	195,100
Yield Strength (MPa)	495	510	540
No. of ribs at the x -section, k	3	3	3
Area of one rib, F_R (mm ²)	6.57	13.29	33.44
Rib angle, α (°)	53.0	50.8	50.7
Rib face angle, β (°)	46.3	47.0	48.2
Rib spacing, C_s (mm)	7.46	10.98	15.84
Relative rib area (RRA)	0.056	0.056	0.060
	$RRA = \frac{kF_R \sin \alpha}{\pi D_b C_s}$		



order to clearly define the modulus of elasticity (E_s) and the yield strength (f_y) (Table 1). The rib geometry of the reinforcing bars also were measured and listed in Table 1 with reference to Fig. 1. All three reinforcing bars can be classified as high relative rib area reinforcing bars good for high bond strength.

The CFRP and GFRP fabrics used in this investigation were unidirectional and with continuous fiber forms. The manufacturer specified material properties of FRP fabrics and the epoxy resin are presented in Table 1.

2.3. Strengthening of specimens

The same FRP application procedure was used in all strengthened test specimens. Special consideration was given to the surface and corner preparation of the specimens before the application of the epoxy glued FRP fabrics. All specimen corners were grinded to a radius of 25 mm before the application of the FRP overlays. Steel wire brushing and air washing was applied to the surface of the specimens to remove the dust and loose particles from the surface.

During the application process of FRP to the specimen surface over the bond length, one layer of epoxy was applied to the specimen surface initially. Later FRP fabrics were placed with an orientation perpendicular to the reinforcing bar axis. Each FRP layer was impregnated with a steel roller and coated with epoxy adhesive. The final overlap length of FRP fabrics were 100 mm. All strengthened specimens were cured in the laboratory for not less than 7 days before the test.

2.4. Test setup and loading history

The H-shaped eccentric pullout specimens (Fig. 1) were tested horizontally in a specially designed test setup. The tension force on the reinforcing bar (P) was applied by two hollow type, manually driven hydraulic jacks seated on either end of the protruding reinforcing bar, and the level of the force was measured by two 100 kN capacity load cells. Reversed tension–unload–tension type of loading scheme on either end of the reinforcing bar was applied to all specimens. Three reversed load cycles were made at 10%, 20%, 30% and 40% load levels of the specimen's calculated bond capacity. The nominal bond strength for all specimens was calculated as $2f_{cn}^{(1/2)}$ and the test load P was calculated by the product of the nominal bond strength and the bonded surface area of the reinforcing bar. All specimens were loaded to failure after the 40% load cycle.

The test specimens were fixed horizontally, and the moment caused by the P force and the horizontal reaction was resisted by the coupling moment created by the vertical support forces, V ; in turn V acts as shear force on the specimen.

Four 30 mm capacity linear variable differential transducers (LVDT) with a sensitivity of 0.01 mm were used to measure the free and loaded end slip values on either ends of the specimens. All displacement and load readings, along with the average strain measurements on the FRP layers (in the direction of fibers) (Fig. 1), were monitored and recorded by an electronic data acquisition system. The average strain measurements on FRP were made by using an LVDT driven clip gauge with a $L_{SR} = 100$ mm gauge length.

3. Experimental observations

3.1. Cracks and failure modes

All specimens reported in this study reached their ultimate failure load mainly through splitting type of bond failure. The strains on the FRP overlays, which was measured perpendicular to the reinforcing bar axis, and reinforcing bar free end slip values reached their maximum right prior to the bond failure.

The splitting cracks on the anchorage region of the specimens without FRP overlays, were unique and aligned with the reinforcing bars (Fig. 2). These cracks were between the reinforcing bar and the specimen's top surface, which

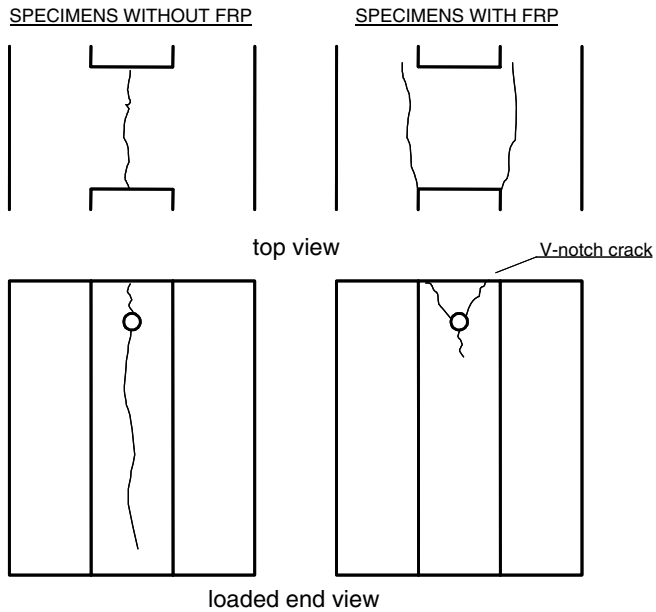


Fig. 2. Splitting failure cracks in specimens.

points out the smallest cover thickness, and were observable at the loaded ends. In addition, V-notch cracks with an approximate V-notch angle of less than 30° were also observed at the free end of these specimens.

On the other hand, two main splitting cracks starting from the reinforcing bar and forming a V-notch at either end were observed on all specimens wrapped with FRP overlays. The angle between the V-notch cracks varied mainly depending on the modulus of elasticity and the total thickness of the FRP overlays; in other words depending on the amount of clamping force generated by the FRP overlay. The splitting cracks observed at the loaded end of the specimen were almost horizontal (V-notch failure surface flattens) for most of the confined specimens. The V-notch angle at the free end also increased with increasing number of layer of FRP overlays.

It was observed that the splitting cracks along the reinforcing bar axis were also traceable through the depth of the specimens that were without FRP overlays. The application of the FRP overlay confined these splitting cracks to the cover region and prevented the expansion and progress of these cracks through the depth of the specimen by changing the crack orientation. It should be noted that the higher the elastic modulus or number of layers of FRP overlays, the confined the cracking to the reinforcing bar periphery (Fig. 2).

Although the effects of conventional transverse reinforcement and the FRP overlays on bond strength enhancement and on splitting crack development are similar, unlike the transverse reinforcement, FRP overlays not only delayed the crack propagation but also altered their orientations from the shortest distance to the surface to a longer concrete path (Fig. 2).

The degradation of pull-out stiffness, which is the slope of the load versus loaded-end-slip graphics, of all

specimens tested under tension–unload–tension type of reversed loading was also investigated [34]. It was observed that the stiffness degradation under reversed loading (loaded maximum to 40% of capacity) was insignificant at approximately service load levels.

3.2. Enhancement in bond stress at failure

The concrete properties (f'_c and f'_{cs}), reinforcing bar diameter (D_b), anchorage length (l_b), type and number of layer (n) of FRP overlay, and the experimentally measured average bond stress at failure (u_e) of all specimens are given in Table 2; where the average bond stress at failure, u_e is calculated according to Eq. (1)

$$u_e = \frac{P}{\pi D_b l_b} \quad (1)$$

The average bond stress at failure, u_e for the specimens with FRP overlays were consistently above their counterpart specimens without FRP (Table 2), regardless of the FRP type and number of layers (n), concrete compressive strength (f'_{cn}), and the reinforcing bar diameter (D_b). When the increase in average bond stress at failure is investigated (Table 3), it is observed that the percent increase in u_e closely depends on the variables listed above. The average enhancement in bond stress at failure, u_e due to FRP overlays for a nominal concrete strength of $f'_{cn} = 20$ MPa was between 16% and 42%, while it was between 18% and 40% for $f'_{cn} = 40$ MPa concrete. The percent enhancement in bond stress at failure is also affected by the bar diameter, in other words the cross-sectional area over perimeter ratio. The average enhancement in bond stress at failure for $D_b = 12$ mm diameter reinforcing bar was 28% while this enhancement was 31.5% and 35% for $D_b = 16$ mm and $D_b = 26$ mm diameter bars, respectively, for $f'_{cn} = 20$ MPa concrete (Table 3). Furthermore, the type of FRP has an influence on the percent increase in the splitting failure load. The difference in modulus of elasticity of GFRP and CFRP, in turn, the difference in the clamping stresses developed under a given strain on the FRP overlay may be the reason for such a difference. Considering the test results, bond strength enhancement through externally applied FRP overlays may well be an easy and effective way on the anchorage or lap splice regions of the flexural members.

The strain values measured on the FRP overlays (ϵ_{FRPe}), perpendicular to the reinforcing bar axis, monitored throughout the test to calculate the tensile stress on FRP composite (σ_{FRPe}) at splitting bond failure load level as shown in Eq. (2) and as given in Table 2, column 8

$$\sigma_{FRPe} = \epsilon_{FRPe} E_{Comp} \quad (2)$$

where the modulus of elasticity of the composite, E_{Comp} is calculated according to Eq. (3), by assuming approximately 50% volume fractions were used both for epoxy and FRP

Table 2
Specimen specifications and test results

	Specimen	(1) f'_c (MPa)	(2) f'_{cs} (MPa)	(3) D_b (mm)	(4) l_b (mm)	(5) FRP type	(6) n	(7) u_e (MPa)	(8) σ_{FRPc} (MPa)	(9) σ_{CSCc} (MPa)
1	EC20D12-F00-A	21.3	2.18	12	84	–	–	9.46	–	–
2	EC20D12-F00-B	21.6	2.24	12	84	–	–	10.26	–	–
3	EC20D12-FC2-A	21.3	2.18	12	84	CFRP	2	11.64	189.34	1.23
4	EC20D12-FC2-B	21.6	2.24	12	84	CFRP	2	11.28	234.97	1.53
5	EC20D12-FC4-A	21.3	2.18	12	84	CFRP	4	13.46	312.43	4.06
6	EC20D12-FC4-B	21.6	2.24	12	84	CFRP	4	14.55	181.92	2.36
7	EC20D12-FG3-A	21.3	2.18	12	84	GFRP	3	13.10	92.01	1.20
8	EC20D12-FG3-B	21.6	2.24	12	84	GFRP	3	13.17	54.31	0.71
9	EC20D12-FG5-A	21.3	2.18	12	84	GFRP	5	12.08	51.18	1.12
10	EC20D12-FG5-B	21.6	2.24	12	84	GFRP	5	11.86	62.07	1.35
11	EC20D16-F00-A	21.4	2.17	16	112	–	–	7.61	–	–
12	EC20D16-F00-B	21.6	1.93	16	112	–	–	7.90	–	–
13	EC20D16-FC2-A	21.4	2.17	16	112	CFRP	2	11.75	269.10	1.31
14	EC20D16-FC2-B	21.6	1.93	16	112	CFRP	2	9.99	209.23	1.02
15	EC20D16-FC2-r	19.3	1.99	16	112	CFRP	2	9.78	206.83	1.01
16	EC20D16-FC4-A	21.4	2.17	16	112	CFRP	4	10.23	219.33	2.14
17	EC20D16-FC4-B	21.6	1.93	16	112	CFRP	4	10.97	283.03	2.76
18	EC20D16-FC4-r	19.3	1.99	16	112	CFRP	4	10.23	573.17	5.59
19	EC20D16-FG3-A	21.4	2.17	16	112	GFRP	3	9.50	–	–
20	EC20D16-FG3-B	21.6	1.93	16	112	GFRP	3	8.96	72.02	0.71
21	EC20D16-FG5-A	21.4	2.17	16	112	GFRP	5	11.91	70.46	1.15
22	EC20D16-FG5-B	21.6	1.93	16	112	GFRP	5	9.46	63.72	1.04
23	EC20D16-FG5-r	19.3	1.99	16	112	GFRP	5	10.56	210.04	3.43
24	EC20D26-F00-A	24.6	2.33	26	91	–	–	6.79	–	–
25	EC20D26-F00-B	21.2	2.08	26	91	–	–	6.82	–	–
26	EC20D26-FC2-A	24.6	2.33	26	91	CFRP	2	9.36	306.07	0.92
27	EC20D26-FC2-B	21.2	2.08	26	91	CFRP	2	8.49	188.79	0.57
28	EC20D26-FC4-A	24.6	2.33	26	91	CFRP	4	10.85	615.72	3.69
29	EC20D26-FC4-B	21.2	2.08	26	91	CFRP	4	9.27	574.97	3.45
30	EC20D26-FC4-r	19.3	1.99	26	91	CFRP	4	8.80	436.02	2.62
31	EC20D26-FG3-A	24.6	2.33	26	91	GFRP	3	8.96	151.55	0.92
32	EC20D26-FG3-B	21.2	2.08	26	91	GFRP	3	8.80	111.82	0.68
33	EC20D26-FG5-A	24.6	2.33	26	91	GFRP	5	9.55	116.72	1.17
34	EC20D26-FG5-r	19.3	1.99	26	91	GFRP	5	9.08	119.71	1.20
35	EC40D12-F00-A-r	44.8	3.48	12	42	–	–	12.23	–	–
36	EC40D12-F00-B-r	41.0	3.35	12	42	–	–	11.21	–	–
37	EC40D12-FC2-A	42.1	3.06	12	42	CFRP	2	13.83	361.68	2.35
38	EC40D12-FC2-A-r	44.8	3.48	12	42	CFRP	2	14.99	115.60	0.75
39	EC40D12-FC2-B	45.5	3.29	12	42	CFRP	2	13.54	199.21	1.29
40	EC40D12-FC2-B-r	41.0	3.35	12	42	CFRP	2	15.14	206.17	1.34
41	EC40D12-FC4-A	42.1	3.06	12	42	CFRP	4	14.41	228.98	2.98
42	EC40D12-FC4-A-r	44.8	3.48	12	42	CFRP	4	15.43	264.25	3.44
43	EC40D12-FC4-B	45.5	3.29	12	42	CFRP	4	17.17	164.48	2.14
44	EC40D12-FC4-B-r	41.0	3.35	12	42	CFRP	4	15.72	120.07	1.56
45	EC40D12-FG3-A-r	44.8	3.48	12	42	GFRP	3	15.14	38.22	0.50
46	EC40D12-FG3-B-r	41.0	3.35	12	42	GFRP	3	13.68	47.80	0.63
47	EC40D12-FG5-A	42.1	3.06	12	42	GFRP	5	15.43	101.54	2.21
48	EC40D12-FG5-A-r	44.8	3.48	12	42	GFRP	5	13.24	88.81	1.94
49	EC40D12-FG5-B	45.5	3.29	12	42	GFRP	5	15.28	88.37	1.93
50	EC40D12-FG5-B-r	41.0	3.35	12	42	GFRP	5	14.99	47.54	1.04
51	EC40D16-F00-A	40.6	3.75	16	56	–	–	9.09	–	–
52	EC40D16-F00-B	42.9	3.57	16	56	–	–	10.89	–	–
53	EC40D16-FC2-A	40.6	3.75	16	56	CFRP	2	14.33	225.50	1.10
54	EC40D16-FC2-B	42.9	3.57	16	56	CFRP	2	12.28	225.50	1.10
55	EC40D16-FC4-A	40.6	3.75	16	56	CFRP	4	15.55	264.72	2.58
56	EC40D16-FC4-B	42.9	3.57	16	56	CFRP	4	13.02	238.11	2.32
57	EC40D16-FG3-A	40.6	3.75	16	56	GFRP	3	11.71	58.42	0.57
58	EC40D16-FG3-B	42.9	3.57	16	56	GFRP	3	11.87	92.13	0.90
59	EC40D16-FG5-A	40.6	3.75	16	56	GFRP	5	12.77	76.23	1.25
60	EC40D16-FG5-B	42.9	3.57	16	56	GFRP	5	14.24	73.64	1.20
61	EC40D26-F00-A	43.5	3.32	26	91	–	–	7.60	–	–
62	EC40D26-F00-B	45.2	3.52	26	91	–	–	8.74	–	–
63	EC40D26-FC2-A	43.5	3.32	26	91	CFRP	2	11.59	443.79	1.33

Table 2 (continued)

Specimen	(1) f'_c (MPa)	(2) f'_{cs} (MPa)	(3) D_b (mm)	(4) l_b (mm)	(5) FRP type	(6) n	(7) u_e (MPa)	(8) σ_{FRPe} (MPa)	(9) σ_{CSCe} (MPa)	
64	EC40D26-FC2-B	45.2	3.52	26	91	CFRP	2	11.22	357.42	1.07
65	EC40D26-FC4-A	43.5	3.32	26	91	CFRP	4	11.38	668.04	4.01
66	EC40D26-FC4-B	45.2	3.52	26	91	CFRP	4	11.44	603.29	3.62
67	EC40D26-FG3-A	43.5	3.32	26	91	GFRP	3	10.73	85.37	0.52
68	EC40D26-FG3-B	45.2	3.52	26	91	GFRP	3	10.57	99.74	0.60
69	EC40D26-FG5-A	43.5	3.32	26	91	GFRP	5	11.44	108.03	1.09
70	EC40D26-FG5-B	45.2	3.52	26	91	GFRP	5	11.38	107.20	1.08

Table 3

Increase in average bond stress at failure

f'_{cn} (MPa)	D_b (mm)	FRP type	n (layers)	Increase in u_e (%)	
20	12	CFRP	2	16	
			4	42	
		GFRP	3	33	
			5	21	
		16	CFRP	2	35
				4	35
	GFRP		3	19	
			5	37	
	26	CFRP	2	31	
			4	42	
		GFRP	3	30	
			5	37	
40	12	CFRP	2	23	
			4	34	
		GFRP	3	23	
			5	26	
	16	CFRP	2	33	
			4	43	
		GFRP	3	18	
			5	35	
	26	CFRP	2	40	
			4	40	
		GFRP	3	30	
			5	40	

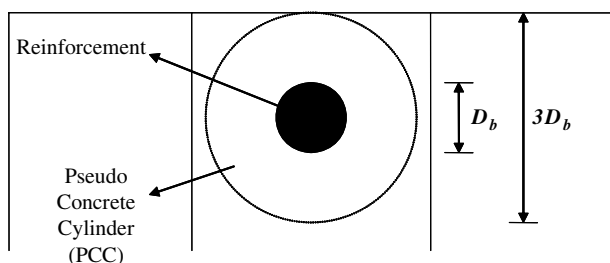


Fig. 3. The pseudo-concrete-cylinder (PCC) around steel reinforcing bar.

during the impregnation and the elastic modulus of FRP and the epoxy resin are given in Table 1

$$E_{Comp} = E_{FRP}VP_{FRP} + E_{Epoxy}VP_{Epoxy} \quad (3)$$

It was observed that the enhancement due to FRP overlays is closely related to the tensile stress in FRP (σ_{FRPe}), hence

related to the clamping stress (σ_{CSCe}) on the pseudo-concrete-cylinder (PCC) (Fig. 3). The clamping stress which was calculated as dividing the clamping force by the product of diameter of PCC and the reinforcing bar anchorage length is given in Eq. (4) and the values are listed in Table 2

$$\sigma_{CSCe} = \frac{\sigma_{FRPe}n l_{FRP}}{3D_b} \quad (4)$$

The relation between the above equation and the attained level of bond strength may be observed from columns 7 and 9 of Table 2. It may be easy to investigate this relation by grouping the results with respect to re-bar diameter for each concrete level. As an example, the bond stress, u_e and the clamping stress, σ_{CSCe} in specimen EC20D12-FC4-A were 13.46 MPa and 4.06 MPa, respectively, while these values were 13.10 MPa and 1.20 MPa for specimen EC20D12-FG3-A. Although the change in clamping stress was above three folds between these two specimens, the change in bond strength enhancement was negligible. Similar trend was observed also in other reinforcement diameter groups. It should be noted that the diminishing effectiveness of increasing overlay thickness and elastic modulus may highlight a change in failure mode.

3.3. Effectiveness of FRP overlays

The relationship between the normalized average bond stress at failure (u_e/f'_c) and the clamping stress on the pseudo-concrete-cylinder (σ_{CSCe}), calculated according to Eq. (4), is presented in Figs. 4 and 5 for $f'_{cn} = 20$ MPa and $f'_{cn} = 40$ MPa concrete specimens, respectively. It is observed that the increasing clamping stresses on PCC resulted in an increase in the normalized average bond stress at failure (u_e/f'_c). It should be pointed out that, after a certain clamping stress level the bond strength enhancement takes place at a slower pace rate. This critical level of clamping stress is called the limiting clamping stress on PCC ($\sigma_{CSCe-lim}$) and it points out the boundary of gradual change in bond failure mode. As it is pointed out by the previous researchers [25,29], the modes of bond failure are bounded by two extremes, namely splitting and pull-out failures. In case of small confining pressures the failure is mainly splitting type, while heavy confinement or the lack of ribs on the reinforcing bars lead to a pull-out type (shearing the con-

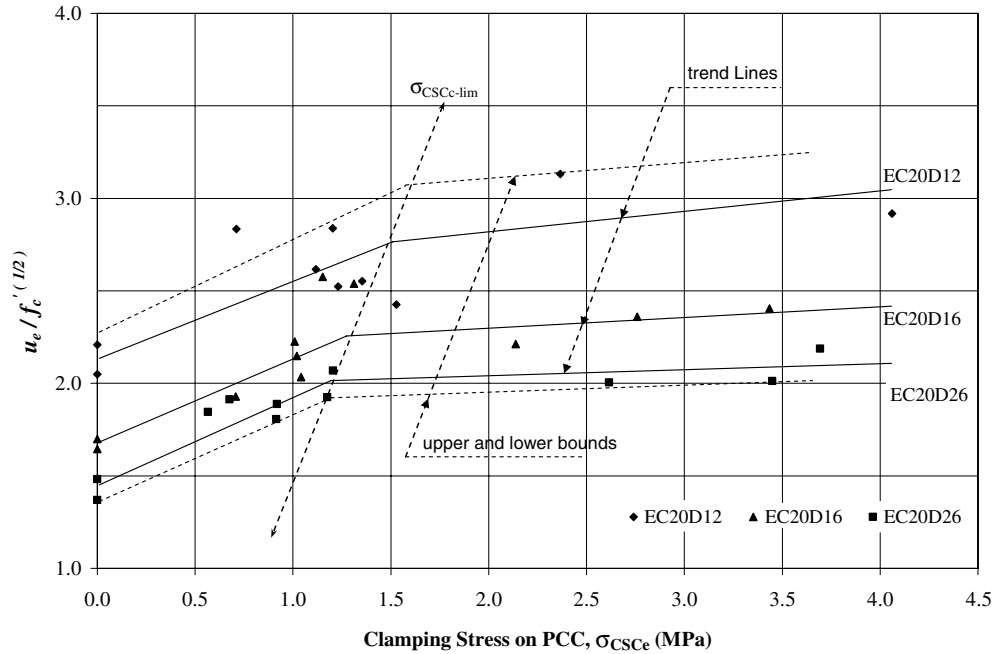


Fig. 4. Normalized bond strength versus clamping stress ($f'_{cn} = 20$ MPa).

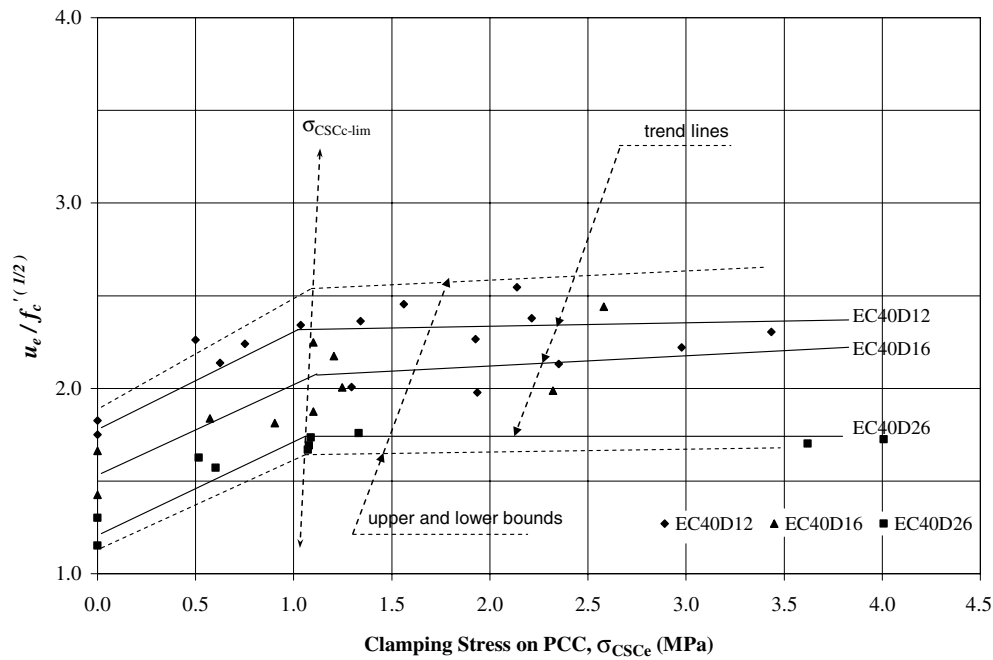


Fig. 5. Normalized bond strength versus clamping stress ($f'_{cn} = 40$ MPa).

crete lugs) of failure. The change in failure mode from one to another is gradual and the limiting clamping stress points out the border between the splitting failure zone and the zone at which mixed failure (splitting and pull-out) takes place. It was observed that the limiting clamping stress is primarily influenced by the concrete strength and the reinforcing bar diameter as shown in Figs. 4 and 5.

4. Modeling the response

The experimental part of this study revealed that the beneficial effects of the FRP overlays on bond strength enhancement of reinforcing bars, which was presented in Figs. 4 and 5, may be modeled through a bilinear approach as shown in Fig. 6. The horizontal axis of the model is defined as the calculated clamping stress on the pseudo-

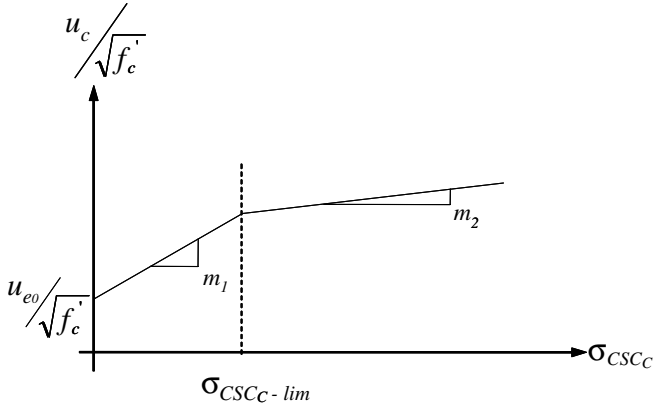


Fig. 6. Idealized effectiveness of FRP clamping on bond strength.

concrete-cylinder, σ_{CSCc} , while the vertical axis shows the calculated normalized bond strength, $u_c / \sqrt{f'_c}$. The change in the effectiveness of the clamping stresses, where the slope of the trend line changes, is called the limiting clamping stress on PCC, $\sigma_{CSCc-lim}$.

4.1. Limit on clamping stress and bond strength enhancement

The limiting clamping stress that controls the effectiveness of the FRP overlay $\sigma_{CSCc-lim}$ (Fig. 6) is primarily related to, and also a function of, the concrete compressive strength and the reinforcing bar diameter as given in Eq. (5)

$$\sigma_{CSCc-lim} = 1 + \left[(7.07 - \sqrt{f'_c}) \frac{k_1}{D_b} \right] \tag{5}$$

where the aspect coefficient, k_1 is used to consider the perimeter over area relation of different reinforcing bar

sizes. The aspect coefficient, k_1 is graphically presented in Fig. 7. Linear interpolation is possible for the concrete strength classes between the specified values of Fig. 7.

The enhancement in normalized bond strength due to FRP overlays before and after the limiting clamping stress may be modeled by Eqs. (6a) and (6b). The initial slope of the model (Fig. 6) is assumed constant, while the second half of the model has a variable slope depending on the concrete compressive strength

$$\frac{u_c}{\sqrt{f'_c}} = \frac{u_{eo}}{\sqrt{f'_c}} + 0.47\sigma_{CSCc} \quad (\sigma_{CSCc} \leq \sigma_{CSCc-lim}) \tag{6a}$$

$$\frac{u_c}{\sqrt{f'_c}} = \frac{u_{eo}}{\sqrt{f'_c}} + 0.47\sigma_{CSCc-lim} + \left(\frac{1 + 0.1\sqrt{f'_c}}{100} \right) \times (\sigma_{CSCc} - \sigma_{CSCc-lim}) \quad (\sigma_{CSCc} > \sigma_{CSCc-lim}) \tag{6b}$$

It should be recalled that the experimental clamping stress on the PCC, σ_{CSCc} is calculated by using the stress on FRP composite as given in Eq. (4). A through investigation on the test data revealed that the predicted strains on FRP at the time of splitting bond failure (ϵ_{FRPc}) is closely related to the reinforcing bar diameter (D_b), and the modulus of elasticity of the composite overlay; ϵ_{FRPc} is calculated as given in Eq. (7)

$$\epsilon_{FRPc} = \epsilon_{co} + 0.0004 \left[\frac{D_b^2 n t_{FRP} E_{Comp}}{4 \times 10^6} \right] \tag{7}$$

where the concrete surface strain for the unconfined specimens at the time of bond failure assumed constant for all specimens; $\epsilon_{co} = 0.0012$.

The clamping stress developed by FRP overlay is calculated as shown in Eq. (8). The numerical result of Eq. (8)

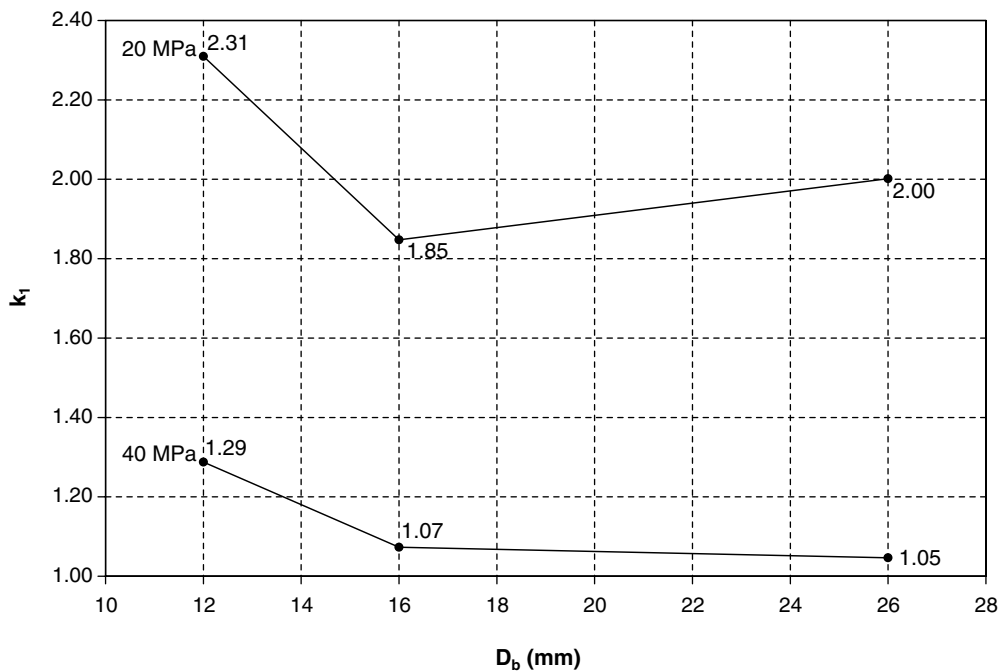


Fig. 7. Aspect coefficient, k_1 for the proposed model.

Table 4
Comparison of experimental results with the proposed model

Specimen	(1) $u_e/f_c^{(1/2)}$	(2) k_1	(3) $\sigma_{CSCc-lim}$ (MPa)	(4) σ_{CSCc} (MPa)	(5) $\Delta(u_e/f_c^{(1/2)})$	(6) $u_e/f_c^{(1/2)}$	(1/6) $(u_e/f_c^{(1/2)})/(u_e/f_c^{(1/2)})$
1 EC20D12-F00-A	2.13	–	–	–	–	–	–
2 EC20D12-F00-B	–	–	–	–	–	–	–
3 EC20D12-FC2-A	2.52	2.24	1.46	1.29	0.61	2.74	0.92
4 EC20D12-FC2-B	2.43	2.23	1.45	1.29	0.61	2.74	0.89
5 EC20D12-FC4-A	2.92	2.24	1.46	3.24	0.71	2.84	1.03
6 EC20D12-FC4-B	3.13	2.23	1.45	3.24	0.71	2.84	1.10
7 EC20D12-FG3-A	2.84	2.24	1.46	0.76	0.36	2.49	1.14
8 EC20D12-FG3-B	2.83	2.23	1.45	0.76	0.36	2.49	1.14
9 EC20D12-FG5-A	2.62	2.24	1.46	1.42	0.67	2.80	0.94
10 EC20D12-FG5-B	2.55	2.23	1.45	1.42	0.67	2.80	0.91
11 EC20D16-F00-A	1.67	–	–	–	–	–	–
12 EC20D16-F00-B	–	–	–	–	–	–	–
13 EC20D16-FC2-A	2.54	1.80	1.27	1.16	0.55	2.22	1.14
14 EC20D16-FC2-B	2.15	1.79	1.27	1.16	0.55	2.22	0.97
15 EC20D16-FC2-r	2.23	1.88	1.31	1.16	0.55	2.22	1.00
16 EC20D16-FC4-A	2.21	1.80	1.27	3.21	0.63	2.30	0.96
17 EC20D16-FC4-B	2.36	1.79	1.27	3.21	0.63	2.30	1.03
18 EC20D16-FC4-r	2.33	1.88	1.31	3.21	0.64	2.31	1.01
19 EC20D16-FG3-A	2.05	1.80	1.27	0.65	0.31	1.98	1.04
20 EC20D16-FG3-B	1.93	1.79	1.27	0.65	0.31	1.98	0.97
21 EC20D16-FG5-A	2.57	1.80	1.27	1.29	0.60	2.27	1.13
22 EC20D16-FG5-B	2.03	1.79	1.27	1.29	0.60	2.27	0.89
23 EC20D16-FG5-r	2.40	1.88	1.31	1.29	0.61	2.28	1.05
24 EC20D26-F00-A	1.43	–	–	–	–	–	–
25 EC20D26-F00-B	–	–	–	–	–	–	–
26 EC20D26-FC2-A	1.89	1.78	1.14	1.16	0.54	1.97	0.96
27 EC20D26-FC2-B	1.84	1.94	1.18	1.16	0.55	1.98	0.93
28 EC20D26-FC4-A	2.19	1.78	1.14	3.76	0.57	2.00	1.10
29 EC20D26-FC4-B	2.01	1.94	1.18	3.76	0.59	2.02	1.00
30 EC20D26-FC4-r	2.00	2.03	1.21	3.76	0.61	2.04	0.98
31 EC20D26-FG3-A	1.81	1.78	1.14	0.59	0.28	1.71	1.06
32 EC20D26-FG3-B	1.91	1.94	1.18	0.59	0.28	1.71	1.12
33 EC20D26-FG5-A	1.93	1.78	1.14	1.31	0.54	1.97	0.98
34 EC20D26-FG5-r	2.07	2.03	1.21	1.31	0.57	2.00	1.04
35 EC40D12-F00-A-r	1.79	–	–	–	–	–	–
36 EC40D12-F00-B-r	–	–	–	–	–	–	–
37 EC40D12-FC2-A	2.13	1.18	1.06	1.29	0.50	2.29	0.93
38 EC40D12-FC2-A-r	2.24	1.05	1.03	1.29	0.49	2.28	0.98
39 EC40D12-FC2-B	2.01	1.01	1.03	1.29	0.49	2.28	0.88
40 EC40D12-FC2-B-r	2.36	1.24	1.07	1.29	0.51	2.30	1.03
41 EC40D12-FC4-A	2.22	1.18	1.06	3.24	0.53	2.32	0.96
42 EC40D12-FC4-A-r	2.30	1.05	1.03	3.24	0.52	2.31	1.00
43 EC40D12-FC4-B	2.55	1.01	1.03	3.24	0.52	2.31	1.10
44 EC40D12-FC4-B-r	2.45	1.24	1.07	3.24	0.54	2.33	1.05
45 EC40D12-FG3-A-r	2.26	1.05	1.03	0.76	0.36	2.15	1.05
46 EC40D12-FG3-B-r	2.14	1.24	1.07	0.76	0.36	2.15	1.00
47 EC40D12-FG5-A	2.38	1.18	1.06	1.42	0.50	2.29	1.04
48 EC40D12-FG5-A-r	1.98	1.05	1.03	1.42	0.49	2.28	0.87
49 EC40D12-FG5-B	2.27	1.01	1.03	1.42	0.49	2.28	1.00
50 EC40D12-FG5-B-r	2.34	1.24	1.07	1.42	0.51	2.30	1.02
51 EC40D16-F00-A	1.54	–	–	–	–	–	–
52 EC40D16-F00-B	–	–	–	–	–	–	–
53 EC40D16-FC2-A	2.25	1.05	1.05	1.16	0.50	2.04	1.10
54 EC40D16-FC2-B	1.87	0.96	1.03	1.16	0.49	2.03	0.92
55 EC40D16-FC4-A	2.44	1.05	1.05	3.21	0.53	2.07	1.18
56 EC40D16-FC4-B	1.99	0.96	1.03	3.21	0.52	2.06	0.97
57 EC40D16-FG3-A	1.84	1.05	1.05	0.65	0.31	1.85	0.99
58 EC40D16-FG3-B	1.81	0.96	1.03	0.65	0.31	1.85	0.98
59 EC40D16-FG5-A	2.00	1.05	1.05	1.29	0.50	2.04	0.98
60 EC40D16-FG5-B	2.17	0.96	1.03	1.29	0.49	2.03	1.07
61 EC40D26-F00-A	1.23	–	–	–	–	–	–
62 EC40D26-F00-B	–	–	–	–	–	–	–
63 EC40D26-FC2-A	1.76	0.88	1.02	1.16	0.48	1.71	1.03

Table 4 (continued)

Specimen	(1) $u_e/f_c^{(1/2)}$	(2) k_1	(3) $\sigma_{CSCc-lim}$ (MPa)	(4) σ_{CSCc} (MPa)	(5) $\Delta(u_e/f_c^{(1/2)})$	(6) $u_e/f_c^{(1/2)}$	(1/6) $(u_e/f_c^{(1/2)})/(u_e/f_c^{(1/2)})$	
64	EC40D26-FC2-B	1.67	0.80	1.01	1.16	0.48	1.71	0.98
65	EC40D26-FC4-A	1.73	0.88	1.02	3.76	0.52	1.75	0.99
66	EC40D26-FC4-B	1.70	0.80	1.01	3.76	0.52	1.75	0.97
67	EC40D26-FG3-A	1.63	0.88	1.02	0.59	0.28	1.51	1.08
68	EC40D26-FG3-B	1.57	0.80	1.01	0.59	0.28	1.51	1.04
69	EC40D26-FG5-A	1.73	0.88	1.02	1.31	0.48	1.71	1.01
70	EC40D26-FG5-B	1.69	0.80	1.01	1.31	0.48	1.71	0.99

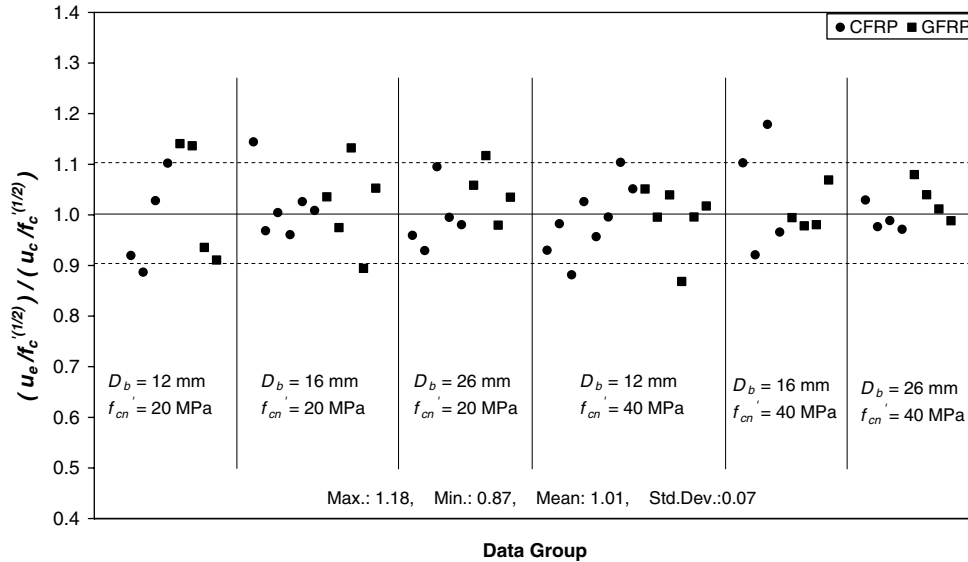


Fig. 8. Comparison of the proposed model with the experimental data.

need to be compared with the limiting clamping stress (Eq. (5)) before calculating the bond strength enhancement according to Eq. (6a) or Eq. (6b)

$$\sigma_{CSCc} = \frac{(\varepsilon_{FRPc} E_{Comp}) n t_{FRP}}{3D_b} \quad (8)$$

4.2. Model predictions versus test data

The normalized test data and model predictions of the 70 eccentric pullout specimens, with or without FRP overlays, are also given in Table 4. The experimental versus calculated values for the normalized results, with a mean value of 1.01 and a standard deviation of 0.07, are graphically presented in Fig. 8. Although the model predictions have more or less the same level of accuracy for different variable groups (Fig. 8), calculated values yielded better correlation for the specimens with larger bar diameters. This effect may be attributed to the higher relative rib area of $D_b = 26$ mm diameter reinforcing bars (Table 1), that results in higher radial stresses and disturbance on the PCC.

5. Conclusions

This paper presents the experimental results of a research on the effect of FRP wrapping on bond strength enhancement of single reinforcing bars embedded in NSC. All specimens were designed and constructed with insufficient anchorage length and small cover thickness equal to reinforcing bar diameter. The following conclusions are drawn based mainly on the results of the current study. It should be noted that, more comprehensive predictions and design equations on the member response and bond strength enhancement may be obtained with further investigations incorporating several other variables.

- FRP wrapping resulted in bond strength enhancement in all specimens regardless of the concrete strength, bar diameter and the type and number of layers of FRP overlay.
- The orientation and number of the splitting cracks in radial direction, starting from the reinforcing bar and ending at the nearest concrete free surface, are altered by the application of FRP overlays. A single and vertical crack on specimen's cross-section led the non-wrapped

- specimens to failure, while two radial cracks forming a V-notch are observed at the time of failure of the FRP wrapped specimens. The V-notch angle is mainly affected by the clamping force resulted from the FRP wrapping; the effective the FRP wrapping the bigger the V-notch angle.
- All specimens of the current investigation, wrapped or non-wrapped, failed by splitting type of bond failure.
 - The bond strength enhancement is closely related to the type and the number of layers of the FRP overlays. It is observed that the bond strength enhancement for the same FRP application is higher in the case of larger bar diameters.
 - It is believed that the use of FRP overlays improve the small concrete cover thickness and anchorage length deficiencies by means of strengthening the pseudo-concrete-cylinder, PCC.
 - It can be concluded that the level of bond strength enhancement through FRP wrapping is related to a dependent variable named σ_{CSCc} , which is the clamping stress on the pseudo-concrete-cylinder, PCC.
 - Although successive increases in the number of layers of FRP or the modulus of elasticity of the FRP overlay result in an increase in σ_{CSCc} , the enhancement in bond strength beyond a limiting value of the clamping stress, $\sigma_{CSCc-lim}$, is far less than that of the small clamping stresses.
 - A model is proposed to predict the bond strength enhancement through FRP wrapping, where the section is under combined flexure and shear. It is observed that the model predictions and test results yielded good correlation with the experimental results of the current investigation.

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