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ASSESSMENT OF DESIGN GUIDELINES TO EVALUATE THE FRP SHEAR CONTRIBUTION OF STRENGTHENED PRESTRESSED CONCRETE BEAMS

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ABSTRACT

This paper is mainly presented on statistical assessment and analysis of the accuracy of the current design guidelines to evaluate the shear resistance of the fiber-reinforced polymer (FRP) sheets for prestressed concrete (PC) beams strengthened by externally bonded FRP sheets. The evaluation of the current prediction models is based on a database of experimental results from the previous and current author's research. The specifications of the beams are diverse and wide enough such as beam types (prestressed concrete beams using bonded tendons - BPC beams and unbonded tendons - UPC beams), cross-section shape, concrete strength, the effective prestress in strands, tendon profile, and shear span to depth ratio - a/d and so on. This study proved the inaccuracy of the formulas in recent design guidelines to evaluate the shear contribution of FRP sheets for prestressed concrete beams.

Keywords: Fiber-reinforced polymer (FRP) sheets, shear contribution, prestressed concrete, design guidelines, evaluation

1. INTRODUCTION

In recent decades, the technique of shear strengthening using fiber-reinforced polymer (FRP) sheets has been quite popular and mainly focus on reinforced concrete (RC) structures. However, the study of this technical solution on prestressed concrete (PC) members is limited because there are only a few studies available in the literature [1-7]. Previous studies mainly focussed on

ISSN: 2456-1851

Volume: 07, Issue: 02 "March-April 2022"

studying the effect of several major parameters, which influenced the shear contribution of FRP to shear resistance, for instance, the stirrups ratio, the FRP shear reinforcement ratio, the strengthening scheme, the beam geometry, the concrete strength, the effective prestress in the strands and the ratio of the shear span to effective depth. The contemporary design guidelines have introduced specific provisions to determine the shear resistance for PC beams strengthened with FRP sheets e.g., Fib 14, HB 305, ISIS, TR 55, JSCE, CNR-DT 200 R1, ACI 440-2R and Fib 90 [8-15].

These calculation terms in the design guidelines were built mainly based on experimental studies of RC beams strengthened with FRP sheets. Besides, the superposition theorem with separately shear resistance contributions of several components such as concrete, stirrups and externally bonded FRP sheets were used. However, the interaction between these components and their effect was ignored. The shear contribution of FRP sheets is quite like that of stirrups with the assumption of FRP strips crossing the main shear crack with an angle of 45o related to the longitudinal axis of the beam. Some factors such as concrete strength, shear strengthening configurations (completely wrapping, U-wrap, and two-side bonding), and the stiffness of FRP sheets are taken into consideration when predicting the effective stress/strain whose equations in the guidelines were derived from the studies on RC structures. The shear behaviour of RC beams and PC beams has many differences. Besides, Nguyen et al. [6] observed a reduction in FRP sheet strain when increasing the level of prestress. However, the influences of the effective prestress and tendon profile on the shear resistance of FRP strengthened PC beams have not been considered in the design guidelines. Therefore, directly using these design guidelines for calculating the FRP shear contribution of PC beams may lead to large variations and is inappropriate.

This paper analysis reviews to evaluate the formulas of the prediction shear resistance of FRP sheets in the current design guidelines [9-15]. Moreover, the study compares the shear resistance of FRP sheets calculated in the current design guidelines with the corresponding experimental results. The evaluation of the accuracy of the predictive standard shear resistance of FRP sheets for PC beams is necessary to see rationality and ensure the safety of the standards to apply in actual designs.

2. DESIGN GUIDELINES FOR FRP CONTRIBUTION TO SHEAR RESISTANCE

In the design guidelines, the shear contribution of FRP sheets of RC beams was estimated similarly as stirrups with the assumption of FRP strips crossing the main shear crack with an angle of 45^o relative to the longitudinal axis of the beam. All of those FRP strips have the same stress level at failure, called effective stress. This effective strain can be significantly smaller than the rupture strain of FRP sheets due to the premature debonding phenomenon. Predicting

ISSN: 2456-1851
Volume: 07, Issue: 02 "March-April 2022"

the effective stress or strain whose equations in the guidelines were derived from the studies on RC structures. Some factors such as concrete strength, shear strengthening configurations (completely wrapping, U-wraps/clamps, and two-side bonding), and the stiffness of FRP sheets are taken into consideration.

Some authors indicated the unsuitability of the predictive formulas shear resistance of FRP sheets in the design guidelines [2,5,6,7]. Several influencing parameters were mentioned in design guidelines as a bond model, FRP effective strain or stress, concrete strength, anchorage length, cracking angel, strip width to spacing ratio. While a few key factors haven't yet been captured by design guidelines and codes as shear span to effective depth ratio, transverse steel ratio, anchorage systems, prestressing force cable. Therefore, the scope of using standards is limited. However, due to its simplicity and sufficient accuracy in predicting the shear resistance of the beam, it is still used to calculate in the current design guidelines. Table 1 lists the major influencing factors to the shear resistance of FRP sheets in the current design guidelines.

Additionally, describing the shear resistance mechanisms of PC beams strengthened FRP sheets is not simple. The prestress level and tendon profile are significant because they influence the effective reduction in FRP sheet strains.

In short, the current design guidelines [9-15] may lead to inaccurate predictions of the shear contribution of FRP sheets in PC beams since the prestress level and tendon profile showed a significant influence on the effective strain of FRP sheets. Therefore, it is necessary to examine the accuracy of the design guidelines when estimating the shear contribution of FRP sheets in PC beams.

Table 1: Status of influencing factors to shear resistance of FRP sheets in the current design guidelines.

Influencing factors	Design guidelines							
	Fib90	ACI 440	CNR-DT200	TR 55	HB 305	Fib14	ISIS	JSCE
1. Bond model	✓	✓	✓	x	✓	x	✓	x
2. Effective FRP strain/ stress	✓	✓	✓	✓	✓	✓	✓	✓
3. Configuration	✓	✓	✓	✓	✓	✓	✓	✓
4. FRP sheet ratio	✓	✓	✓	✓	x	✓	✓	✓
5. Concrete strength	✓	✓	✓	✓	✓	✓	✓	✓
6. Strip width to spacing ratio	x	x	✓	x	x	x	✓	x

ISSN: 2456-1851

Volume: 07, Issue: 02 "March-April 2022"

7. Cracking angel	✓	x	✓	✓	✓	✓	x	✓
8. Anchorage length	✓	✓	✓	✓	x	x	✓	x

Note: ✓= included x = not included

3. VALIDATION OF DESIGN GUIDELINES

3.1 Data analysis

To validate the rationality and accuracy of the formulas predicting the shear resistance of FRP sheets in the design guidelines, test results from other research studies were used. There were thirty-fiveFRP-shear strengthened beams in total withnine concrete beamspre-tensioned with bonded tendons and twenty-six UPC beams. The examined factors includethe strengthening configuration (completely wrapping, U-wraps with/without anchorage systems), beam's section (rectangular, T-section and I-section), beam's height (h) from 300 to 1600 mm, the shear span to effective depth (a/d) from 1.5 to 3.1, FRP shear reinforcement ratio (ρ_f) from 0.06% to 2.17%, tendon's profile (straight and harped), the effective concrete stress (f_{pc}) from 3.32 to 9.56 MPa and compressive strength of concrete cylinders(f_c)from 30.6 to 71.2 MPa.All beams were tested under monotonic loading (four-point bending) up to failure. The experimental FRP shear contribution $V_{fu,exp}$was determined as the difference between the shear capacity of the strengthened beams ($V_{u,exp,FRP}$) and unstrengthened reference beams ($V_{u,exp,0}$). This method is very popular and widely accepted as it was utilized in numerous studies to analyse the experimental data. The experimental databases of FRP shear-strengthened PC beams used to validate the accuracy of the current design guidelines are summarized in **Table 2.**

3.2 Evaluation of design guidelines

The results of statistical analysis evaluate the accuracy of the current design guidelines with the mean value (Mean) and the coefficient of variation (COV) of the ratio between the design shear resistance of FRP sheets and the corresponding experimental values ($V_{fu,theor}/V_{fu,exp}$). **Table 3** and **Fig. 1** show large variationsbetween the theoretical predictions bythe design guidelines and experimental results. The predicted value of JSCE, CNRDT-200 R1, HB 305, ACI 440.2R, Fib 90 and Fib 14 are unsafe and greater than the experimental results by 358%, 262%, 253%, 229%, 221% and 178% with the corresponding COVs of 0.63, 0.71, 0.62, 0.48, 1.13 and 0.51, respectively. The predicted value of TR 55 and ISIS are closer to the experimental values, but they have large deviations with Mean = 1.22 and COV = 0.63 for TR55 and Mean = 1.35 and COV = 0.63 for ISIS.

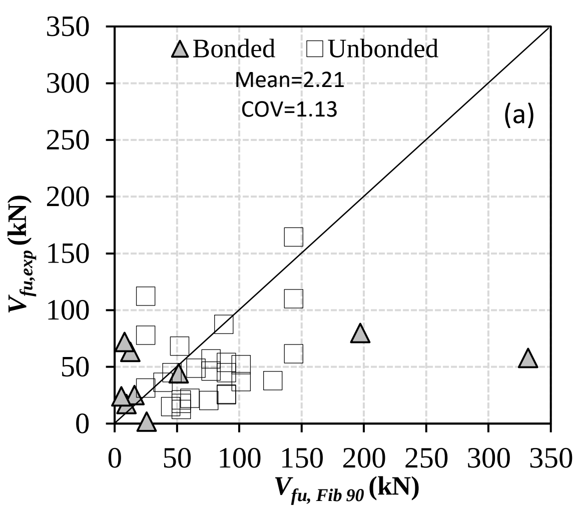
There were several causes for differences between the predictions and the experimental results. First, all design guidelines were derived based on the experimental results of conventional

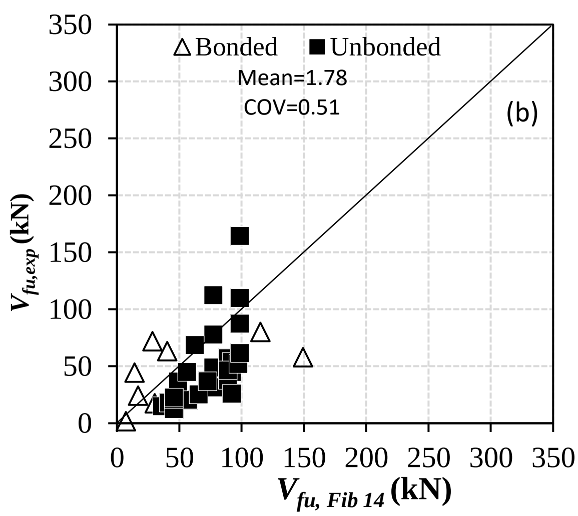
ISSN: 2456-1851

Volume: 07, Issue: 02 "March-April 2022"

reinforced concrete (RC) beams rather than prestressed concrete (PC) beams. Second, because of the effects of prestressing, the strain in FRP sheets in PC beams is smaller than that in RC beams. It is important to mention that Nguyen et al. [6] also observed a reduction in FRP sheet strain when increasing the level of prestressing as the effects of the prestress were magnified. So, the effective work of FRP sheets is decreased. Third, the interactive bonding surface between concrete and FRP sheets was evaluated unproperly. Nevertheless, all design guidelines also ignore the interaction of other important parameters such as shear span to effective depth ratio, transverse steel, anchorage systems, prestressing force cable.

To further investigate the accuracy shear resistance of FRP sheets between predictive design values and the corresponding experimental values, the variation ($V_{fu,theor}/V_{fu,exp}$) is examined against factors including the concrete compressive strength f'_c (**Fig. 2**), the effective concrete prestresses f_{pc} (**Fig. 3**), the strip width to spacing ratio w_f/s_f (**Fig. 4**), the shear span to effective depth ratio a/d (**Fig. 5**), the transverse steel ratio ρ_{sw} (**Fig. 6**), and the FRP shear reinforcement ratio ρ_f (**Fig. 7**). There is a large dispersion of the ratio $V_{fu,theor}/V_{fu,exp}$regarding the six factors, so the design guidelines are unreliable to predict the shear resistance of FRP sheets retrofitted PC beams. Therefore, it is necessary to consider adjusting these formulas or establishing a new formula for PC beams strengthened by FRP shear resistance.





International Journal of Engineering Technology and Scientific Innovation

ISSN: 2456-1851

Volume: 07, Issue: 02 "March-April 2022"

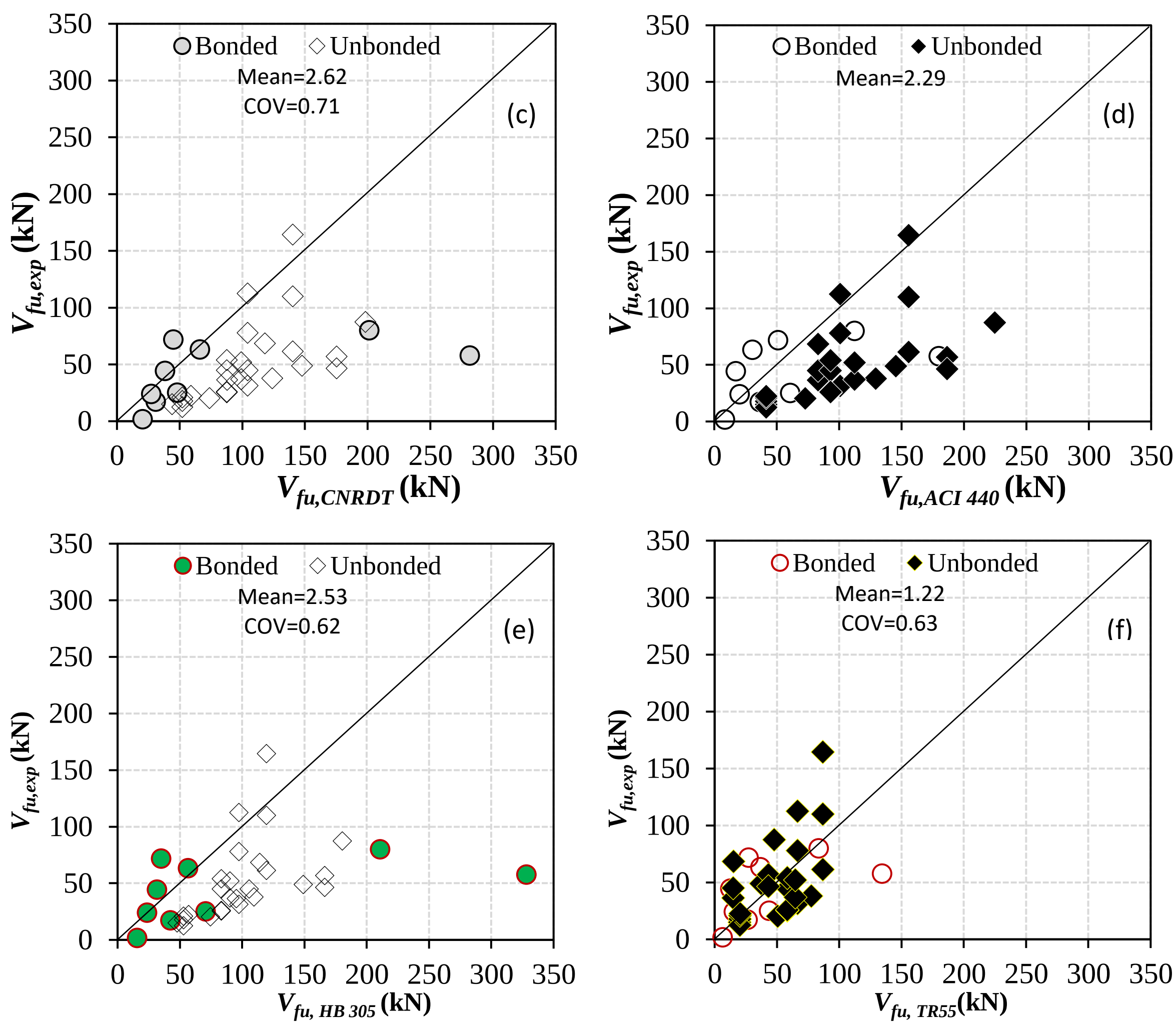


Fig. 1: Experimental versus theoretical design guidelines FRP shear contribution: (a) Fib 90; (b) Fib 14(c) CNR-DT 200; (d) ACI 440-2R; (e) HB 305;(f) TR55

ISSN: 2456-1851

Volume: 07, Issue: 02 "March-April 2022"

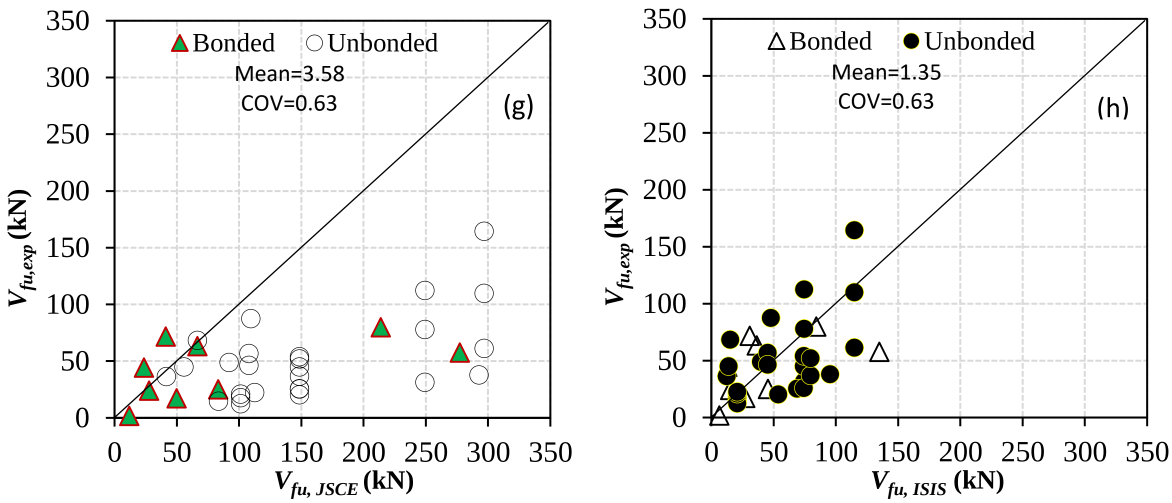


Fig. 1: Experimental versus theoretical design guidelines FRP shear contribution: (g) JSCE; (h) ISIS

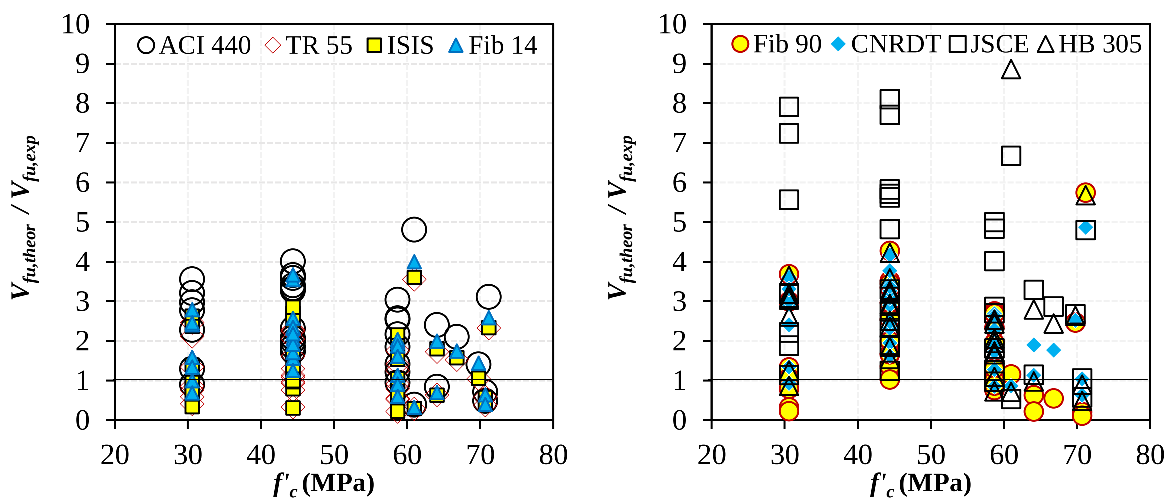


Fig. 2: Evaluation FRP shear contribution versus concrete compressive strength

ISSN: 2456-1851

Volume: 07, Issue: 02 "March-April 2022"

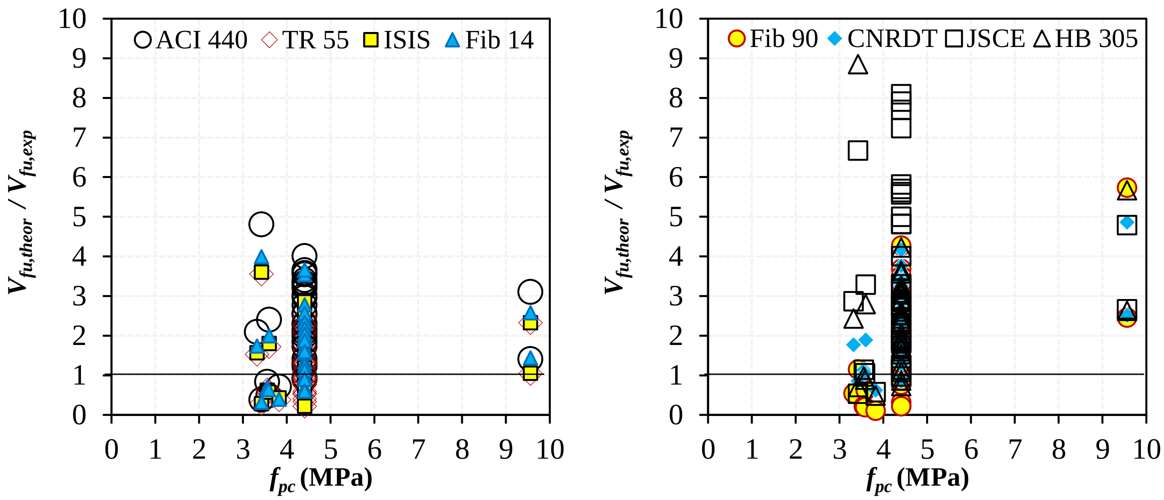


Fig. 3: Evaluation FRP shear contribution versus concrete effective prestress

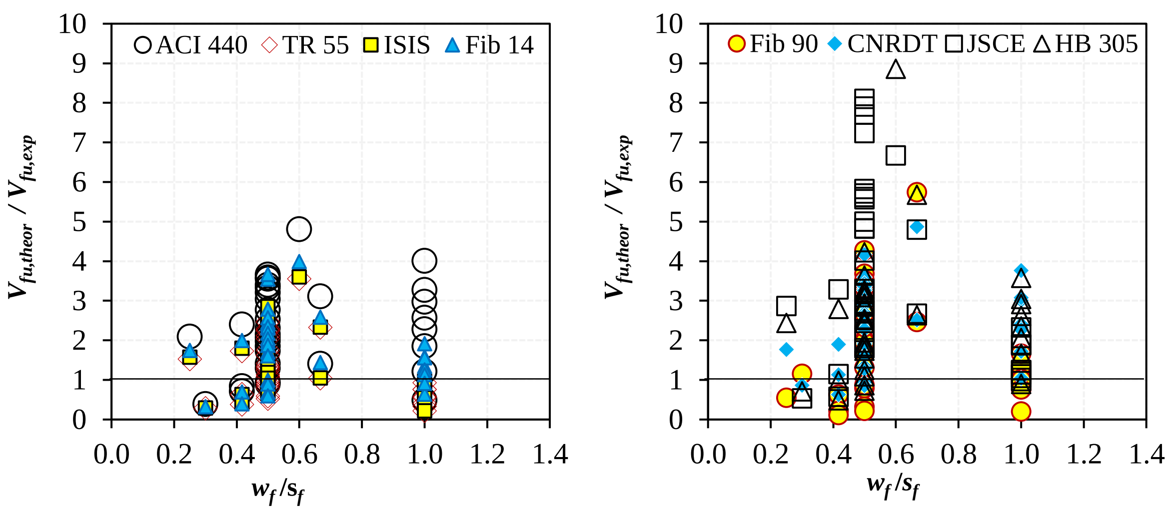


Fig. 4: Evaluation FRP shear contribution versus strip width to spacing ratio

ISSN: 2456-1851

Volume: 07, Issue: 02 "March-April 2022"

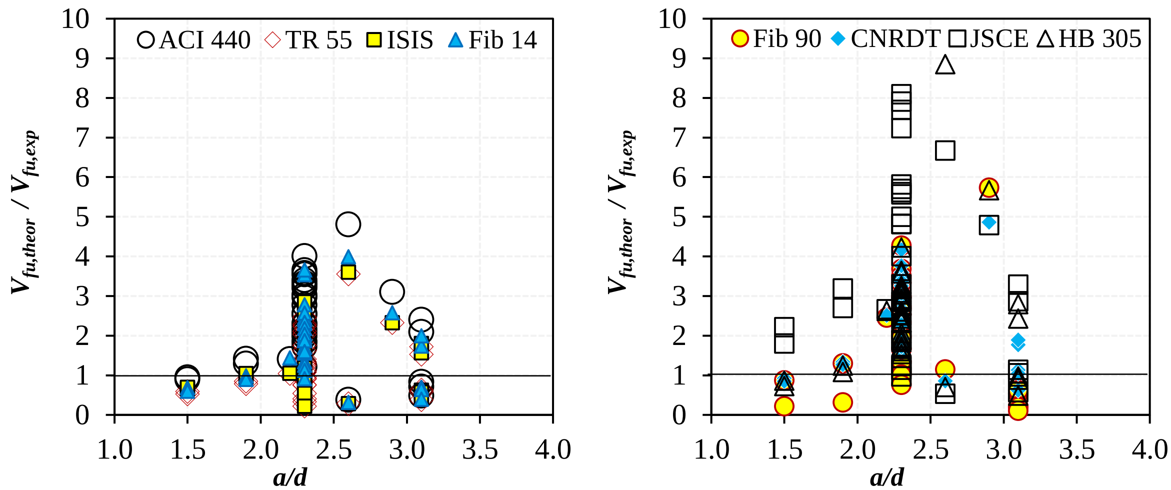


Fig. 5: Evaluation FRP shear contribution versus shear span to effective depth ratio

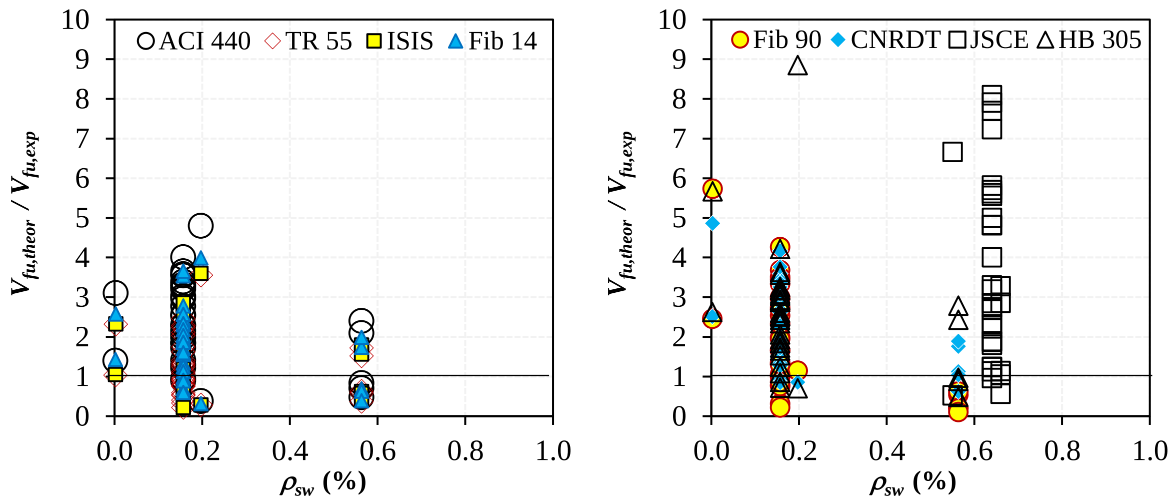


Fig. 6: Evaluation FRP shear contribution versus transverse steel ratio

ISSN: 2456-1851

Volume: 07, Issue: 02 "March-April 2022"

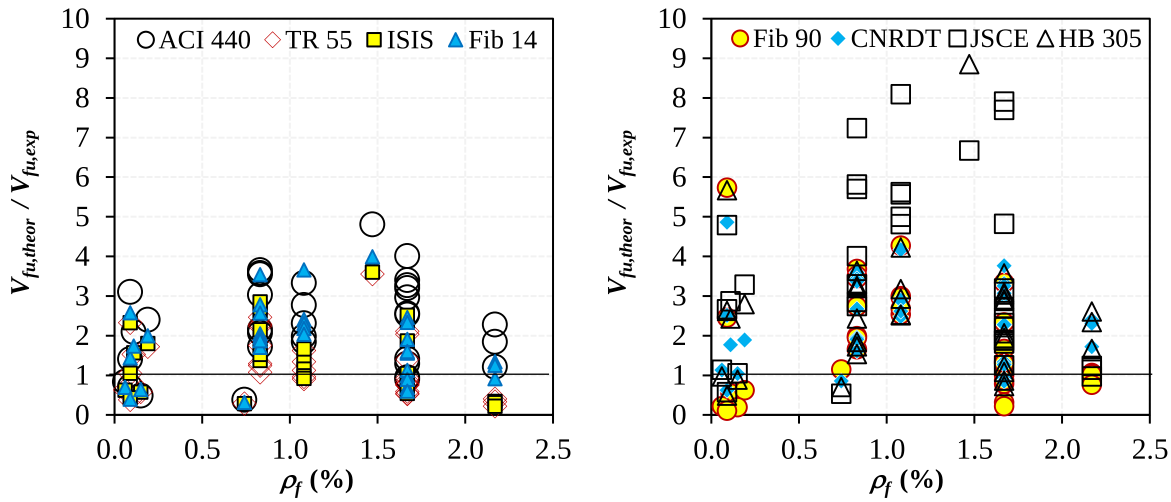


Fig. 7: Evaluation FRP shear contribution versus FRP shear reinforcement ratio

Table 2: Experimental databases of FRP shear-strengthened PC beams

Ref	Sign of beams	Shape	b_w	d	a/d	L	f'_c	f_{pc}	ρ_s	ρ_{sw}	ρ_p	FRP	w_f	s_f	ρ_f	$V_{fu,exp}$
			mm	mm		mm	Mpa	Mpa	%	%	%		mm	mm	%	kN
FRP-strengthened beams prestressed by bonded tendons:																
Murphy et al. [1]	T3-12-S90-NA	I	152	1077	2.2	5490	69.8	9.56	3.5	0.002	1.47	C	300	450	0.09	80.1
	T4-12-S90-SDMA	I	152	1397	2.9	7320	71.2	9.56	0	0.003	1.47	C	300	450	0.09	57.8
Kang & Ary [3]	IB-10	I	102	435	2.6	4572	61.0	3.42	2.2	0.197	0.55	C	76.2	254	0.74	3.6
	IB-5	I	102	435	2.6	4572	61.0	3.42	2.2	0.197	0.55	C	76.2	127	1.47	89.0
Nguyen et al. [5]	B0-1.1SF	R	150	238	3.1	1660	66.8	3.32	1.97	0.563	0.66	C	50	200	0.11	17.4
	B0-1.9SF	R	150	238	3.1	1660	64.1	3.60	1.97	0.563	0.66	C	50	120	0.19	25.3
	B0-0.6SF	R	150	238	3.1	1660	64.1	3.55	1.97	0.563	0.66	C	50	120	0.06	24.2
	B0-1.0CF	R	150	238	3.1	1660	70.7	3.58	1.97	0.563	0.66	C	150	150	0.15	63.3
	B1-0.9SFb	R	150	238	3.1	1660	70.7	3.82	1.97	0.563	0.66	C	100	240	0.09	71.9
FRP-strengthened beams prestressed by unbonded tendons:																
Nguyen-	P-A1-2.3-C	T	120	406	2.3	3200	30.6	4.41	1.80	0.157	0.64	C	75	150	0.83	20.5

International Journal of Engineering Technology and Scientific Innovation

ISSN: 2456-1851

Volume: 07, Issue: 02 "March-April 2022"

Minh et al. [6]	P-A1-2.3-G	T	120	406	2.3	3200	30.6	4.41	1.80	0.157	0.64	G	75	150	1.08	15.0
	P-A1-2.3-G-Cont.	T	120	406	2.3	3200	30.6	4.41	1.80	0.157	0.64	G	1	1	2.17	36.5
	P-A1-2.3-C-Cont.	T	120	406	2.3	3200	30.6	4.41	1.80	0.157	0.64	C	1	1	1.67	49.0
	P-A2-2.3-C	T	120	406	2.3	3200	30.6	4.41	1.80	0.157	0.64	C	75	150	1.67	31.5
	P-A2-1.9-C	T	120	406	1.9	3200	30.6	4.41	1.80	0.157	0.64	C	75	150	1.67	78.0
	P-A2-1.5-C	T	120	406	1.5	3200	30.6	4.41	1.80	0.157	0.64	C	75	150	1.67	112.5
	P-B1-2.3-C	T	120	406	2.3	3200	44.4	4.41	1.80	0.157	0.64	C	75	150	0.83	25.5
	P-B1-2.3-G	T	120	406	2.3	3200	44.4	4.41	1.80	0.157	0.64	G	75	150	1.08	18.0
	P-B1-2.3-G-Cont.	T	120	406	2.3	3200	44.4	4.41	1.80	0.157	0.64	G	1	1	2.17	45.0
	P-B1-2.3-C-Cont.	T	120	406	2.3	3200	44.4	4.41	1.80	0.157	0.64	C	1	1	1.67	57.0
	P-B2-2.3-C	T	120	406	2.3	3200	44.4	4.41	1.80	0.157	0.64	C	75	150	1.67	38.0
	P-C1-2.3-C	T	120	406	2.3	3200	58.7	4.41	1.80	0.157	0.64	C	75	150	0.83	37.0
	P-C1-2.3-G	T	120	406	2.3	3200	58.7	4.41	1.80	0.157	0.64	G	75	150	1.08	22.5
	P-C1-2.3-G-Cont.	T	120	406	2.3	3200	58.7	4.41	1.80	0.157	0.64	G	1	1	2.17	68.5
	P-C1-2.3-C-Cont	T	120	406	2.3	3200	58.7	4.41	1.80	0.157	0.64	C	1	1	1.67	87.5
	P-C2-2.3-C	T	120	406	2.3	3200	58.7	4.41	1.80	0.157	0.64	C	75	150	1.67	61.5
	P-C2-1.9-C	T	120	406	1.9	3200	58.7	4.41	1.80	0.157	0.64	C	75	150	1.67	110.0
	P-C2-1.5-C	T	120	406	1.5	3200	58.7	4.41	1.80	0.157	0.64	C	75	150	1.67	164.5
Vo-Le et al. [7]	P-B1-2.3-C-AN1	T	120	406	2.3	3200	44.4	4.41	1.80	0.157	0.64	C	75	150	0.83	45.0
	P-B1-2.3-C-AN2	T	120	406	2.3	3200	44.4	4.41	1.80	0.157	0.64	C	75	150	0.83	54.0
	P-C1-2.3-C-AN1	T	120	406	2.3	3200	44.4	4.41	1.80	0.157	0.64	C	75	150	0.83	52.0
	PH-B1-2.3-C-Cont	T	120	406	2.3	3200	44.4	4.41	1.80	0.157	0.64	C	1	1	1.67	46.5
	PH-B1-2.3-C-AN1	T	120	406	2.3	3200	44.4	4.41	1.80	0.157	0.64	C	75	150	0.83	26.0
	PH-B1-2.3-G-AN1	T	120	406	2.3	3200	44.4	4.41	1.80	0.157	0.64	G	75	150	1.08	12.5
	PH-B1-2.3-G-AN2	T	120	406	2.3	3200	44.4	4.41	1.80	0.157	0.64	G	75	150	1.08	21.0

ISSN: 2456-1851

Volume: 07, Issue: 02 "March-April 2022"

Table 3: FRP shear contribution: predicted vs experimental

Ref	Sign of beams	$V_{fu,exp}$ kN	$V_{fu,Fib\ 90}/V_{fu,exp}$	$V_{fu,ACI\ 440}/V_{fu,exp}$	$V_{fu,CNRDT}/V_{fu,exp}$	$V_{fu,TR\ 55}/V_{fu,exp}$	$V_{fu,HB\ 305}/V_{fu,exp}$	$V_{fu,Fib\ 14}/V_{fu,exp}$	$V_{fu,ISIS}/V_{fu,exp}$	$V_{fu,JSCE}/V_{fu,exp}$
Murphy et al. [1]	T3-12-S90-NA	80.1	2.46	1.40	2.51	1.04	2.63	1.44	1.05	2.67
	T4-12-S90-SDMA	57.8	5.74	3.11	4.87	2.33	5.67	2.58	2.33	4.80
Kang & Ary [3]	IB-10	3.6	1.15	0.38	0.86	0.28	0.71	0.32	0.29	0.53
	IB-5	89.0	14.41	4.81	11.50	3.56	8.86	3.99	3.60	6.67
Nguyen et al. [5]	B0-1.1SF	17.4	0.55	2.09	1.77	1.53	2.44	1.74	1.57	2.87
	B0-1.9SF	25.3	0.63	2.40	1.89	1.73	2.79	1.99	1.80	3.29
	B0-0.6SF	24.2	0.22	0.84	1.13	0.63	0.97	0.70	0.63	1.15
	B0-1.0CF	63.3	0.20	0.48	1.04	0.58	0.89	0.64	0.58	1.05
	B1-0.9SFb	71.9	0.11	0.71	0.63	0.38	0.49	0.40	0.43	0.57
Nguyen-Minh et al. [6]	P-A1-2.3-C	20.5	3.69	3.55	3.60	2.47	3.64	2.78	2.62	7.24
	P-A1-2.3-G	15.0	3.00	2.77	2.93	1.34	3.18	2.41	1.39	5.56
	P-A1-2.3-G-Cont.	36.5	1.06	2.28	2.40	0.41	2.61	1.34	0.34	1.14
	P-A1-2.3-C-Cont.	49.0	1.33	2.97	3.01	0.76	3.04	1.58	0.81	1.88
	P-A2-2.3-C	31.5	0.79	3.20	3.31	2.11	3.09	2.46	2.37	7.91
	P-A2-1.9-C	78.0	0.32	1.29	1.34	0.85	1.25	0.99	0.96	3.19
	P-A2-1.5-C	112.5	0.22	0.90	0.93	0.59	0.87	0.69	0.66	2.21
	P-B1-2.3-C	25.5	3.52	3.65	3.43	2.29	3.26	2.57	2.70	5.82
	P-B1-2.3-G	18.0	2.97	2.31	2.90	1.13	2.93	2.31	1.16	5.62
	P-B1-2.3-G-Cont.	45.0	1.02	1.85	2.32	0.33	2.35	1.25	0.31	1.24
	P-B1-2.3-C-Cont.	57.0	1.36	3.27	3.07	0.76	2.92	1.56	0.79	1.90
	P-B2-2.3-C	38.0	3.34	3.40	3.26	2.04	2.88	2.34	2.51	7.70
	P-C1-2.3-C	37.0	2.74	3.03	2.68	2.29	2.44	1.97	2.15	4.01

ISSN: 2456-1851

Volume: 07, Issue: 02 "March-April 2022"

	P-C1-2.3-G	22.5	2.69	1.85	2.62	1.13	2.53	2.04	0.92	5.00
	P-C1-2.3-G-Cont.	68.5	0.76	1.21	1.72	0.33	1.66	0.91	0.22	0.97
	P-C1-2.3-C-Cont	87.5	1.00	2.57	2.27	0.76	2.06	1.13	0.55	1.25
	P-C2-2.3-C	61.5	2.33	2.53	2.28	1.41	1.94	1.60	1.87	4.83
	P-C2-1.9-C	110.0	1.31	1.41	1.27	0.79	1.09	0.90	1.05	2.70
	P-C2-1.5-C	164.5	0.87	0.95	0.85	0.53	0.73	0.60	0.70	1.80
Vo-Le et al. [7]	P-B1-2.3-C-AN1	45.0	1.99	2.07	1.95	1.30	1.85	2.05	1.65	3.30
	P-B1-2.3-C-AN2	54.0	1.66	1.73	1.62	1.08	1.54	1.71	1.37	2.75
	P-C1-2.3-C-AN1	52.0	1.95	2.16	1.91	1.25	1.73	1.87	1.53	2.85
	PH-B1-2.3-C-Cont	46.5	1.67	4.01	3.77	0.93	3.58	1.91	0.97	2.32
	PH-B1-2.3-C-AN1	26.0	3.45	3.58	3.37	2.24	3.20	3.54	2.85	5.71
	PH-B1-2.3-G-AN1	12.5	4.27	3.33	4.17	1.62	4.22	3.67	1.66	8.10
	PH-B1-2.3-G-AN2	21.0	2.54	1.98	2.48	0.97	2.51	2.18	0.99	4.82
Mean			**2.21**	**2.29**	**2.62**	**1.22**	**2.53**	**1.78**	**1.35**	**3.58**
COV			**1.13**	**0.48**	**0.71**	**0.63**	**0.62**	**0.51**	**0.63**	**0.63**

4. CONCLUSION

This study assesses the accuracy of predicting the shear resistance of the FRP sheets for strengthened PC beams in the design guidelines based on 35 experimental datasets. All current design guidelines are overestimated the shear resistances of FRP sheets as compared to experimental results. So, they are unsafe for purpose design. Therefore, it is necessary to consider adjusting these formulas or establishing a new formula for PC beams strengthened by FRP shear resistance with mention the interaction of key factors including shear span to effective depth ratio, transverse steel ratio, anchorage systems, prestressing force cable.

Moreover, because of the lack of experimental results, there is a need for further studies to properly evaluate the efficiency of using FRP sheets strengthening PC beams.

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