Assessment of Design Guidelines for Fiber-Reinforced Polymer Shear Contribution of Prestressed Concrete Beams Strengthened by Fiber-Reinforced Polymer Sheets

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Abstract. This research is mainly focussed on statistical assessment and analysis of the accuracy of predicting the shear resistance of the fiber-reinforced polymer (FRP) sheets for prestressed concrete beams strengthened by FRP sheets presented in the current design guidelines. 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, effective pre-stress stress, and shear span to depth ratio - a/d …. The results of the evaluation have shown that the formulas in recent design guidelines overestimated the shear contribution of FRP sheets for prestressed concrete beams.

Keywords: Shear, strengthened, FRP sheets, prestressed concrete beam, design guidelines.

1. Introduction

In recent decades, the technique of shear strengthening using fiber reinforced polymer (FRP) sheets have been quite popular and mainly focused on reinforced concrete (RC) structures. However, the study of this technical solution on prestressed concrete (PC) members is really scarce and limited because there are only a few studies available in the literature [1-7]. Previous studies mainly focussed on 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 current design guidelines have introduced specific provisions to determine the shear resistance for PC beams strengthened with FRP sheets [8-11].

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These calculation terms in 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 concrete, stirrups and FRP sheets was used. However, the interaction between these components and the effect of them were ignored. In fact, the shear behavior of RC beams and PC beams have many differences. Therefore, the use of the terms in the design guidelines to analyze and predict the shear resistance of FRP sheets reinforcement on PC beams may lead to irrational results.

This paper makes analysis reviews to evaluate the formulas of the prediction shear resistance of FRP sheets in the current design guidelines [8-11]. Moreover, the study compares the shear resistance of FRP sheets calculated in the current design guidelines with the corresponding experimental results. The evaluation the accuracy of the predictive standard shear resistance of FRP sheets for PC beams is really necessary to see rationality and ensure the safety of the standards to apply in actual designs.

2. Contribution of FRP sheets to shear resistance

Describing the shear resistance mechanisms of PC beams strengthened FRP sheets is not simple. Therefore, the common method to calculate the shear resistance of PC beams strengthened FRP sheets is mainly based on the superposition theorem with separately shear resistance contributions of concrete, stirrups, prestressing force cable, and FRP sheets. However, this superposition model does not explicitly describe the shear resistance mechanisms of PC beams and the interaction between these mechanisms.

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

	Design guidelines			
Influencing factors	ACI 4402R	CNR-DT 200	TR55	CIDAR
1. Bond model	✓	✓	x	✓
2. Effective FRP strain	✓	✓	✓	✓
3. Configuration	✓	✓	✓	✓
4. FRP sheet ratio	✓	✓	✓	x
5. Concrete strength	✓	✓	✓	✓
6. Strip width to spacing ratio	x	✓	x	✓
7. Cracking angel	x	✓	✓	✓
8. Anchorage length	✓	✓	✓	✓
9. Transverse steel ratio	x	x	x	x

Note: ✓: included; x: not included.

Many models predicted the shear resistance of externally bonded FRP sheets. The researchers calculated the shear resistance of FRP sheets similar to stirrups and mentioned the influences of the effective FRP stress. 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 such as bond model, FRP effective strain, 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 such 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.

3. Comparison of experimental results and predictions by design guidelines.

In order 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. A database representing 33 prestressed concrete beams strengthened in shear with FRP U-jacket was collected from published literature [1,4,5,6,7]. These PC beams used unbonded and bonded tendons. The investigated factors include: the cross-sectional beam (rectangular, I and T), the concrete strength (f'_c) from 30.6 to 71.2 MPa, the effective concrete stress (f_{pc}) from 3.32 to 9.56 MPa, the transverse steel ratio (ρ_{sw}) from 0.0 to 0.56%, the shear span to effective depth (a/d_e) from 1.5 to 3.1, the strengthening scheme (U-strips, U-wrap and full-wrap), the FRP shear reinforcement ratio (ρ_f) from 0.06 to 2.17%, the trajectory cable (curved cable and straight cable). All beams were tested under monotonic loading (four-point bending) up to failure.

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 ($V_{f,theor}/V_{f,exp}$) in **Fig. 1**. In general, all design guidelines are overestimated as compared to experimental results. So, they are not safe for purpose design. The predicted value of CIDAR and ACI 440.2R are unsafe with Mean = 2.05 and COV = 0.50 for CIDAR; Mean = 1.98 and COV = 0.49 for ACI 440. The predicted value of TR 55 and CNRDT 200 are closer to the experimental values, but they have large deviations with Mean = 1.50 and COV = 0.59 for TR55 and Mean = 1.32 and COV = 0.44 for CNRDT 200.

There were a number of causes for differences between the predictions and the experimental results. First, all design guidelines have been built based on data of RC beams strengthened FRP sheets. Second, the effective work of FRP sheets is evaluated unproperly with the interactive bonding surface between concrete and FRP sheets. 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, number layers.

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

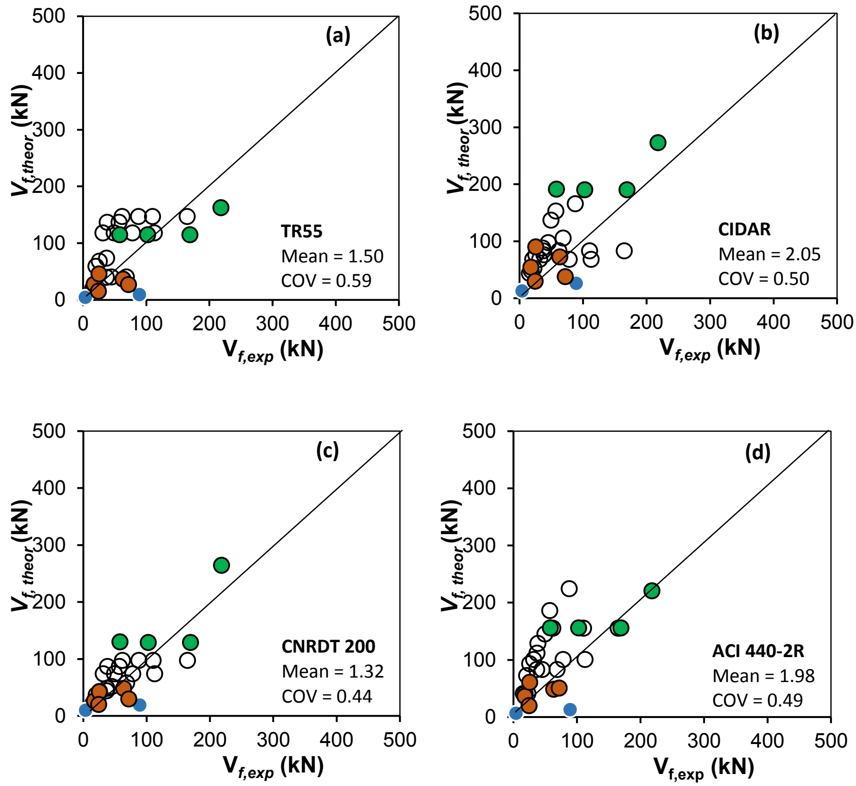

Fig. 1. Comparison between design guidelines and experimental shear strength: (a) TR55; (b) CIDAR; (c) CNRDT 200; (d) ACI 440-22R.

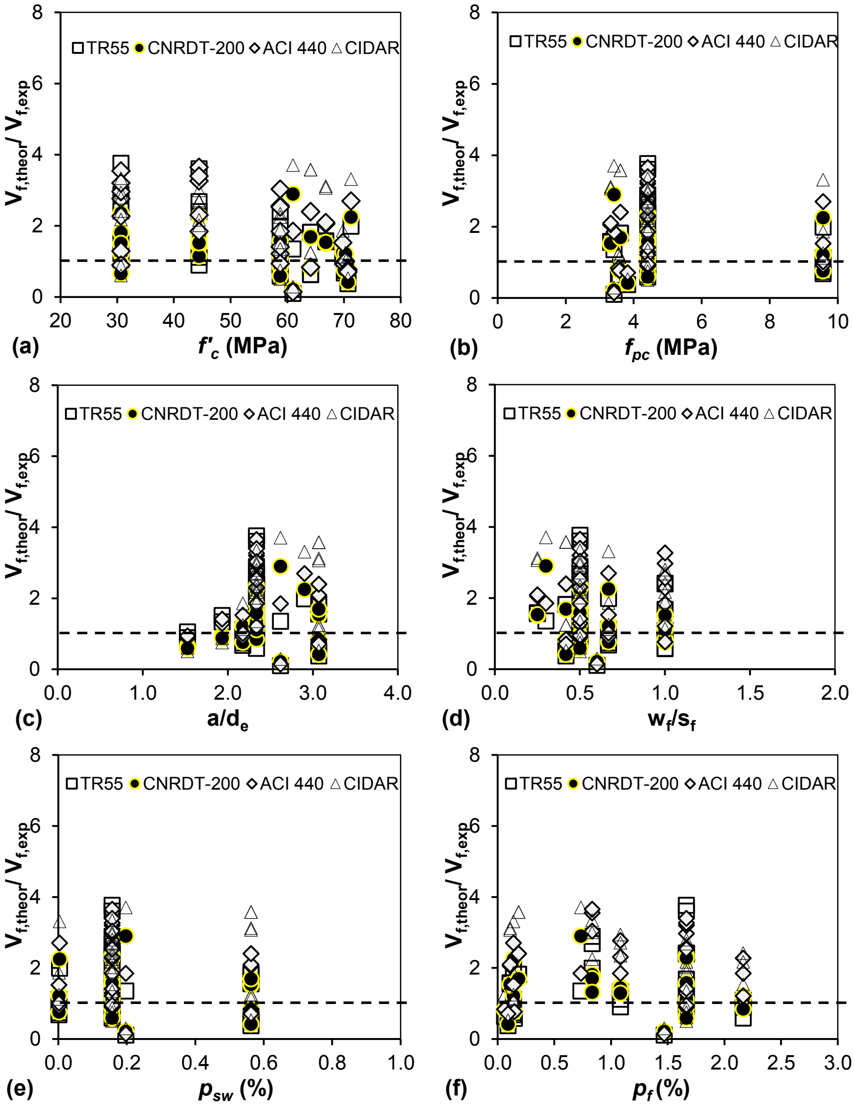

Fig. 2. Evaluation of predictive design guidelines for various parameters: (a) f'_c; (b) f_{pc}; (c) a/d_e; (d) w_f/s_f; (e) ρ_{sw}; (f) ρ_f

4. Conclusions

This study assesses the accuracy of predicting the shear resistance of the FRP sheets for strengthened PC beams in the design guidelines based on 33 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.

Because of the lack of the 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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