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Examination of data on the shear contribution of fiber-reinforced polymer composites used to strengthen reinforced concrete beams with U-jacketing

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Abstract

Lots of research has looked at reinforced concrete beams with externally bonded fiber-reinforced polymer (FRP) and how it contributes to shear strength. Four current design guidelines for the shear contribution of reinforced concrete beams that use U-jacketing fiber-reinforced polymer composites are compared in this paper using over 200 experimental results. The effects of shear span-to-effective depth ratio, beam size, and stirrup ratio are considered. There is a strong correlation between the forecast accuracy of various design standards and these three influencing elements. Thus, an improved shear strength model is suggested in this study that takes into account the impact of shear span-to-effective depth ratio, beam size, and stirrup ratio. When it comes to predicting the shear contribution of fiber-reinforced polymers, the suggested model is superior.

Keywords

Fiber-reinforced polymer (FRP), shear contribution, U-jacketing, reinforced concrete (reinforced concrete) beam, data analysis, design guideline

Introduction

In recent decades, a prominent approach for improving the structural performance of damaged reinforced concrete (RC) elements has been the external bonding (EB) of fiber-reinforced polymer (FRP) composites. The many benefits of FRP composites, such as their low weight relative to their strength, high modulus of elasticity, and resistance to corrosion, as well as their simplicity of installation in reinforcing applications, are to blame. 1–3 To minimize brittle shear failure, typical RC beams are often constructed with a larger shear capacity instead of a higher flexural capacity. Nevertheless, there are a number of reasons why an RC beam might lose some of its shear capacity. These include changes in loading conditions or the severe corrosion of transverse reinforcements caused by chloride attack, among others. Although RC beams are more robust when bent, they may also lose some of their shear strength. A shear strengthening would so be required. 4, 5 Side bonding, U-jacketing, and complete wrapping are three typical designs for FRP shear strengthening (Figure 1). Fiberglass reinforced plastic composites often fail by either a rupture or debonding event. Usually, wrapping strengthened beams and few U-jacketing strengthened beams tends to fail by FRP rupture, while a majority of U-jacketing and side bonding strengthened beams tend to fail by FRP debonding. 6,7

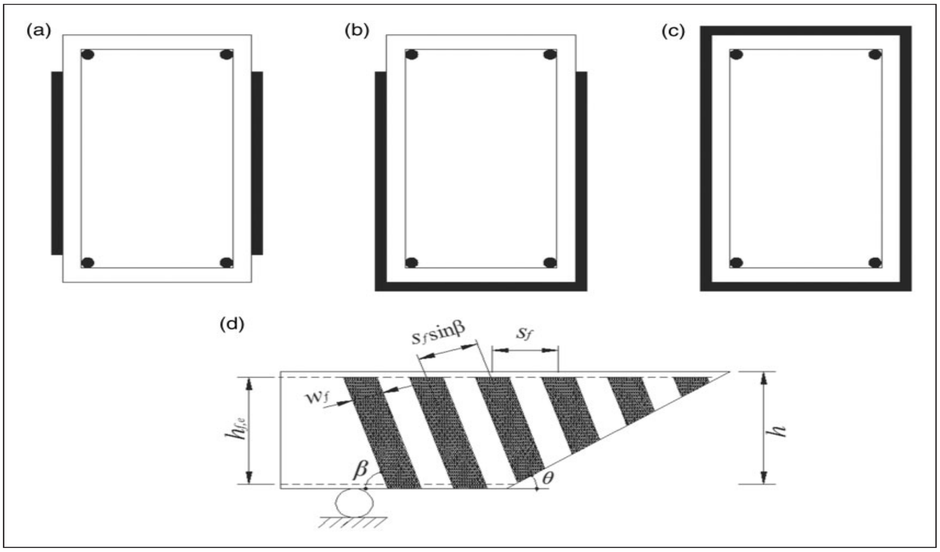

Figure 1. FRP shear-strengthening configurations and geometric sketch. (a) Side bonding, (b) U-jacketing, (c) full wrapping, and (d) geometric dimensions.
FRP: fiber-reinforced polymer.

The prediction models of RC beams shear strengthened with EB-FRP have been the subject of several research throughout the last few decades. Analytical and numerical approaches are used by certain researchers in an effort to resolve the prediction models. For instance, in order to calculate the FRP effective strength, an analytical model based on the stress distribution factor in FRP—a parameter that describes the nonuniform stress of FRP along the beam main crack—was provided by Chen and Teng6,7. In their discussion of the shear contribution of FRP reinforced beams, Pellegrino and Modena8 introduce a component that is associated with the impact of transverse reinforcements. The shear resistance contribution of FRP is, however, investigated by Wu and Jiang9 using numerical calculations. In order to forecast the FRP effective strain, Neubauer and Rostasy10 provide a design approach based on semiempirical equations. In addition, other research organizations have developed frameworks for forecasting the FRP shear contribution of reinforced concrete (RC) beams reinforced with epoxy-filled polyester (EB-FRP) materials. These include ACI 440.2 R (2008), fib-TG9.3 (2001), GB50608 (2010), CNR-DT200R (2013), and many more. 14 Some semiempirical or even empirical equations are still included in these current models or design guides, despite the plethora of research. The limitations of a single laboratory-derived model when applied to real-world engineering are further exacerbated by differences between the two contexts, such as the differences in materials and structural member qualities. Therefore, it is important for the design guidelines and any recommended models to demonstrate that their design equations hold water in a variety of real-world contexts.
Such a research is essential for filling the information vacuum. The forecast accuracy of the FRP shear contribution, as estimated from the four design guides ACI, fib, GB, and CNR, is the primary topic of this research, which compiles over 200 experimental data from prior literature on RC beams shear strengthened with U-jacketing FRP composites. Researchers have looked at how the size impact, stirrup ratio, shear span-to-effective depth ratio (a/d ratio), and shear contribution of FRP are affected by these factors. In addition, a sophisticated model for FRP shear contribution prediction has been put out that takes into account the impact of the aforementioned three elements.

Database description

Since most of the existing concrete structures use cast-in-place concrete to construct RC members, the full-wrapping strengthening configuration is difficult to be applied due to slot cutting the slab for FRP strips going through. Side-bonding FRP is not desired since it is the least effective among these three

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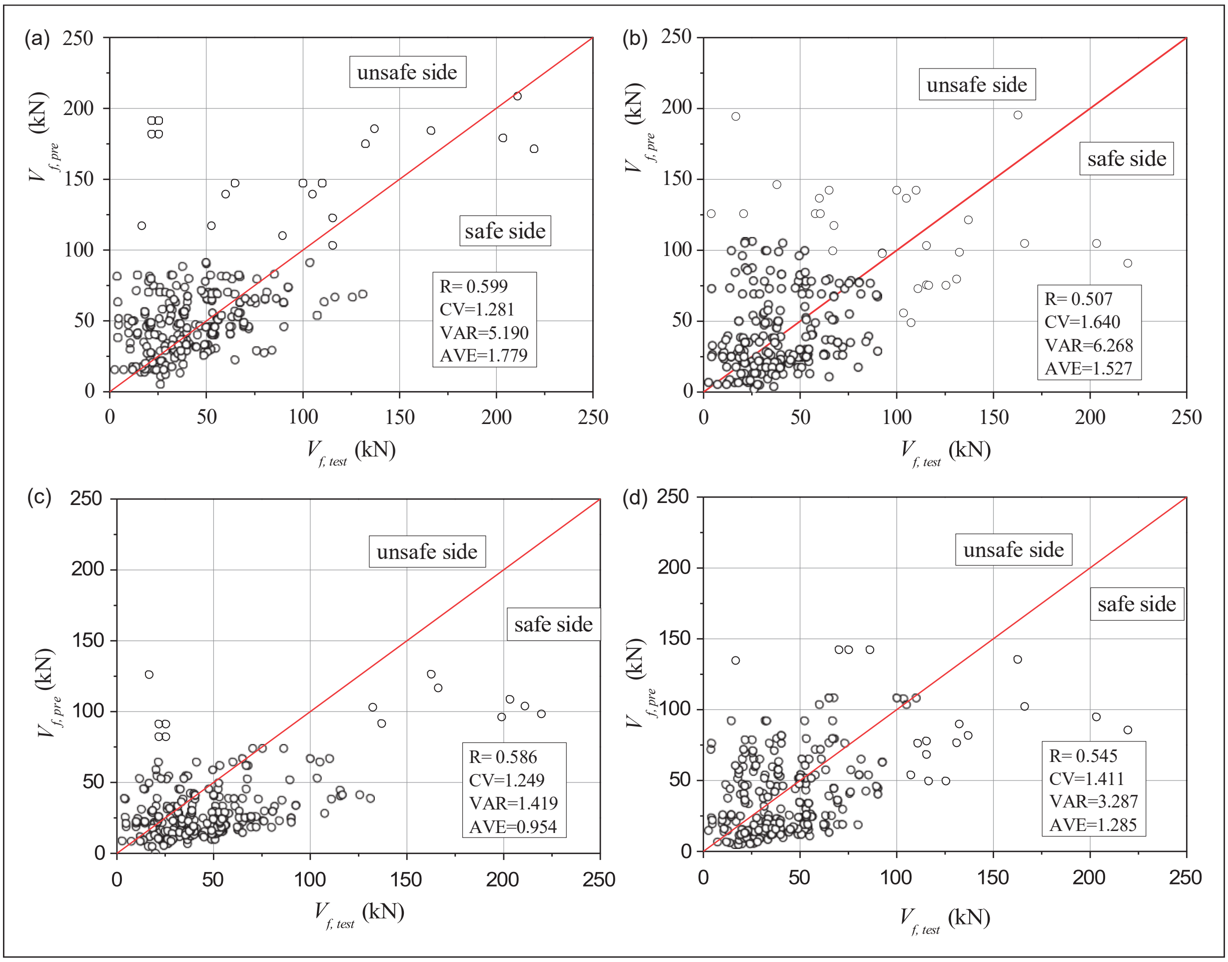

Figure 2. Comparison between test results and predictions from design guidelines. (a) GB design guideline, (b) ACI design guideline, (c) *fib* design guideline, and (d) CNR design guideline.
GB: GB50608; ACI: ACI 440.2R; fib: fib-TG9.3; CNR: CNR-DT200R1.

Together with the interdependence between the anticipated Vf according to the design specifications and the observed test outcomes, the CV value may provide a consistent assessment of the variability in the probability distribution of the Vf, pre/Vf, and test ratios.
Based on Figure 2, it is evident that the fib prediction outperforms the other three design guidelines in terms of correlation with the test outcomes (R = 0.586, CV = 1.249, and VAR = 0.954). This is in addition to the fact that it is extremely near to the best R value from the GB guideline (R = 0.599). Based on the test results, fib prediction fits the data the best, followed by GB and CNR predictions, which have superior R and CV values. On the other hand, ACI prediction has the most dispersion (CV = 1.640) and the lowest correlation (R = 0.507).

Effect of important influence factors on predictions from design guidelines

Concrete strength, a/d ratio, beam size, and stirrup ratio are known to be a few of the key elements that may greatly impact the shear performance of Standard RC beams, which may also be used to reinforce RC components with FRP. The four design criteria have taken the following variables into consideration, as shown in Table 2. Among these four recommendations, the fib design guideline has the best statistic coefficients, in part because it takes into account more parameters than the others (as shown in the table). The next subsections will examine the impact on the predictions from different design standards, although these recommendations still do not take into account several essential aspects like

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a/d ratio, beam size, and stirrup ratio.

Due to the complex shear behaviors of RC beams caused by multiple influence factors, it is helpful to draw on existing test results from the database that analyze different influence factors. These results are based on experimental conditions and strengthening specifications that are similar, but the corresponding influence factors are varied. In this way, the relationship between a/d ratio, stirrup ratio, and beam size is examined using forty-six, forty-two, and twenty-four experimental data, respectively.

Effect of concrete strength on predictions

Concrete strength is not believed to have a significant impact on the shear performance of reinforced concrete elements reinforced with fiber-reinforced plastic. According to Chen and Teng7, the shear strength model should take concrete strength into account as a critical parameter for the FRP shear contribution of an RC beam that has been shear reinforced using a FRP U-jacketing scheme. The coupling impact between concrete strength and bonding length considerably affects the bond capacity between FRP and concrete, according to the test findings of the inquiry by Li et al.,62. Assuming a standard rectangular RC beam with dimensions of 410 mm in height and 250 mm in width and an a/d ratio of 3.0, shear reinforced with CFRP, may help with comprehension.

Table 1. Influence factors included in various design guidelines.

Design guideline	GB	ACI	*fib*	CNR
Concrete strength	×	×	⌣	×
FRP effective strain/stress	×	⌣	⌣	⌣
FRP reinforcement ratio	⌣	⌣	⌣	⌣
Strengthening configuration	⌣	⌣	⌣	⌣
a/d ratio	×	×	×	×
Stirrup ratio	×	×	×	×
Beam size	×	×	×	×

ACI: ACI 440.2R; CNR: CNR-DT200R1; FRP: fiber-reinforced polymer; GB: GB50608.

Note: ‘‘˘’’ means the factor is considered in the design guideline, as well as ‘‘×’’ is not considered.

(Young’s Modulus $E_f = 230$ GPa) U-jacketing configur- ation, and 0.33 mm FRP thickness has been defined. Varying the concrete strength from 15 to 75 MPa, the FRP shear contributions are computed following the above design equations. The results have been plotted in Figure 3. The figure shows that the *fib* predictions are the most insensitive due to concrete strength taken into account. However, ACI predictions are more sensitive to the changes of concrete strength. In addition, there is a level section in the curve of ACI guideline while con- crete strength is more than a certain value, as the max- imum FRP effective strain ($\varepsilon_{f,\ e}$) is limited as 0.004 by ACI design guideline. The effect of concrete strength on the FRP shear contribution for GB, *fib*, and CNR guidelines is similar, which is lead to the predictions gradually increasing with increment of concrete strength (Figure 3). The trend of predictions could be explained as, in FRP U-jacketing configuration, FRP shear contribution V_f is often governed by the bond strength between FRP and concrete, which closely relies on concrete strength.

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Effect of shear span-to-effective depth (a/d) ratio on predictions

The a/d ratio is a key component of FRP shear-strengthening techniques, according to previous research5,39,63,64. Both the shear failure mechanism and the efficacy of FRP composites may be impacted by this. The FRP composites are underutilized when the a/d ratio is low because the stress builds slowly as a result of the concrete arch action. What this means is that engineers should take the a/d ratio into account while reinforcing RC beams with EB-FRP.

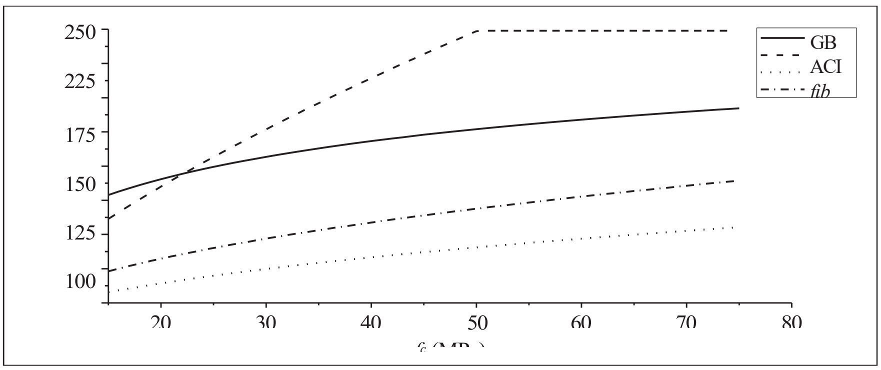

Figure 3. Effect of concrete strength on FRP shear contributions predicted from design guidelines. FRP: fiber-reinforced polymer.

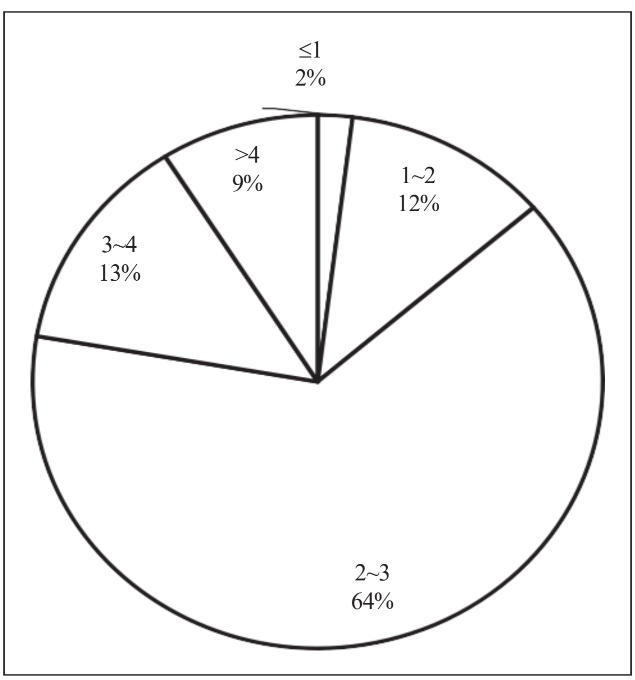

Figure 4. Distribution of shear span-to-effective depth ratios in database.

To account for the impact of the a/d ratio, Chen et al.65 provide a novel model using finite element analysis. A novel model for shear beams and one-way slabs that accounts for the a/d ratio is proposed by Zhang et al.66 based on a wealth of experimental data. Table 1 and Figure 4 show that the majority of the specimens included in this paper's experiments had an a/d ratio between 2.0 and 3.0. Previous studies did not give low or high a/d ratios much

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thought, however.

Figure 5 demonstrates how the four design standards' predictions change as the a/d ratio changes. Based on the data presented in Figure 5, which shows the distribution of Vf, pre/Vf, test ratios for different design guidelines, it can be concluded that ACI, fib, and CNR guidelines offer relatively conservative predictions for FRP shear contribution Vf within the 2.0 to 3.0 a/d ratio range, with only a small number of predictions exceeding the value Vf, pre/Vf, test = 1.0. Nonetheless, it is clear that the overestimation risk of predictions based on these design criteria would rise if a/d is greater than or equal to 3.0.

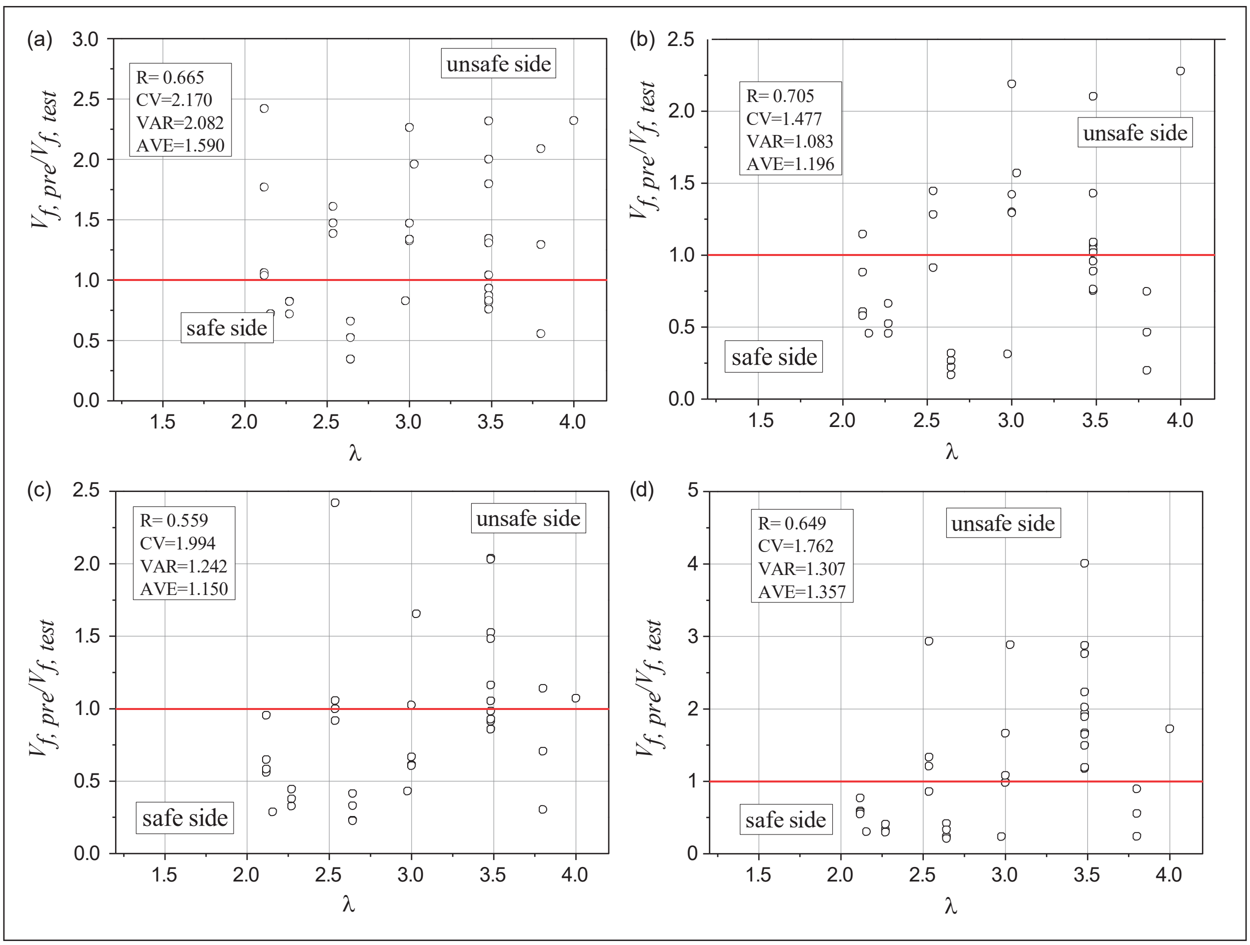

Figure 5. Effect of *a/d* ratio on FRP shear contributions predicted from design guidelines. (a) GB design guideline, (b) ACI design guideline, (c) *fib* design guideline, and (d) CNR design guideline.
ACI: ACI 440.2R; CNR: CNR-DT200R1; FRP: fiber-reinforced polymer; GB: GB50608.

Conclusion

In this study, we examine how well the four design recommendations for FRP U-jacketing—ACI, fib, CNR, and GB—predict the shear contribution of the material. Three factors affecting FRP shear contribution have been studied: a/d ratio, size impact, and stirrup ratio. After looking at the data from the experiments, we can say the following:

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