

Shear strength contribution of transverse FRP reinforcement in bridge girders

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ABSTRACT: Current design guidelines use modified shear equations to calculate the shear strength contribution of fiber reinforced polymer (FRP) transverse reinforcement in the steel- or FRP-reinforced concrete beam, which was originally developed for steel as longitudinal and transverse reinforcement. These shear equations are semi empirical in nature with the core equation determined analytically and coefficients determined from regression analysis. A database from the published literature, composed of slender concrete beams ($a/d > 2.5$) reinforced with FRP rebars contained 112 beams without stirrups and 54 beams with FRP stirrups, was utilized to compare the performance of ACI 440.1R-06 and JSCE 1997 guidelines. The JSCE 1997 guideline had better performance for calculating the concrete shear strength than the ACI guideline with an average calculated over experimental shear strength of 1.41 compared to 1.92. However, the ACI guideline outperformed the JSCE 1997 guideline for calculating the transverse shear strength with an average calculated shear over experimental shear of 1.69 compared to 2.26.

1 INTRODUCTION

Bridges are often exposed to high chlorine concentration due to the use of de-icing salts on bridge decks that make them susceptible to corrosion. In 2009 it was estimated that it would cost more than \$78 billion dollars to repair all corroded steel reinforced concrete (RC) structures in Canada (NSERC, 2009). These costly repairs due to corrosion have encouraged research in fiber reinforced polymer bars (FRP) because of its corrosion resistant property. FRP rebar are formed by bonding fibers with a resin where the fibers are carbon, glass or aramid. Two different types of resins are used: vinyl ester or epoxy. Some examples of bridges constructed using FRP reinforcement in Canada are the Van-Alain Bridge, and the Cookshire-Eaton Bridge in Quebec (El-Salakawy et al., 2005; Benmokrane, 2006).

FRP rebars offer distinct advantages for bridge construction over steel due to its unique material properties. The first advantage is that since the FRP bars are comparatively corrosion resistant the concrete cover over the rebar can be reduced, in turn reducing the amount of concrete used. The second advantage is that FRP rebar is lightweight in comparison to steel, reducing the self-weight of the structure. The third advantage of FRP rebar is its high ultimate strength in comparison to steel. Due to high corrosion resistance of FRP, inspection and maintenance needs are expected to decrease; reducing the lifetime maintenance and repair cost of bridges. On the other hand, there are disadvantages of FRP rebar that one must be knowledgeable to take advantages of the material. The first disadvantage is its lower modulus of elasticity compared to that of steel causing greater deflections at the same reinforcement ratios. The second disadvantage is that FRP rebar does not yield like steel, therefore, new design methodologies must be used to design with FRP. Although researchers have developed techniques for understanding concrete elements reinforced with FRP, there is still room for improvement. The third disadvantage of FRP is its anisotropic material property, which makes it weak in shear action; therefore, FRP has poor dowel action.

Over the last twenty years, various researchers have been extensively involved in developing models, guidelines and codes for FRP reinforced concrete elements (Nanni & Dolan, 1993). In this paper, the design guidelines developed in Japan, JSCE-1997, and the American, ACI 440.1R-06, performance for beams with FRP transverse reinforcement was determined by comparing the calculated results to experimental data. This was achieved by composing a database of FRP reinforced beams that failed in shear from the literature up to 2010. Since FRP is a relatively new material; guidelines are conservative, increasing the construction cost of a structure. This research will significantly improve the confidence level for the end users while using the

JSCE (JSCE, 1997) and ACI guidelines (ACI Committee 440, 2006). This research will also provide some directions towards the improvement upon the guidelines.

2 SHEAR MECHANISMS

There are six mechanisms for shear resistance in a beam (Razaqpur, Isgor, Greenaway, & Selley, 2004):

- The shear resistance of the uncracked concrete compression zone
- Dowel action of the flexural reinforcement
- Aggregate interlock along the crack
- Arching action
- Residual tensile stresses across cracks
- Shear forces carried by shear reinforcement

The shear resistance of uncracked concrete depends on the depth of the compressive zone and the concrete strength (Razaqpur et al., 2004). The shear resistance increases as the uncracked concrete zone gets deeper or concrete strength increases.

Dowel action is the ability of longitudinal reinforcement to transfer shear forces (fib Task Group 9.3, 2007). In FRP longitudinal reinforced concrete structures, dowel action is negligible because of the anisotropic behavior of the FRP material. This results in a low transverse stiffness (fib, 2007).

The aggregate interlock, also referred to as the shear friction, depends on the maximum aggregate size and the shear crack width (Razaqpur et al., 2004). The wider the crack, smaller the aggregate and higher the concrete strength, the less effective this mechanism is for shear resistance.

Arching action is the ability of the concrete to directly transfer shear forces to the supports through concrete struts. Arching action is negligible in slender beams, where the shear span to depth ratio is greater than 2.5 (Razaqpur et al., 2004).

Residual tension in cracked concrete only exists for cracks less than 0.15 mm wide (Razaqpur et al., 2004). This means that the shear cracks will be able to transfer shear forces until they are larger than 0.15 mm. This has been seen to be significant for members with a depth less than 100 mm where crack widths are small (ASCE-ACI Committee 445, 1998). The shear forces carried by the transverse reinforcement can be explained with the truss analogy (ASCE-ACI Committee 445, 1998). The transverse reinforcement bridges shear cracks and transfers shear forces of the crack.

3 MODEL DEVELOPMENT

There are several ways in which guidelines to calculate the shear strength of a reinforced concrete beam reinforced with FRP transverse reinforcement have been developed. The most common approach to develop models for FRP reinforced concrete was to modify the existing code equations developed for steel reinforcement to better represent the behavior of FRP. This was the approach used by JSCE 1997, and ACI 440.1R (fib, 2007). JSCE 1997 used the strain approach (fib, 2007). The strain approach is based on developing the same design force as if it was a steel RC member (fib, 2007). ACI 440.1R was modified to account for the change in axial stiffness (fib, 2007).

3.1 Strain Approach

The strain approach modifies a shear equation developed for steel to adopt it for FRP reinforcement. The strain approach's aim is for the FRP reinforced section to develop the same strains and therefore, the same forces by adjusting the axial stiffness of the member as if it was reinforced with steel. This is done by multiplying the area of the FRP reinforcement by the modular ratio (fib, 2007).

$$A_s = A_{fr} \frac{E_{fr}}{E_s} \quad (1)$$

4 DESIGN ALGORITHMS

In the shear design algorithms the concrete shear strength, V_c and stirrup shear strength, V_{fv} are treated as independent parameters to determine the ultimate shear strength, V_n given in the following equation:

$$V_n = V_{fv} + V_c \quad (2)$$

The ACI 440.1R-06 and JSCE 1997 calculate the concrete shear force differently while the stirrup shear force is calculated based upon the 45 degree parallel truss model.

The concrete shear strength is given in the ACI 440.1R-06 as: (in SI units)

$$V_c = \frac{2}{5} \sqrt{f'_c} b c \quad (3)$$

$$c = dk \quad (4)$$

$$k = \sqrt{2\rho_{fl}n_f + (\rho_{fl}n_f)^2} - \rho_{fl}n_f \quad (5)$$

$$n_f = E_{fl}/E_c \quad (6)$$

where f'_c = specified compressive cylinder strength, b = beam width, d = effective depth of reinforcement, E_f = elastic modulus of FRP reinforcement, E_c = elastic modulus of concrete. ρ_{fl} = reinforcement ratio of longitudinal reinforcement.

The stirrup shear strength is given in the ACI 440.1R-06 as:

$$V_{fv} = \frac{A_{fv}\sigma_{fv}d}{s} \quad (7)$$

$$\sigma_{fv} = 0.004E_{fv} \leq f_{FRPbend} \quad (8)$$

$$f_{FRPbend} = \frac{\left(\frac{0.05r_b}{d_b} + 0.3\right)}{1.5} f_{fu} \leq f_{fu} \quad (9)$$

where A_{fv} = Area of stirrup, σ_{fv} = strength of the stirrup, s = stirrup spacing, r_b = radius of the stirrup bend, d_b = diameter of the stirrup, E_{fv} = elastic modulus of the stirrup, f_{fu} = ultimate strength of the stirrup.

The concrete shear strength is given in the JSCE 1997 as:

$$V_c = \beta_d \beta_p \beta_n f_{vcd} b d / \gamma_b \quad (10)$$

$$f_{vcd} = 0.2(f'_c)^{\frac{1}{3}} \leq 0.72 \text{ MPa} \quad (11)$$

$$\beta_d = \left(\frac{1000}{d}\right)^{\frac{1}{4}} \leq 1.5 \quad (12)$$

$$\beta_p = \left(100 \frac{\rho_{fl} E_{fl}}{E_s}\right)^{\frac{1}{3}} \leq 1.5 \quad (13)$$

$$\beta_n = 1 + \frac{M_o}{M_d} \leq 2 \text{ for } N_f \geq 0 \quad (14)$$

$$\beta_n = 1 + \frac{2M_o}{M_d} \leq 2 \text{ for } N_f < 0 \quad (15)$$

where γ_b = safety factor, generally 1.3, E_s = elastic modulus of steel, taken as 200 GPa, M_o = decompression moment, M_d = design bending moment N_f = design axial compressive force.

The stirrup shear strength is given in the JSCE 1997 as:

$$V_{fv} = [A_{fv} E_{fv} \varepsilon_{fv} (\sin \alpha_s + \cos \alpha_s) / s] j d \leq \frac{f_{FRPbend}}{E_{fv}} b d \quad (16)$$

$$\varepsilon_{fv} = 0.0001 \sqrt{f'_{mcd} \frac{\rho_{fl} E_{fl}}{\rho_{fv} E_{fv}}} \left[1 + 2 \left(\frac{\sigma_N}{f'_{mcd}} \right) \right] \leq \frac{f_{FRPbend}}{E_{fv}} \quad (17)$$

$$f'_{mcd} = \left(\frac{h}{100} \right)^{-\frac{2}{10}} f'_c \quad (18)$$

$$jd = d/1.15 \quad (19)$$

where γ_b = safety factor, generally 1.15, α_s = angle of stirrups, h = height of beam, σ_N = stress in concrete due to axial loads.

5 DATABASE

A database composed of 166 beams reported in the literature up to 2010 (Ahmed, Salakawy & Benmokrane, 2010a; Ahmed, Salakawy & Benmokrane, 2010b; Razaqpur et al., 2004; Gross, Yost, Dinehart, Svensen, & Liu, 2001; El-Sayed, El-Salakawy, & Benmokrane, 2006a; El-Sayed, El-Salakawy, & Benmokrane, 2006b; Guadagnini, Pilakoutas, & Waldron, 2006; Ashour, 2006; Tureyen, & Frosch, 2002; Tariq, & Newhook, 2003; Zhao, Maruyama, & Suzuki 1995; Nagasaka, Fukuyama, & Tanigaki, 1993; Li, & Wang, 2002; Swamy, & Aburawi, 1997; Tottori & Wakui, 1993; Alsayed, Al-Salloum, & Almusallam, 1997; Matta, Nanni, Hernandex, & Benmokrane, 2008; Steiner, El-Sayed, Benmokrane, Matta, & Nanni, 2008; Maruyama, & Zhao, 1994; Gross, Dinehart, Yost, & Theisz, 2004; Fico, Prota, & Manfredi, 2007).

For the database, only rectangular slender beams with $a/d > 2.5$ and with FRP reinforcement that failed in shear were considered. There were 112 beams with no shear reinforcement and 54 beams with shear reinforcement. All of the properties are summarized in Table 1. If an aggregate size was not reported, an aggregate size of 15 mm was assumed. Where a bend radius was not reported a bend radius of $3d_b$ (d_b is the bar diameter) was assumed following a practice done by Fico et al. (2007). This would allow for conservative calculation of the shear strength by codes and models.

Table 1. Summary of database values

Properties	Min	Max
b (mm)	114	457
d (mm)	128	889
a (mm)	338	2743
a/d	2.5	6.5
h (mm)	147	978
f'_c (MPa)	22.9	84.2
ag (mm)	9.5	25
ρ_f (%)	0.25	3.08
E_f (GPa)	32	200
f_{ft} (MPa)	565	2640
ρ_{fv} (%)	0.04	1.43
E_{fv} (GPa)	39	144
f_{fv} (MPa)	565	2040

6 RESULTS AND DISCUSSION

The ACI and JSCE guidelines were compared based on the average ratio of the tested to the calculated shear strength, V_{test}/V_{calc} , its standard deviation (SD) and the average absolute error (AAE) calculated using Eq 20.

$$AAE = \frac{1}{n} \sum \frac{|V_{test} - V_{calc}|}{V_{test}} \quad (20)$$

The results from beams without stirrups and with stirrups were compared separately in Tables 2 and 3, respectively.

Design guidelines for shear should have some margin of conservativeness. This can be achieved by either having a conservative model, or by applying safety factors to the design equation. The ACI 440.1R-06 guideline was developed to be innately conservative and does not implement safety factors. The JSCE guidelines 1997 implement safety factors to develop conservativeness. For model comparisons, the safety factors were set to 1 and to compare confidence levels the recommended safety factors were used.

6.1 Discussion of Beams without Stirrups

The results of the ACI 440.1R-06 and JSCE guidelines 1997 are shown in Table 2. The ACI 440.1R-06 was the more conservative model in calculating the concrete shear strength of a beam with a V_{test}/V_{calc} of 1.92 in comparisons to the JSCE 1997 results of 1.41. The most accurate guideline was the JSCE 1997 with an AAE of 25.88% compared to the ACI 440.1R-06 results of 44.93%. JSCE had much better precision with a SD of 0.39, compared to an ACI SD of 0.50. While the ACI guideline was easier to implement than the JSCE guideline, the JSCE had much better performance and was a better model. The ACI 440.1R had conservative estimations of beam strength in which no beams had a V_{test}/V_{calc} less than 1.

The JSCE guideline was made to be used with a safety factor; this would increase the conservativeness of this guideline. When the safety factor set to one, 4 beams in the database were overestimated and would have failed before expected. It was found that using the recommended safety factor of 1.3 would increase the V_{test}/V_{calc} and the SD to 1.83 and 0.51, respectively and prevent any beam from being overestimated. From the results, one could conclude that JSCE could provide some margin of safety without a safety factor.

Table 2. Comparison of guideline results of beams without stirrups

Guideline	Average V_{test}/V_{calc}	Standard Deviation	CoV (%)	AAE (%)
ACI 440.1R-06	1.92	0.50	25.91	44.93
JSCE 1997 (without safety factor)	1.41	0.39	27.72	25.88
JSCE 1997 (with safety factor of 1.3)	1.83	0.51	27.72	42.07

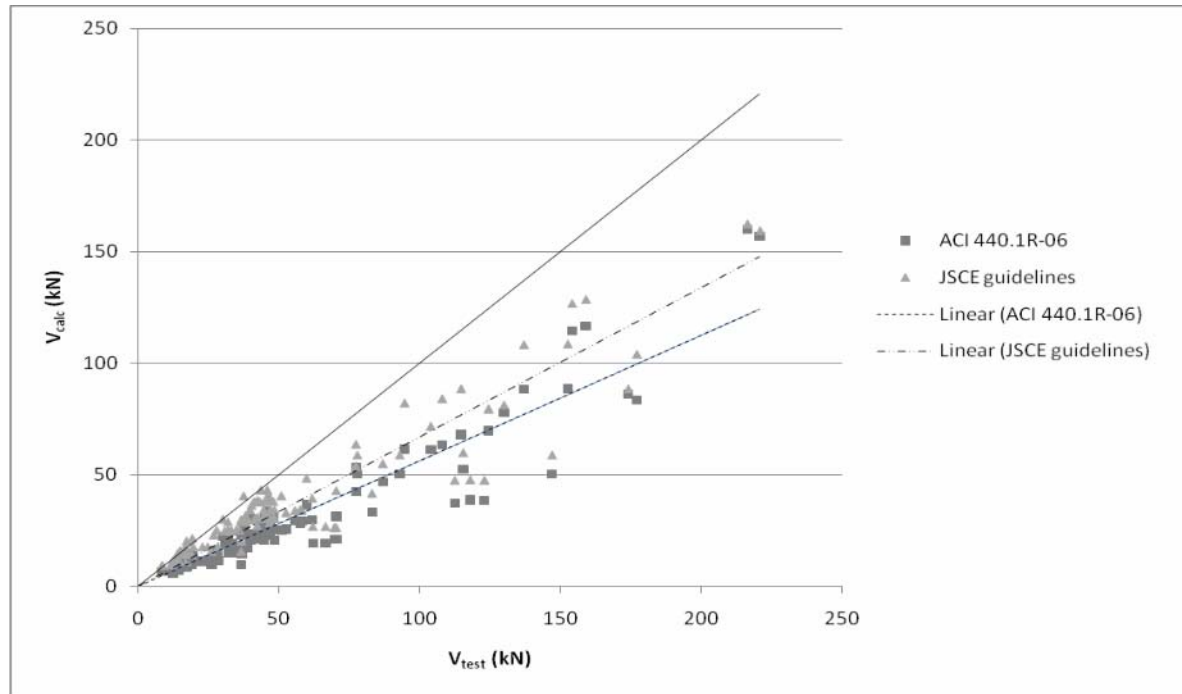


Figure 1. Comparison of guidelines of beams without stirrups

6.2 Discussion of Beams with Stirrups

The models, in general, are more conservative when a beam has FRP stirrups. This is due to two reasons. 1) Most of the models conservatively limit the strength of the stirrup to make it align with steel and to limit

crack width. While in reality, the FRP stirrup can have greater strains than that of steel. 2) The models assume that stirrups do not affect the concrete shear resistance, while, in fact the stirrups would increase the concrete shear resistance (Nehdi et al., 2006). The ACI 440.1R stirrup shear strength equations produced much better results than the JSCE 1997 guidelines. The JSCE guidelines were excessively conservative with a V_{test}/V_{calc} of 2.26. The ACI 440.1R-06 produced a more reasonable result but still overly conservative with a V_{test}/V_{calc} of 1.69. The ACI 440.1R-06 and JSCE only differ in their calculation of the stirrup strain. The ACI 440.1R-06 sets the stirrup strain to a value of 0.004. The JSCE guidelines calculated the stirrup strain for each beam. This strain calculation produced conservative result with an average strain in the FRP stirrups of 0.0018 which in turn produced conservative stirrup shear strength.

The model performance for shear-reinforced beams suggests that these guidelines under estimate the shear strength of RC beams with transverse FRP reinforcement. The ACI 440.1R-06 was more precise than the JSCE guidelines with a SD of 0.39 compared to a SD of 0.60, respectively. The ACI 440.1R-06 produced the best results but was still overly conservative.

Table 3. Comparison of model results of beams with stirrups

Guideline	Average V_{test}/V_{calc}	Standard Deviation	CoV (%)	AAE (%)
ACI 440.1R-06	1.69	0.39	23.26	38.98
JSCE 1997	2.26	0.60	26.55	52.62

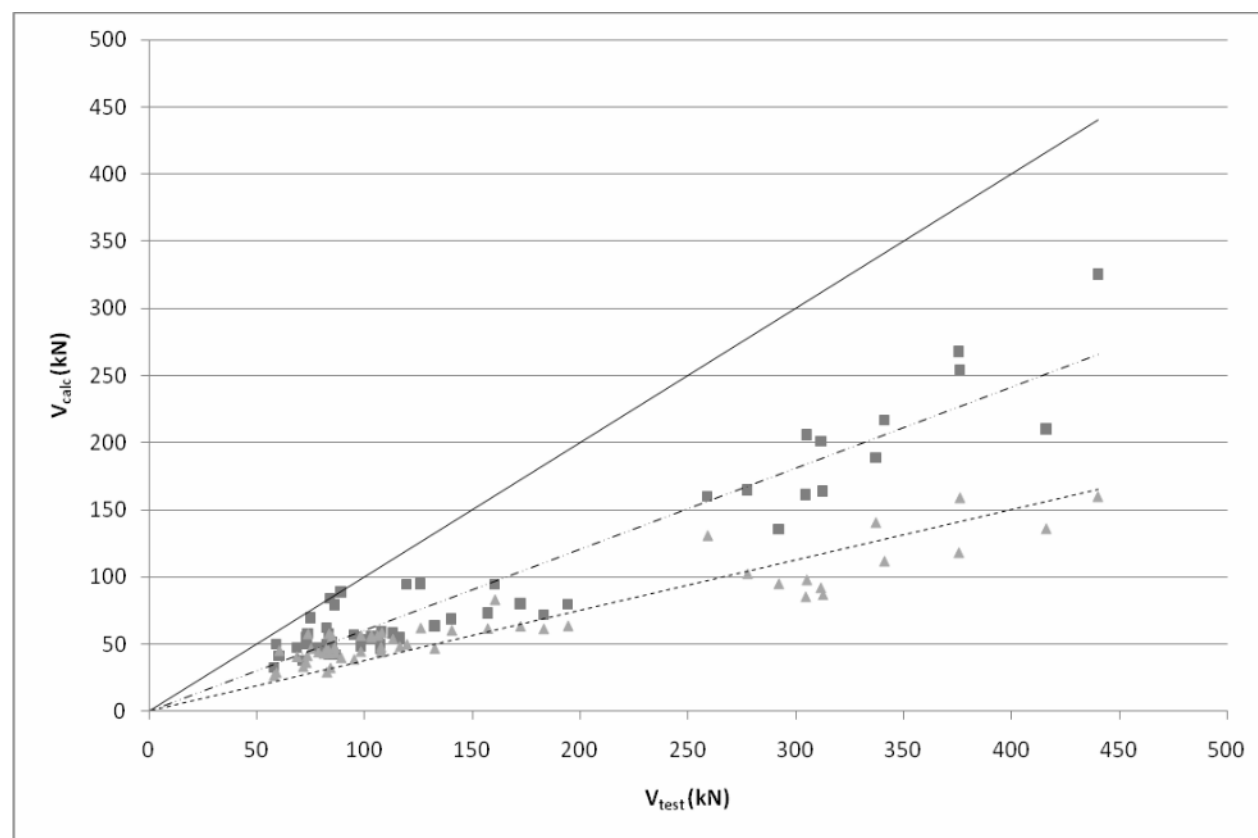


Figure 2. Comparison of guidelines of beams with stirrups

7 CONCLUSION

Based on the analyses presented in this paper, the following conclusions and recommendations are made:

- 1) The reviewed guidelines are overly conservative for calculating stirrup shear strength with a V_{test}/V_{calc} greater or around 1.7. The overly conservative guidelines cause uneconomical use of FRP reinforcement or congestion of reinforcements during concrete casting
- 2) It was found that the ACI 440.1R-06 produced better stirrup shear strength estimates whereas the JSCE produced better concrete shear strength estimates.
- 3) Improvement of the current shear models is needed.

7.1 Recommendations

For future research, different methods to develop the shear models should be explored and more experimental data of FRP reinforced beams should be acquired. One could use an optimization technique to complement analytical approaches to develop a shear equation. Experimental data of concrete beams with FRP stirrups would assist in developing models that can accurately predict the shear strength.

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