Fourth International Conference on FRP Composites in Civil Engineering (CICE2008)
22-24 July 2008, Zurich, Switzerland

Scaling of strength of FRP reinforced concrete beams without shear reinforcement

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ABSTRACT: Among the unresolved issues in the design of structural concrete reinforced with fiber reinforced composite (FRP) bars, the understanding of size effect in the reduction of the shear strength of deep beams without shear reinforcement is of fundamental and practical significance. Size effect accrues primarily from the larger width of diagonal cracks as the effective depth is increased, and has been extensively documented in the case of steel reinforced concrete (RC) through a number of laboratory tests. In FRP RC, the lower longitudinal elastic modulus of the flexural reinforcement results in deeper and wider cracks. Yet, the calibration of any of the current semi-empirical design algorithms is based on test results of beams and one-way slabs with maximum effective depth of 360 mm, which is not representative of relevant large-scale applications. This paper presents and discusses the results of laboratory testing of large-size and scaled FRP RC beams without shear reinforcement, having maximum effective depth of 147, 294 and 883 mm, and effective reinforcement ratio of 0.12% and 0.24%. It is shown that the shear strength of the large-size specimens with less flexural reinforcement decreases on average by 55% compared with the smaller specimens. However, the conservativeness of the current design algorithms generally offsets the size effect. The provisions of the UK Institution of Structural Engineers (ISE) and the Italian National Research Council (CNR) provide the most accurate estimates, where the former yields more conservative and consistent results.

1 INTRODUCTION

The nominal shear strength of concrete members reinforced with steel or fiber reinforced polymer (FRP) bars is obtained by adding the contribution of the shear reinforcement to the shear force “carried by the concrete”, which is typically computed using semi-empirical design algorithms. For beams with relatively large shear span-to-depth ratio, arching effects are negligible, and therefore only the contributions from shear in the uncracked compression zone, aggregate interlock, dowel action, and tensile cohesive stresses in the concrete are lumped in the formulations for the concrete shear strength. Such algorithms may reflect the results of laboratory tests conducted on large steel RC beams without shear reinforcement, which have long provided substantial evidence of the decrease in shear stress at failure at increasing effective depth, and especially for smaller longitudinal reinforcement ratios (Kani 1967, Shioya et al. 1989, Collins & Kuchma 1999).

The size effect accrues primarily from the larger width of diagonal cracks as the beam effective depth is increased (Bažant & Kim 1984, Collins et al. 1996). In the case of FRP RC, size effect is of concern because the relatively low longitudinal elastic modulus of the reinforcement (typically 40 GPa for glass FRP bars) determines deeper and wider cracks. In addition, reduced dowel action is contributed due to the small transverse strength, which is resin-dominated. However, the calibration of any current design algorithms relies on databases that include test results from specimens with a maximum effective depth of 360 mm, which was reported in a previous study (Tureyen & Frosch 2002). These dimensions are not representative of large-scale FRP RC members, such as softeyes in slurry walls for tunnel excavation, retaining walls in coastal bluffs, and slab bridges, for which the conservativeness of the design algorithms remains unproven (Matta et al. 2007).

This paper reports on an experimental investigation on large-size and scaled concrete beams reinforced with longitudinal glass FRP (GFRP) bars. The objective of this paper is twofold: first, to provide quantitative estimates of the decrease in shear strength that was observed at increasing effective depths; second, to evaluate the efficiency of the provisions set forth in existing guides and codes of practice that cover the design of FRP RC structures.

2 DESIGN ALGORITHMS

Size effect is not explicitly addressed in the design equation for the concrete shear strength that has been adopted by the current ACI 440 design guidelines (ACI 2006), which is given as

$$V_c = \frac{2}{5} k \sqrt{f'_c}\, b_w d \tag{1}$$

where $k = [2\,\rho_f n + (\rho_f n)^2]^{1/2} - \rho_f n$; ρ_f = FRP flexural reinforcement ratio; n = ratio of the longitudinal elastic modulus of the FRP bars used as flexural reinforcement, E_f, to the elastic modulus of concrete; f'_c = specified cylinder compressive strength of concrete in MPa; b_w = width of the web in mm; and d = effective depth in mm. The formula recognizes the predominant influence of the axial stiffness of the flexural reinforcement and of the concrete tensile strength, herein assumed proportional to $(f'_c)^{1/2}$.

A number of existing design algorithms that attempt to account for size effect get round the lack of experimental evidence by adapting formulations derived for steel RC. The Japanese Society of Civil Engineers (JSCE 1997) recommends

$$V_c = 0.2\, \sqrt[3]{100\rho_{eff}}\, \sqrt[4]{\frac{1000}{d}}\, \sqrt[3]{f'_c}\, b_w d \tag{2}$$

where ρ_{eff} = effective reinforcement ratio = $\rho_f E_f / E_s$, with E_s = elastic modulus of steel, thus accounting for the reduced stiffness of FRP reinforcement compared to steel; $(100\rho_{eff})^{1/3} \leq 1.5$; and $(f'_c\ \mathrm{MPa}^2)^{1/3} \leq 3.6$ MPa. The size effect parameter $(1000\ \mathrm{mm} / d)^{1/4} \leq 1.5$ is based on Weibull statistical theory, and is taken from the provisions for steel RC. Similarly, the Institution of Structural Engineers (ISE 1999) recommends

$$V_c = 0.79\, \sqrt[3]{100\rho_{eff}}\, \sqrt[4]{\frac{400}{d}}\, \sqrt[3]{\frac{f_{cu}}{25}}\, b_w d \tag{3}$$

irrespective of the effective depth, where f_{cu} = specified cube compressive strength of concrete.

In the case of $d \geq 300$ mm, the ISIS Canada Research Network (ISIS 2001) recommends

$$V_c = \sqrt{\frac{E_f}{E_s}} \left(\frac{260}{1000 + d}\right) \lambda \phi_c \sqrt{f'_c}\, b_w d \;\geq\; 0.1\, \sqrt{\frac{E_f}{E_s}}\, \lambda \phi_c \sqrt{f'_c}\, b_w d \tag{4}$$

similarly to the Canadian Standard Association (CSA 2002) that uses

$$V_c = \left(\frac{130}{1000 + d}\right) \lambda \phi_c \sqrt{f'_c}\, b_w d \;\geq\; 0.008\, \lambda \phi_c \sqrt{f'_c}\, b_w d \tag{5}$$

where $\lambda = 1$ for normal density concrete, and ϕ_c = resistance factor for concrete.

The Italian National Research Council has recently introduced a modified Eurocode 2 algorithm (CNR 2006) in the form

$$V_c = 1.3 \sqrt{\frac{E_f}{E_s}}\, \tau_{Rd} k_d \left(1.2 + 40\rho_f\right) b_w d,\ \rho_f \leq 0.02 \tag{6}$$

where τ_{Rd} is the design shear stress, which may be taken as $0.047(R_{ck})^{2/3} / \gamma_c$, with R_{ck} = characteristic cube compressive strength of concrete, and γ_c = material safety factor for concrete. The parameter $k_d = (1600 - d) \geq 1$ enables to address size effect for effective depths up to 600 mm.

The Canadian Highway Bridge Design Code (CSA 2006) mandates a procedure to compute the concrete shear strength that is based on the modified compression field theory (Collins et al. 1996), and is expressed as

$$V_c = 2.5\beta\phi_c f_{cr} b_w d_v \sqrt{\frac{E_f}{E_s}}$$
$$\beta = \left(\frac{0.4}{1+1500\varepsilon_x}\right)\left(\frac{1300}{1000+s_{ze}}\right), \; s_{ze} = \frac{35d_v}{15+a_g} \geq 0.85d_v \quad (7)$$

where the parameter β accounts for the ability of the concrete section to transmit stresses across diagonal cracks, and is a function of the crack spacing parameter s_{ze}, and of the longitudinal strain in the flexural reinforcement, $2\varepsilon_x$, while a_g = maximum aggregate size, d_v = flexural lever arm, and f_{cr} = cracking strength of concrete = $0.4(f'_c \text{ MPa})^{1/2} \leq 3.2$ MPa. Size effect is explicitly accounted for by correlating the increase in crack width with the crack spacing and the tensile strain in the critical section, under the assumption that the strength decrease originates from reduced aggregate interlock.

3 EXPERIMENTAL PROGRAM

The test matrix comprises ten specimens whose cross sections and reinforcement layouts are shown in Figure 1. Series S1 includes two large-size cross sections with effective depth of 883 mm. Three Ø32 mm longitudinal GFRP bars were used to obtain an effective reinforcement ratio ρ_{eff} = 0.12%, which is a representative lower-bound percentage that is aimed at evaluating any size effect in a worst-case scenario. Specimen S1-2 was constructed with minimum shear reinforcement, as required in most concrete structures, using U-shaped Ø16 mm bars to form closed stirrups. The objective was to assess size effect and the effectiveness of shear reinforcement in providing the required postcracking strength. Each of Series S3 and S6 includes three similar specimens reinforced with Ø16 mm longitudinal GFRP bars that provide the same percentage of reinforcement as of Series S1, and having effective depth scaled by 1/3 and 1/6, respectively. In addition, Series S1B includes two large-size specimens reinforced with two bundles of three Ø32 mm longitudinal bars each, and were aimed at comparatively evaluating size effect with Series S1 in the case of a relatively large effective reinforcement ratio of 0.24%. Bars from different manufacturers were used to construct Specimens S1B-1 and S1B-2.

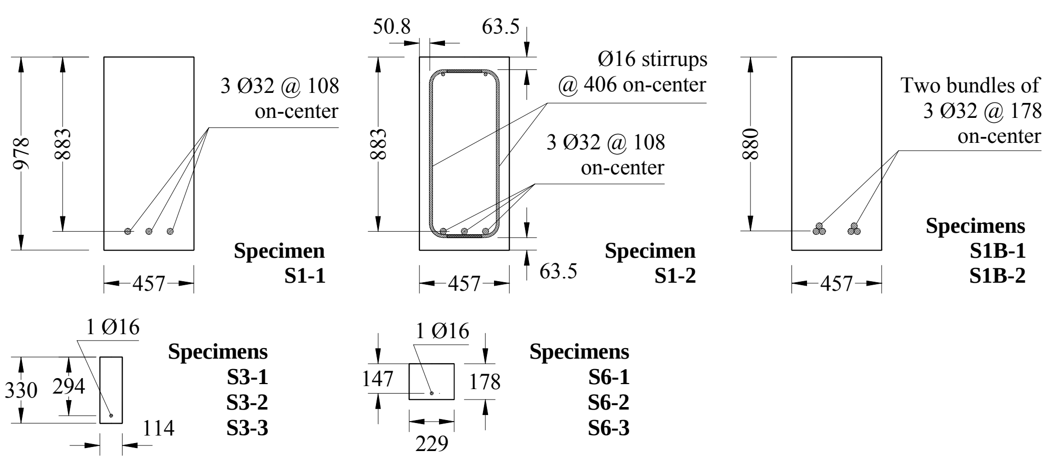

Figure 1. Cross section of beam specimens. Dimensions in mm.

The beams were tested in four-point bending using the setup shown in Figure 2. For each specimen, Table 1 summarizes the length of the shear span, constant moment region, and the anchorage length past the supports to prevent bar slip. The total length was 9.14, 3.35, and 2.44 m for Series S1 and S1B, S3, and S6, respectively. The test arrangements were scaled to ensure a constant shear span-to-depth ratio of 3.11 to obtain lower-bound values of shear strength. The loads were applied using manually operated hydraulic actuators, and measured with load cells. The specimens were instrumented with strain gauges onto the reinforcement and the concrete at relevant sections, and with displacement transducers along the length and at the supports.

Table 1 also summarizes the relevant material properties, including the average cylinder compressive strength of the concrete, f_c, as determined per ASTM C39 at the time of testing, and the average longitudinal elastic modulus of the E-glass/vinyl ester GFRP bars (Ø32 mm for Series S1 and S1B, and Ø16 mm for Series S3 and S6), E_f, as obtained from tensile tests.

4 RESULTS AND DISCUSSION

All specimens failed in diagonal tension, as depicted in Figure 3. The experimental values of concrete shear of each specimen are reported in Table 1, where the effect of self-weight at a distance d from the loading section is also considered. A reasonable estimate was provided for Specimen S1-2 by increasing the load at which the first inclined (≥ 45°) shear crack formed by 8.1%, as observed on average for six FRP RC beam specimens without shear reinforcement, with ρ_{eff} = 0.19% and d = 360 mm, in a previous investigation (Tureyen & Frosch 2002).

A quantitative estimate of size effect for Series S1, S3 and S6 (ρ_{eff} = 0.12%) is given in Figure 4a, where the parameter V_c / ($f_c^{1/2}$ $b_w d$) is used as the shear strength indicator to account for the different values of concrete strength. A clearly decreasing trend is noted at increasing effective depths, which is more pronounced between Series S6 and S3. With respect to Series S6, an average strength reduction of 43% and 55% is exhibited by Series S3 and S1, respectively. Figure 4b shows that Series S1B (ρ_{eff} = 0.24%) presents a descending trend when compared to test results found in the literature (Matta et al. 2007), which were obtained from FRP RC specimens having effective reinforcement ratio and shear span-to-depth ratio in the range 0.22%-0.27% and 2.61-6.05, respectively. In addition, the effect of the higher percentage of reinforcement of Series S1B is reflected in the 48% greater average strength than Series S1.

Figure 2. Test setup: schematic (a), and photograph of setup for Series S1 and S1B (b) and Series S6 (c).

Table 1. Relevant geometric and material properties, and experimental V_c of beam specimens

Specimen Series	Specimen ID	d (mm)	a (mm)	a/d	m	l	f_c (MPa)	E_f (GPa)	ρ_f (%)	ρ_{eff} (%)	V_c (Exp.) (kN)
S1	S1-1	883	2743	3.11	1829	914	29.5	40.7	0.59	0.12	154.1
	S1-2						38.8				158.9
S3	S3-1	294	914	3.11	305	610	59.7	40.8	0.59	0.12	15.2
	S3-2						32.1				19.3
	S3-3						32.1				18.1
S6	S6-1	147	457	3.11	305	610	59.7	40.8	0.59	0.12	28.6
	S6-2						32.1				36.8
	S6-3						32.1				26.3
S1B	S1B-1	880	2743	3.11	1829	914	29.5	40.7	1.18	0.24	220.7
	S1B-2						30.7	41.4			216.2

Figure 3. Photographs of failed specimens.

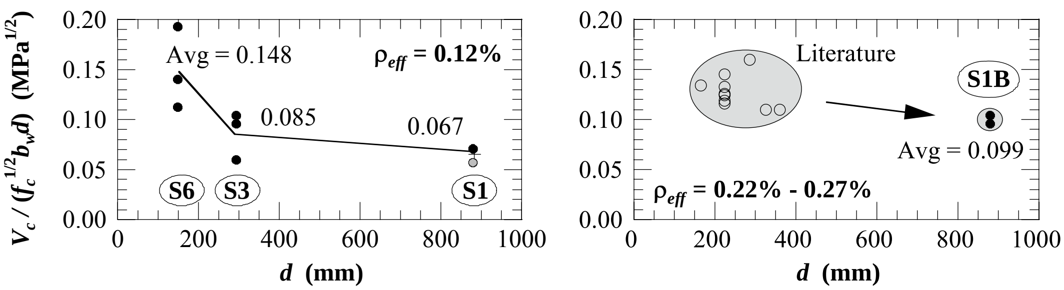

Figure 4. Influence of effective depth on shear strength: specimens with ρ_{eff} = 0.12% (a), and large specimens with ρ_{eff} = 0.24% with scaled specimens in the literature having ρ_{eff} in the range 0.22%-0.27% (b).

A comparison of the experimental strength values in Table 1 with those computed using the design provisions in Equations 1-7 is illustrated in Figure 5. The average ratio of experimental to theoretical strength, standard deviation, and coefficient of variation are also indicated. It is noted that: a) when applying the ISE (1999) and CNR (2006) algorithms, a ratio of cylinder to cube compressive strength of concrete of 0.80 was assumed; b) in the case of Series S3 and S6, the ISIS (2001) and CSA (2002) provisions for d < 300 mm were followed in lieu of Equations 4 and 5; c) in Equation 7 (CSA 2006), ε_x was computed at a distance d from the loading section; and d) in Equations 4, 5 and 7 (ISIS 2001, CSA 2002, 2006), a value of 0.83 was used for ϕ_c for comparison purposes (CSA 2004). In Equation 6 (CNR 2006), γ_c was assumed as 1.

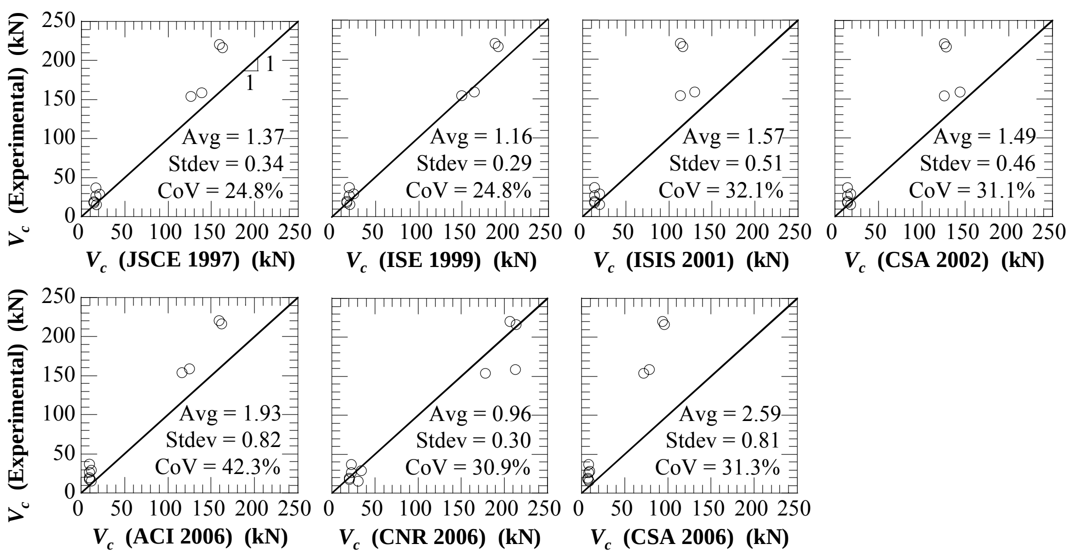

Figure 5. Comparison of experimental shear strength with estimates from design algorithms.

The ISE (1999) and CNR (2006) algorithms provide the most accurate estimates, where the former yields the more consistent and conservative results. The design provisions in the CSA (2006) specifications produce overconservative results irrespective of size, which is partially attributed to accounting for the reduced stiffness of the longitudinal FRP reinforcement in the computation of both the ε_x and the $(E_f / E_s)^{1/2}$ parameters, where the latter may be unnecessary.

5 CONCLUSIONS

This paper reports on the preliminary results of a pilot investigation aimed at studying the size effect on the concrete shear strength in FRP RC members. The following conclusions can be drawn: 1) the shear strength is strongly affected by size effect: an average reduction up to 55% was verified in large-size specimens compared to 1/6 scaled counterparts; 2) the strength decrease appears to be more pronounced in members with smaller reinforcement ratio; 3) the conservativeness of current design algorithms generally offsets the size effect; and 4) among the design algorithms that were compared, the ISE (1999) provisions best mediate between accuracy, consistency, and conservativeness, irrespective of size.

ACKNOWLEDGEMENTS

The financial support of the NSF Industry/University Cooperative Research Center "Repair of Buildings and Bridges with Composites", and the assistance of the Center's industry members Hughes Brothers, Inc. and Pultrall, Inc. in supplying the GFRP reinforcement are gratefully acknowledged. The tests were performed at the Missouri University of Science and Technology Structures Lab, and special thanks are due to the lab's electronic technicians for their assistance.

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