Towards improved shear design for reinforced concrete beams strengthened with externally bonded fibre reinforced polymers

Cortés-Puentes, W. L.; Almansour, H.; Palermo, D.

Publisher's version / Version de l'éditeur:

Annual Conference of the Canadian Society for Civil Engineering 2011: Ottawa, Ontario, Canada, 14-17 June 2011, 2, pp. 1531-1540, 2011-06-14

Towards improved shear design for reinforced concrete beams strengthened with externally bonded fibre reinforced polymers

NRCC-54455

Cortés-Puentes, W.L.; Almansour, H.; Palermo, D.

June 2011

A version of this document is published in / Une version de ce document se trouve dans:
2nd International Engineering Mechanics and Materials Specialty Conference, Ottawa, Ontario, June-14-17, 2011, pp. 1-10

Towards Improved Shear Design for Reinforced Concrete Beams Strengthened with Externally Bonded Fibre Reinforced Polymers

W. L. Cortés-Puentes[1], H. Almansour[2], and D. Palermo[1]
1 Faculty of Engineering, University of Ottawa, Ottawa, Ontario
2 National Research Council Institute for Research in Construction

Abstract: This paper proposes the use of the general method based on the modified compression field theory (MCFT) adopted by CSA-A23.3-04 to improve CSA-S806-02 estimation of the shear strength of reinforced concrete (RC) beams strengthened with fiber reinforced polymers (FRP). The estimations are compared with the results of four existing standards for shear design of reinforced concrete beams strengthened with FRP: CSA-S806-02, ISIS-M04-01, ACI-440.2R-08, and JSCE (2001). The accuracy of standards and the proposed approach are evaluated against an experimental database of 150 beams tested by various researchers. The results indicate that the proposed approach provides better estimats than existing approaches. Although the prediction of the shear capacity of the beams strengthened with FRP is generally acceptable, this paper highlights the importance of improving shear design to reduce scatter between different design standards and test results. The findings from this comparison represent a first step toward the development of a more rational shear design method for reinforced concrete beams shear strengthened with externally bonded FRP.

1 Introduction

Strengthening with externally bonded FRP has emerged as an alternative for enhancing the shear capacity of existing RC structures. FRP is recognized worldwide for overcoming shear-related deficiencies of reinforced concrete due to, deterioration, increase of service loads, insufficient transverse reinforcement and/or lack of seismic detailing. However, from the structural mechanics point of view, FRP shear strengthening of RC adds complexities to the shear resistance mechanism. Shear capacity of reinforced concrete strengthened with FRP is not a simple superposition of the contribution of concrete, steel and FRP as has commonly been assumed by different design standards. Furthermore, strain and stress distributions in concrete due to the application of the external FRP, specifically at the surface, may alter the cracking pattern and result in unexpected failure mode. Most standards simplify the analysis and design of FRP strengthened RC structures by assuming isotropic behaviour of the FRP. These assumptions result in practical expressions with simple and straightforward design procedures that, in general, do not adequately capture the behaviour of the strengthened structure. Design procedures should be based on methods that account for the interaction of concrete, reinforcing steel, and externally bonded FRP, and be capable of predicting more accurately the load transfer mechanism and damage. One approach is the general method prescribed in the CSA A23.3-04 (CSA 2004) for the calculation of the shear capacity of concrete reinforced with steel. This method, which is based on the modified compression field theory (MCFT), permits the prediction of the strength and cracking characteristics of reinforced concrete subjected to shear and axial stresses (Vecchio and Collins 1986).

The capability of the MCFT for predicting cracking characteristics of RC status may improve the estimation of the strain of externally bonded FRP and, hence, the contribution of FRP to shear strength. Therefore, the implementation of the MFCT into the existing Canadian Standard for designing RC strengthened with externally bonded FRP, S806-02 (CSA 2002), is an important step toward obtaining a more rational design procedure. This aims to address some deficiencies that have resulted from not considering modern theories for the prediction of shear response of RC. For example, better estimation of crack angle results in a more realistic prediction of the response compared to the typically used 45° crack angle derived from the classic truss analogy model. A further deficiency in current design standards is the estimation of the effective strain in FRP. Therefore, accurate prediction of the behaviour of the FRP along with a rational method for calculating the response of cracked concrete is crucial for obtaining a comprehensive design procedure for RC beams strengthened with externally bonded FRP.

2 Design Models for Shear

The truss analogy, developed approximately a century ago, represents the most popular and well-examined model for estimating the shear strength of reinforced concrete beams. However, other models like the MCFT and the shear friction method have been proved to be rational, reliable, and more accurate. Due to its simplicity, the truss model analogy has been used in most of the existing reinforced concrete design codes to evaluate shear strength of conventional RC beams and estimate shear strength of RC beams strengthened with externally bonded FRP.

Although the shear capacity of RC beams strengthened with FRP depends on many interrelated parameters and on full composite action of concrete, reinforcing steel, and FRP, most codes assume that satisfactory predictions can be predicted through the principle superposition. Thus, the total shear resistance is simplified to the sum of the contribution of concrete, transverse shear reinforcement, and externally bonded FRP as follows:

[1] $V_n=V_c+V_s+V_f$

The concrete shear resistance, V_c, is generally expressed in terms of the square root of concrete compressive strength. The design expression accounts for compressive stress of concrete between cracks, aggregate interlock, dowel action of longitudinal reinforcement, arch action, and residual tensile stresses across cracks. The contribution of transverse steel to the shear resistance, V_s, is estimated using the truss analogy with a crack angle of 45˚, and assuming that the transverse steel crossing the main shear crack yields. Similarly, the FRP contribution, V_f, is calculated using the truss analogy with crack angle of 45˚. All FRP crossing the main shear crack is assumed to experience the same strain. This requires an estimation of an effective average strain in the FRP to account for the variations of strains due to the location and bonding scheme of the FRP. There is not a unified method for the estimation of the effective strain of FRP; however, several researchers have proposed semi-empirical formulations for FRP bonded on concrete (Maeda et al. 1997, Chaallal et al. 1998, Khalifa et al. 1998, Triantafillou 1998, Carolin and Taljsten 2005, Chen and Teng 2003a,b).

Other models have been proposed for the prediction of the shear strength of RC beams strengthened with FRP. Aprile and Benedetti (2004) proposed a coupled flexural-shear design of RC beams strengthened with externally bonded FRP based on the variable angle truss model (Collins 1978). Deniaud and Cheng (2001) proposed a modified shear friction model, which is a combination of the shear friction method (Loov 1998) for the contribution of concrete and reinforcing steel, and the strip method for the contribution of the externally bonded FRP. It is worth noting that the MCFT (Vechio and Collins 1986), which successfully captures the shear strength of reinforced concrete elements, has not previously been extended to estimate the strength of RC elements strengthened with FRP.

3 Review of Existing Tests on RC Beams Strengthened with Externally Bonded FRP

A database of 150 RC beams strengthened with externally bonded FRP tested to shear failure was collected from the literature (Table 1). Fifty-seven (57) beams were strengthened with side bonding FRP (Figure 1a); 38 beams were strengthened with U-jacketing FRP (Figure 1b); and 55 beams were strengthened with FRP wrapping (Figure 1c). Beams with unidirectional FRP only were included in the database. Web width of the beams ranged from 63.5 mm to 1100 mm, and web height ranged from 102 mm to 700 mm. The selected beams had shear span, *a/d*, not less than 2.0, to avoid shear distortion effects (deep beam action) not accounted for in the equations given by the design standards. Concrete ranged from low-normal strength concrete with f'_c of 20.5 MPa to high strength concrete with $f'c$ of 71.4 MPa. Stiffness of FRP, $\rho_f E_f$, ranged from 21 MPa to 2000 MPa.

Table 1: Summary of database of RC beams strengthened with FRP.

Reference	No of Beams	Scheme*	Material**	b_w x h (mmxmm)	a/d	Avg $f'c$ (MPa)	$\rho_f E_f$ (MPa)
Berset (1992)	2	S	GFRP	114 x 102	3.53	42.9	133/327.2
Uji (1992)	1	W	CFRP	100 x 200	5.71	26	446.2
	3	S	CFRP	100 x 200	5.71	26	445.6/897
Al-Sulaimani et al. (1994)	4	S	GFRP	150 x 150	3.54	37.7	256/640
Ohuchi et al. (1994)	2	W	CFRP	400 x 400	2.50	28	66.7/133.4
Sato et al. (1996)	2	S	CFRP	200 x 300	2.69	40.9	127.7/255.3
	2	U	CFRP	200 x 300	2.69	40.9	127.7/255.3
Miyauchi et al. (1997)	2	W	CFRP	125 x 200	3.03	35.5	80.96/202.4
	1	W	CFRP	125 x 200	2.00	35.5	202.4
Funakawa et al. (1997)	3	W	CFRP	600 x 600	2.50	27	133.6/267.2/400.8
Kamiharako (1997)	2	W	CFRP	250 x 500	2.50	32.6	85.9/48.7
Sato et al. (1997)	2	U	CFRP	150 x 300 (T-Section)	2.59	35.5	340.4
Taerwe et al. (1997)	3	U	CFRP	200 x 450	2.98	35.6	77/38.5
	1	W	CFRP	200 x 450	2.98	35.6	154
Umezu et al. (1997)	12	W	AFRP	150 x 300	3.00	38.8	42.8/21.4/85.65
				300 x 300			42.8/21.4/70.
				600 x 300			35
				450 x 450			46.72
				550 x 550			38.2/46.5
	3	W	CFRP	300 x 300	2.96	41.9	180.6/90.3
				150 x 300			114.6
Triantafillou (1998)	9	S	CFRP	70 x 110	3.20	30	492.3/348.2/738.6 522.2/987/697.9
Chaallal et al. (1998)	2	S	CFRP	150 x 250	2.73	35	2000/1414.2
Khalifa et Al. (1999)	2	U	CFRP	150 x 305	3.47	20.5	200.64/501.6
Khalifa et Al. (2000)	3	U	CFRP	150 x 405	2.85	35	501.6/200.6
	1	S	CFRP	(T-Section)	2.85	35	200.64
Taljsten et al. (2000)	5	W	CFRP	180 x 500	2.61	52.8	618.5/474.2/770 445/890
	2	W	CFRP	180 x 500	2.17	52.8	618.5/890
	1	W	CFRP	180 x 500	3.48	52.8	222
Deniaud et al. (2001)	4	U	GFRP	140 x 400	2.86	29	455.1/158
	3	U	GFRP	140 x 600	2.74	44	158.4/224/455.1
Khalifa et. Al. (2002)	4	U	CFRP	150 x 305	2.92	27.5	200.6/301/501.6
Pellegrino and Modena (2002)	9	S	CFRP	150 x 300	3.00	30.1	513.9/1541.8/1027.8
Beber (2003)	13	S	CFRP	150 x 300	2.90	32.8	170.2/120.4/340.4/

							240.7/1913.3/1352.9
	5	U	CFRP	150 x 300	2.90	32.8	170.2/340.4
	3	W	CFRP	150 x 300	2.90	32.8	170.2
Diagana et al. (2003)	4	U	CFRP	130 x 450	2.22	38	138.9/111.1/65.5/56.1
	4	W	CFRP	130 x 450	2.22	38	138.9/111.1/65.5/56.1
Taljsten (2003)	5	S	CFRP	180 x 500	2.69	67.3	128.7/202.2/286/303.3
Adhikary et al. (2004)	2	U	CFRP	300 x 300	4.29	38.4	256.1/438.5
Ianniruberto and Limbimbo (2004)	4	W	GFRP	150 x 350	3.00	32.8	121.4
Carolin and Taljsten	6	S	CFRP	180 x 500	2.69	62.2	128.7/202.2/286/312.5
(2005)	2	W	CFRP	180 x 500	2.69	49	202.2/286
	2	S	CFRP	180 x 400	2.74	46	286/442
Miyajima et al. (2005)	4	W	CFRP	340 x 440	2.93	29.9	55.1/82.6/96.4/110.1
Guadagnini et al. (2006)	1	W	GFRP	150 x 250	3.35	54.3	24.4
	1	W	GFRP	150 x 250	2.23	53.7	22.3
	1	W	GFRP	150 x 250	1.12	52.7	44.6
Dias and Barros (2008)	2	U	CFRP	150 x 300	2.14	49.2	228.5/457.1
	2	U	CFRP	150 x 300	2.31	56.2	542.8/1085.5

* S = Side bonding; U = U-Jacketing; W = Wrapping
** AFRP = Aramid FRP; CFRP = Carbon FRP; GFRP = Glass FRP

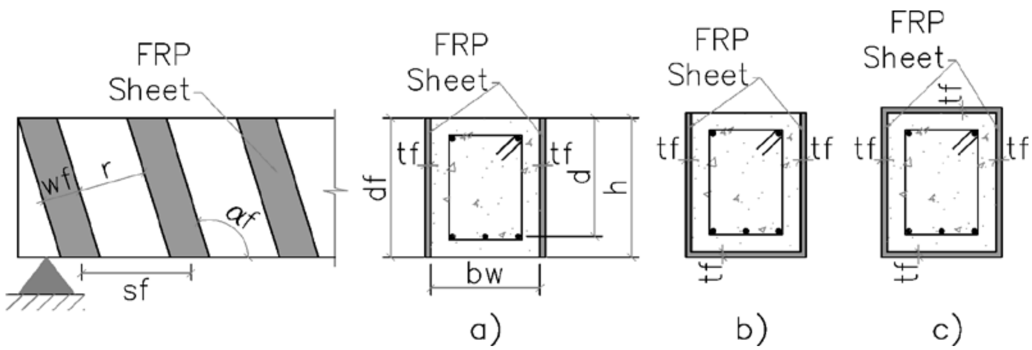

Figure 1: FRP Strengthening Schemes Applied to RC Beams; a) Side Bonding; b) U-Jacketing; c) Wrapping.

4 Prediction of Shear Strength with Existing Design Standards

Four major design standards presented herein, ACI 440.2R-08 (ACI 2008), Canadian CSA S806-02 (CSA 2002), Canadian ISIS M04-01 (ISIS 2001), and Japanese JSCE (JSCE 2001) estimate shear strength of beams with externally bonded FRP by superposing the contribution of concrete, steel, and FRP (Equation 1 and Table 2). All the standards prescribe equations to calculate the contribution of the externally bonded FRP based on the truss model analogy, where the effective strain of FRP is the most important parameter (Table 2). In general, simplified formulations have been adopted from the solution of the governing differential equation for debonding of FRP and have been adjusted to match existing experimental data. For wrapped RC beams, all the standards presented herein assumed rupture as the governing failure mode of FRP. Detailed formulations for determining effective strain of FRP, as well as the contribution of concrete and steel to shear strength, can be found in the standards (ACI 2008, CSA 2002, ISIS 2001, JSCE 2001).

Table 2: Standards for Design of RC Beams Strengthened with FRP.

Standard	Concrete Contribution V_c	Steel Contribution V_s	FRP Contribution V_f
ACI 440.2R-08	$V_c = 0.166\sqrt{f'_c}b_w d$	$V_s = \frac{A_v(\sin\alpha_s + \cos\alpha_s)f_y d}{s}$	$V_f = \psi_f \frac{A_f E_f \varepsilon_{fe} d_f (\sin\alpha_f + \cos\alpha_f)}{s_f}$
CSA S806-02	$V_c = 0.20\lambda\sqrt{f'_c}b_w d$	$V_s = \frac{A_v(\sin\alpha_s + \cos\alpha_s)f_y d}{s}$	$V_f = \frac{A_f E_f \varepsilon_f d_f (\sin\alpha_f + \cos\alpha_f)}{s_f}$
ISIS M04-01	$V_c = 0.20\lambda\sqrt{f'_c}b_w d$	$V_s = \frac{A_v(\sin\alpha_s + \cos\alpha_s)f_y d}{s}$	$V_{frp} = \frac{A_f E_f \varepsilon_f d_f (\sin\alpha_f + \cos\alpha_f)}{s_f}$ $\varepsilon_f = R\ \varepsilon_{fu} \le 0.004$
JSCE (2001)	$V_c = \beta_d \beta_p \beta_n f_{vcd} b_w d / \gamma_b$ $f_{vcd} = 0.20\sqrt[3]{f'_c}$	$V_s = \frac{\left[A_v f_y (\sin\beta + \cos\beta)/s\right]z}{\gamma_b}$	$V_f = K\frac{\left[A_f f_{fud}(\sin\alpha_f + \cos\alpha_f)/s_f\right]z}{\gamma_b}$ $K = 1.68 - 0.67R, \quad 0.4 \le K \le 0.8$

ACI-440.2R-08 provides two sets of equations for calculating the effective strain in FRP: one for FRP wrapping and another for U-jacketing and side bonding. These equations do not explicitly predict the failure mode of FRP. However, equations for wrapping are intended to avoid failure of the FRP in the form of rupture by calculating the effective strain of the FRP to 75% of the ultimate strain and limiting the strain to 0.004. On the other hand, equations for U-jacketing and side bonding are specified to reflect the effective strain due to bonding of FRP to concrete as proposed by Maeda et al. (1997). This model was originally developed for CFRP and not for all FRP types. In addition to the calculation of the effective strain, the ACI-440.2R-08 reduces the shear strength with the factor ψ_f, which is 0.95 for wrapping and 0.85 for u-jacketing and side bonding. The ISIS-M04-01 provisions consist of two sets of equations similar to those given in ACI-440.2R-08 to estimate the effective strain of FRP governed by either rupture or debonding. Similar to the ACI standard, the ISIS manual limits the effective strain to 0.004. Furthermore, ISIS-M04-01 introduced a factor to take into account the difference in the effective strain of GFRP and AFRP from that of CFRP. Neither ACI 440-08 nor ISIS M04-02 defines any lower bound applicability for the beam size or the FRP sheet/laminate length where unrealistic negative strain values may be estimated. Both ACI-440.2R-08 and ISIS-M04-01 present equations for calculating the effective strain of FRP proportional to the stiffness of FRP, $\rho_f E_f$, and strength of concrete f'_c.

CSA-A23.3-04 provides fixed values of effective strains for all the strengthening techniques: 0.004 for wrapping and U-jacketing, and 0.002 for side bonding.. The assumption of the same effective strain for U-jacketing and wrapping is unrealistic because the free end of the FRP in the U-jacketing scheme can be subjected to debonding stresses that are not present in the wrapping scheme. It is clear that the expressions for calculating the effective strains in FRP given by CSA-A23.3-04 need further development to adequately capture the failure mechanism and to improve the prediction of the ultimate shear strength of strengthened RC beams.

Ultimate stress of the FRP in the JSCE recommendations is reduced with a factor *K* to reflect the effective strain distribution of the FRP. This factor, which ranges from 0.4 to 0.8, is based on experimental correlation of RC beams wrapped with carbon and aramid FRPs; therefore, the formulation presented in the JSCE is only applicable to wrapping. The JSCE does not predict the failure mode, i.e. FRP rupture or FRP debonding; however, rupture is the most likely failure mode of beams wrapped with FRP. Similar to the other standards, the equation for calculating effective strain is proportional to the stiffness of FRP, $\rho_f E_f$, and strength of concrete, f'_c.

5 Prediction of Shear Strength with Proposed Design Procedure

The proposed approach superposes the contribution of concrete and steel from the general method specified in CSA A23.3-04 and the contribution of FRP from CSA S806-02 (Table 2) using Equation 1.

Contribution of steel and FRP requires the crack angle determined from CSA A23.3-04. The equations for the concrete contribution, V_c, are as follows:

[2] $$V_c = \beta\sqrt{f'c}\,b_w d_v$$

[3] $$\beta = \frac{0.4}{1+1500\varepsilon_x}\left(\frac{1300}{1000+S_{ze}}\right)$$

Where ε_x is the horizontal strain at mid-height of the beam, and is calculated from the following:

[4] $$\varepsilon_x = \frac{M_n/dv + V_n}{2A_s E_s}$$

In Equation 4, M_n and V_n are the design moment and shear at the critical section; dv is the effective shear depth taken not less than $0.9d$; and A_s and E_s are the area and modulus of elasticity of the flexural reinforcement. Equation 4 does not include the effect of axial load and prestressing, reflecting the loading conditions of the beams in the database of Table 1.S_{ze}, the effective crack spacing is taken as 300 mm for beams with at least minimum shear reinforcement; otherwise, it is calculated using Equation 5.

[5] $$S_{ze} = S_z\left(\frac{35}{15+A_g}\right) \geq 0.85S_z$$

Where S_z is the crack spacing taken as the least of dv and the maximum distance between layers of distributed longitudinal reinforcement and A_g is the maximum aggregate size. The crack angle including the effect of crack spacing (Bentz and Collins 2006) and the steel contribution are estimated as follows.

[6] $$\theta = (29+7000\varepsilon_x)\left(0.88+\frac{s_{ze}}{2500}\right)$$

[7] $$V_s = \frac{A_v \sin\alpha_s(\cot\theta+\cot\alpha_s)f_y d_v}{s}$$

Where A_v, α_s, f_y, and s, are the area, angle with respect to the horizontal, yield stress, and spacing of transverse steel reinforcement, respectively.

6 Comparison of Calculated and Measured Shear Strength Predictions

Calculated and measured shear strengths of collected database of beams are divided into three groups according to the FRP shear strengthening scheme. The calculated shear strength values are plotted against the experimentally measured strengths. The efficiency of different estimation methods are then examined and compared to the ideal estimations, which are the conditions when the estimated values are equal to the experimentally measured values, or the 45° inclined lines in Figure 2. Linear regression of the results for each standard is provided. Table 3 provides statistics of the calculated to measured strength ratio, $V_{n,th}/V_{n,ex}$.

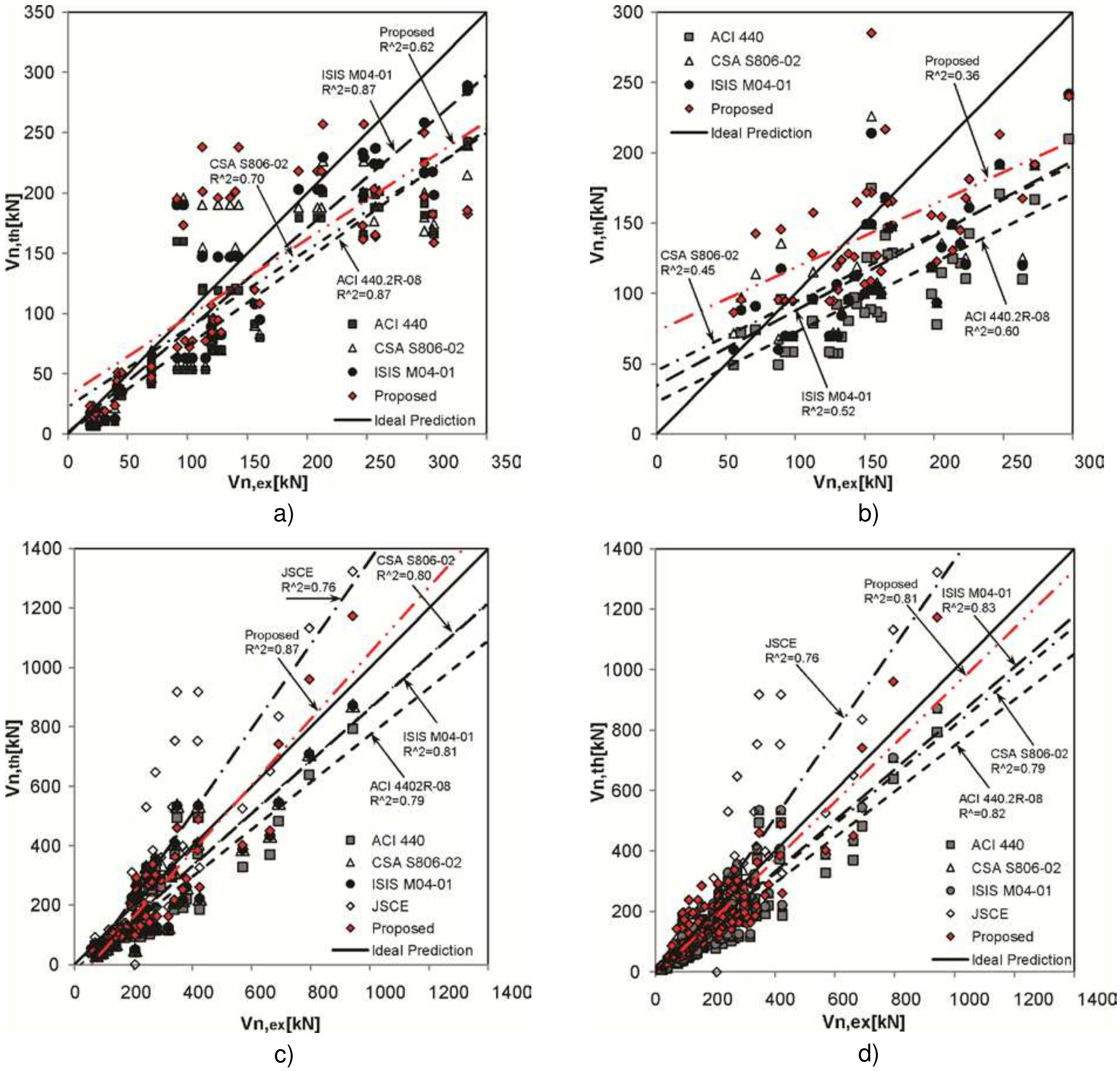

Figure 2: Correlation of Measured and Calculated Shear Strength of RC Beams Strengthened with FRP; a) Side Bonding; b) U-Jacketing; c) Wrapping; c) All Strengthening Schemes.

Table 3: Statistics for Calculated to Measured Strength Ratio ($V_{n,th}/V_{n,ex}$)

	SIDE BONDING		U-JACKETING		WRAPPING		ALL TECHNIQUES	
	Average	**COV (%)**	**Average**	**COV (%)**	**Average**	**COV (%)**	**Average**	**COV (%)**
ACI 440	0.673	43.405	0.667	29.248	0.673	39.620	0.671	38.629
CSA S806-02	0.867	41.968	0.828	35.969	0.770	38.749	0.821	39.594
ISIS M04-01	0.807	44.260	0.790	30.909	0.759	37.380	0.779	38.331
JSCE	N/A	N/A	N/A	N/A	1.093	45.063	1.093	45.063
Proposed	0.943	40.764	0.991	34.930	0.806	30.459	0.905	37.183

The proposed approach provided predictions comparable to CSA S806-02 and ACI 440-2R-08 design standards for side bonding of FRP; however, the trendline displayed lower slope than that of the ISIS

M04-01 (Figure 2a). The statistics in Table 3 show that the proposed approach provides, on average, better estimations of the shear strength than the other standards. It is worth noting that ACI 440-08 and ISIS M04-02 predicted unrealistic effective strains and effective stresses of thirteen small beams from the database where equations calculated negative values for the effective strain. Therefore, for these beams, the FRP contribution to the shear strength was assumed equal to zero. However, the experimental results indicate significant contributions of FRP sheets to the shear strength even for the case of small beams. Conversely, the use of constant strains values for side bonding as given in CSA S806-02 results in underestimation of the strength capacity of the strengthened RC beams, specifically for large beams. The calculated trendline deviates from the ideal predictions as the shear strength and size of beams increase (Figure 2a). Hence, it is aparent that a new FRP strain distribution model that reflects the experimentaly measured values leading to improve shear strength estimation is required.

The trendline of the proposed approach has a slope similar to that of CSA S806-02 and ACI-440-2R-08 (Figure 2b) for U-jacketing of FRP, but is shifted upwards and provides higher shear strength than CSA S806-02 and ACI-440-2R-08 standards. The R-square factor for the proposed approach is low as a result of the lack of a rational method for the estimation of the contribution of strength of FRP in the existing CSA-S806-02. Effective strains in FRP are prescribed values in the CSA-S806-02. Table 3 illustrates that the proposed approach provides better estimations; it predicts average calculated to measured strength ratios close to 1.0 with COV of approximately 35%.

The proposed design approach, which combines the CSA-A23.3-04 and the CSA S806-02 standards, improved the correlation of measured and calculated shear strength for wrapping with FRP and for all techniques combined (Figure 2c and Figure 2d). The trendlines satisfactorily match the trendline corresponding to ideal predictions. Furthermore, the proposed method provides high R-square correlation factors. In addition, the statistics in Table 3 demonstrate enhanced average and COV compared to the existing design standards. The proposed approach estimates an average calculated to measured strength ratio similar to that of JSCE (2001); however, the latter displays a trend that is not conservative, as shown in Figure 2c and Figure 2d.

7 Conclusions

The results indicate that, in general, the proposed design method, which superposes the contribution of concrete and steel from the general method of CSA A23.3-04 and the contribution of FRP from CSA S806-02, provides better correlation with existing data than four existing design standards, ACI-440.2R-08, CSA S806-02, ISIS M04-01 and JSCE (2001). The improvements in calculating the shear strength was significant for FRP wrapping. However, shortcomings in the calculation of effective strain of FRP with the existing CSA S806-02 limited the effectiveness of the proposed approach for estimating the shear strength of RC strengthened with side bonding and U-jacketing FRP. CSA S806-02 provides fixed values of effective strain that do not reflect the response of FRP bonded to reinforced concrete. ACI-440.2R-08 and ISIS M04-01 provide semi empirical equations to estimate the effective strain of FRP; however, for small beams, these equations may result in unrealistic negative contribution of the FRP. JSCE (2001) also provides semi empirical equations for calculating the contribution of FRP and is restricted to wrapping of FRP. The statistics for JSCE (2001) are satisfactory in comparing the average of calculated to measured shear strength; however, the regression of calculated strength against measured strength displays an unsafe trend.

The general method for shear design based on the MCFT (CSA A23.3-04) proves to be more effective than current methods for the prediction of shear capacity of strengthened RC beams where the failure mode is not governed by debonding of FRP. Note that the current design standards were neither effective at capturing the shear capacity for beams that experienced debonding. This method provides a rational procedure to predict the behaviour of RC that benefits the calculation of the contribution of the strengthening FRP and steel reinforcement. Specifically for RC beams strengthened with FRP, the general method provides estimation of the concrete crack angle, which is essential in the calculation of the contribution of the FRP. Given these benefits, the MCFT could be extended to account for the effect of externally bonded FRP in the response of cracked RC. In addition, the resulting method should include an improved formulation for the estimation of the effective strain of the FRP.

8 References

ACI Committee 440. 2008. Guide for the Design and Construction of Concrete Externally Bonded FRP Systems for Strengthening Concrete Structures. ACI 440.2R-08, *American Concrete Institute*, Farmington Hills, MI, USA: 76 p.

Adhikary, B.B., Mutsuyoshi, H., and Ashraf, M. _2004_. Shear Strengthening of Reinforced Concrete Beams Using Fiber-Reinforced Polymer Sheets with Bonded Anchorage. *ACI Struct. J.*, 101(5), 660–668.

Al-Sulaimani G.J., Sharif A., Basunbul I.A., Baluch M.H., Ghaleb B.N. 1994. Shear Repair for Reinforced Concrete by Fiberglas Plate Bonding. *ACI Struct J.*, 91(3): 458–64.

Aprile, A., Benedetti, A. 2004. Coupled Flexural-Shear Design of R/C Beams Strengthened with FRP, *Composite Part b: Engineering*, 35(1): 1-25.

Beber, A.J. 2003. Comportamento Estrutural de Vigas de Concreto Armado Reforçadas com Compósitos de Fibra de Carbono. Doctoral Thesis, *Universidad Federal do Rio Grande do Sul, Porto Alegre, Brazil*: 289 p. (In Portuguese).

Bentz, E.C., and Collins, M.P. 2006. Development of the 2004 Canadian Standards Association (CSA) A23.3 shear provisions for reinforced concrete. *Can. J. Civ. Eng.*, 33, 521–534.

Berset, J.D. 1992. Strengthening of Reinforced Concrete Beams for Shear using FRP Composites, *Master Thesis, Massachusetts Institute of Technology, Cambridge, MA, USA*: 105 p.

Canadian Standards Association (CSA). 2002. Design and Construction of Building Components with Fibre- Reinforced Polymers. CAN/CSA S806-02, *Canadian Standards Association,* Mississauga, Ontario, Canada: 177 p.

Canadian Standards Association (CSA). 2004. Design of Concrete Structures. CAN/CSA A23.3-04, Canadian Standards Association, Rexdale, Ontario, Canada: 214 p.

Carolin, A. and Täljsten, B. 2005. Theoretical Study of Strengthening for Increased Shear Bearing Capacity. *J. Compos. Constr.*, 9(6), 497–506.

Chaallal, O., Nollet, M.J., and Perraton, D. 1998. Strengthening of Reinforced Concrete Beams with Externally Bonded Fibre-Reinforced Plastic Plates: Design Guidelines for Shear and Flexure. *Can. J. Civ. Eng.*, 25, 692–708.

Chen, J.F., Teng, J.G. 2003a. Shear capacity of FRP strengthened RC beams: FRP rupture. *J. of Struct. Eng.*, ASCE, 129(5): 615-625.

Chen, J.F., Teng, J.G. 2003b. Shear Capacity of FRP Strengthened RC Beams: FRP debonding. *Construction and Building Materials*, 17(1): 27-41.

Collins, M.P. 1978. Towards a Rational Theory for R/C Members in Shear. *ASCE Proc. Struct. Div.*:104(4):649–66.

Deniaud, C., Cheng, J.R. 2001. Review of Design Methods for Reinforced Concrete Beams Strengthened with Fibre Reinforced Polymer Sheets. *Can. J. Civ. Eng.*, 28: 271-281.

Diagana, C., Li, A., Gedalia, B., and Delmas, Y. 2003. Shear Strengthening Effectiveness with CFF Strips. *Eng. Struct., 25*(4): 507-516.

Dias, S.J.E., and Barros, J.A.O. 2008. Shear Strengthening of T Cross Section Reinforced Concrete Beams by Near-Surface Mounted Technique. *J. Compos. Constr.,* 12(3): 300-311.

Funakawa, I., Shimono, K., Watanabe, T., Asada, S., and Ushijima, S. 1997. Experimental Study on Shear Strengthening with Continuous Fiber Reinforcement Sheet and Methyl Methacrylate Resin. *Proc., 3rd international symposium on non-metallic (FRP) reinforcement for concrete structures,* Tokyo, Japan, v.1: 491-498.

Guadagnini, M.; Pilakoutas, K., and Waldron P. 2006. Shear Resistance of FRP RC Beams: Experimental Study. *J. Compos. Constr.*, ASCE, 10(6): 464-473.

Ianniruberto, U., and Imbimbo, M. 2004. Role of Fiber Reinforced Plastic Sheets in Shear Response of Reinforced Concrete Beams: Experimental and Analytical Results. *J. Compos. Constr.,* 8(5): 415-424.

ISIS Canada (ISIS). 2001. Strengthening Reinforcing Concrete Structures with Externally-Bonded Fiber Reinforced Polymers. *Intelligent Sensing for Innovative Structures Canada*, Winnipeg, MB, Canada.

Japan Society of Civil Engineering (JSCE). 2001. Recommendations for Upgrading of Concrete Structures with Use of Continuous Fiber Sheets, *Japan Society of Civil Engineering*, Tokyo, Japan: 88p.

Kamiharako, A., Maruyama, K., Takada, K., and Shimomura, T. 1997. Evaluation of Shear Contribution of FRP Sheets Attached to Concrete Beams. *Proc., 3th International Symposium on Non-Metallic (FRP) reinforcement for concrete structures*, Tokyo, Japan, v.1: 467-474.

Khalifa, A., Gold W., Nanni, A., and Aziz, M.I. 1998. Contribution of Externally Bonded FRP to Shear Capacity of Flexural Members. *J. Compos. Constr*., ASCE, 2(4): 195-203.

Khalifa A., Tumialan G., Nanni A., Belarbi A. 1999. Shear Strengthening of Continuous RC Beams Using Externally Bonded CFRP sheets. *Proc., 4th International Symposium on Fiber Reinforced Polymer for Reinforced Concrete Structures (FRPRCS-4)*: 995–1008.

Khalifa, A., and Nanni, A. 2000. Improving Shear Capacity of Existing RC T-Section Beams Using CFRP Composites, *Cem. Concr. Compos*., 22: 165-174.

Khalifa, A., and Nanni, A. 2002. Rehabilitation of Rectangular Simply Supported RC Beams with Shear Deficiencies Using CFRP Composites. *Constr. Build. Mater*., 16(3): 135-146.

Loov, R.E. (1998). Review of A23.3–94 Simplified Method of Shear Design and Comparison with Results Using Shear Friction. *Can. J. Civ. Eng*., 25, 437–450.

Maeda, T., Asano, Y., Sato, Y., Ueda, T., and Kakuta, Y. 1997. A study on bond mechanism of carbon fiber sheet. *Proc., 3th International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures,* Tokyo, Japan, v.1: 279-286.

Miyajima, H., Kosa, K., Tasaki, K., and Matsumoto, S. 2005. Shear Strengthening of RC Beams Using Carbon Fiber Sheets and Its Resistance Mechanism. *Proc. Fifth Workshop on Safety and Stability of Infrastructures against Environmental Impacts, Japan Philippines Exchange Program, Tokyo Institute of Technology – University of the Philippines.*

Miyauchi, K., Inoue, S., Nishibayashi, S., and Tanaka Y. 1997. Shear Behavior of Reinforced Concrete Beam Strengthened with CFRP Sheets. *Trans. Jpn. Concr. Inst*., 19: 97-104.

Ohuchi, H. Ohno, S., Katsumata, H., Kobatake, Y., Meta, T., Yamagata, K., Inokuma, Y., and Ogata N. 1994. Seismic Strengthening Design Technique for Existing Bridge Columns with CFRP. *Seismic Design and Retrofit of Bridges*. Edited by R. Park: 495-514.

Pellegrino, C., and C. Modena, C. 2002. Fiber Reinforced Polymer Shear Strengthening of Reinforced Concrete Beams with Transverse Steel Reinforcement. *J. Compos. Constr.,* ASCE, 6(2), 104-111.

Sato, Y., Ueda, T., Kakuta, Y., and Tanaka, T. 1996. Shear Reinforcement Effect of Carbon Fiber Sheet Attached to Side of Reinforced Concrete Beam. *Advanced Composite Materials in Bridges and Structures*, Edited by M. M. El-Badry, CSCE, Montreal, Quebec, Canada: 621-637.

Sato, Y., Ueda, T., Kakuta, Y., and Ono S. 1997. Ultimate Shear Capacity of Reinforced Concrete Beams with Carbon Fiber Sheet. *Proc., 3th International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures*, Tokyo, Japan, v.1: 499-506.

Taerwe, L., Khalil, H., and Matthys, S. 1997. Behavior of RC Beams Strengthened in Shear by External CFRP Sheets. *Proc., 3th International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures*, Tokyo, Japan, v.1: 507-514.

Täljsten, B. and Elfgren L. 2000. Strengthening Concrete Beams for Shear Using CFRP-Materials: Evaluation of Different Application Methods. *Composites Part B: Engineering*: 87–96

Täljsten, B. 2003. Strengthening Concrete Beams for Shear with CFRP Sheets, *Constr. Build. Mater.* 17: 15-26.

Triantafillou, T.C. 1998. Shear Strengthening of Reinforced Concrete Beams Using Epoxy-Bonded FRP Composites, *ACI Struct J*., 95(2): 107-115.

Umezu, K., Fujita, M., Nakai, H., and Tamaki, K. 1997. Shear Behavior of RC Beams with Aramid Fiber Sheet. *Proc., 3th International Symposium on Non-Metallic (FRP) reinforcement for concrete structures*, Tokyo, Japan, v.1: 491-498.

Uji, K. 1992. Improving Shear Capacity of Existing Reinforced Concrete Members by Applying Carbon Fiber Sheets. *Trans. Jpn. Concr. Inst*., 14: 253-266.

Vecchio, F.J. and Collins, M.P. 1986. The Modified Compression Field Theory for Reinforced Concrete Elements Subject to Shear. *ACI Journal*, 83(2): 219-231.