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Shear Strength Evaluation of Concrete Beams Reinforced with BFRP Bars and Steel fibers without Stirrups

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Abstract: This paper presents experimental and analytical investigations on concrete beams reinforced with basalt fiber reinforced polymer (BFRP) and steel fibers without stirrups. Independent behaviour of BFRP reinforced beams and steel fiber reinforced beams were evaluated and the effect of combining BFRP bars and steel fiber was investigated in detail. It is found that combining steel fibers with BFRP could change the shear failure of BFRP reinforced beam to flexural failure. Further, the existing analytical models were reviewed and compared to predict the shear strength of both FRP reinforced and steel fiber reinforced beams. Based on the review, the appropriate model was chosen and modified to predict the shear strength of BFRP reinforced beam along with steel fibers.

Keywords: Basalt fiber reinforced polymer (BFRP); Steel fibers; Flexure, Shear strength.

1 Introduction

Fiber Reinforced Polymer (FRP) is gaining popularity as an alternate reinforcement in concrete structures mainly due to non corrosive nature. However, the main practical difficulty that is faced during such construction is the stirrups. It is seen that most of the FRP reinforced beams make use of steel stirrups and minimum cover thickness is provided, which nullifies the possibility of overall cross section reduction. The applied shear stresses in a cracked reinforced concrete member without transverse reinforcement are resisted by various shear mechanisms. The ACI Committee- 445 (1998) report identified that shear transfer mechanisms mainly depend on the concrete strength (f_c') and the depth of uncracked zone which is a function of the longitudinal reinforcement properties. Also, arch action occurs in deep beams or members in which shear to depth ratio (a/d) is less than 2.5. This

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does not transmit a tangential force to a nearby parallel plane, but it permits the transfer of a vertical concentrated force to a reaction, thereby reducing the contribution of the other types of shear transfer [El-Sayed, Ehab, and Brahim (2006); Fico, Andrea, and Gaetano (2008)]. Due to the relatively low modulus of elasticity of FRP, concrete members reinforced with FRP bars will develop wider and deeper cracks than members reinforced with steel.

Deeper cracks reduce the contribution to shear strength from the uncracked concrete due to the lower depth of concrete in compression. Additionally, due to the relatively small transverse strength of FRP bars and relatively wider cracks, the contribution of dowel action can be very small compared to that of steel. Finally, the overall shear capacity of concrete members reinforced with FRP bars as flexural reinforcement is lower than that of concrete members reinforced with steel bars [Yost, Shawn, and David (2001)]. Previous studies [Yost, Shawn, and David (2001); Razaqpur et al. (2004)] concluded that current shear design guidelines are very conservative in calculating the shear capacity of FRP-reinforced concrete beams. Consequently, the excessive amount of FRP needed to resist shear could be both costly and likely to create reinforcement congestion problems [Razaqpur et al. (2004); Ricardo (2004)]. Six main parameters were considered to affect the shear strength of FRP-reinforced concrete members such as, the concrete compressive strength (f_c'), beam width (b_w), effective depth (d), shear span-to-depth ratio (a/d), reinforcement ratio (ρ_f) and modular ratio which is defined as the modulus of elasticity of FRP to steel reinforcement (E_f/E_s).

One of the possible solution to avoid shear failure of FRP reinforced beam is to add fibers. It is seen that the addition of steel fibers could replace the conventional steel stirrups and prevented shear failure in concrete beams [Batson, Jenkins, and Spatney (1972)].

This paper reports the experimental study carried out to determine the behaviour of BFRP reinforced beams, steel fiber reinforced beams and beams reinforced with both BFRP and steel fibers. The existing shear strength prediction models are reviewed and assessed to find the suitability for BFRP reinforced beam. In addition, the shear strength prediction models for fiber reinforced concrete were also evaluated. To check the adequacy of existing shear strength prediction models for BFRP reinforced beams, a comparative study has been carried out. Further, to determine the shear strength of steel fiber reinforced beams, few models available in literature are reviewed. In addition, a model has been developed to predict the shear strength of concrete beams reinforced with BFRP bars and steel fibers.

2 Experimental investigations

Present study investigates the behaviour of concrete beams reinforced with BFRP, steel fibers and also combination of steel fibers and BFRP. The main aim for incorporating steel fibers into BFRP reinforced beams is to explore the possibility of converting the failure mode from shear to flexure.

2.1 Materials used

Concrete used for casting RC beam is with mix ratio of 1 : 2.09 : 2.56 and water to cement ratio of 0.44. Steel fibers (1% by volume) of 0.18 mm diameter and length of 13 mm were used to develop steel fiber reinforced concrete (SFRC) mix. The details of mixes along with compressive strength and split tensile strength are given in Table 1. It is observed that there is 16.67% increase in cube compressive strength and 17.83% increase of split tensile strength by adding 1.0% of steel fiber to the control mix.

Table 1: Details of the mixes.

Material	Control mix	SFRC mix
Cement (kg/m^3)	394.09	394.09
Fine Aggregate (kg/m^3)	823.65	823.65
Coarse Aggregate (kg/m^3)	1008.87	1008.87
Water (kg/m^3)	173.40	173.40
Super Plasticizer (ml)	–	250
Steel Fiber (kg/m^3)	–	24
Compressive strength (MPa) mean $\pm$ COV	36.83 $\pm$ 3%	42.98 $\pm$ 5%
Split tensile strength (MPa) mean $\pm$ COV	3.45 $\pm$ 3.5%	4.065 $\pm$ 4%

2.2 Specimen details

In the present study, three types of beams namely, BFRP reinforced beams, steel fiber reinforced beams (SFRC beam) and steel fiber-BFRP reinforced beams were investigated under flexure. Beams of length 1500 mm with cross section 100 mm (width) $\times$ 200 mm (depth) were cast. The geometric configuration of the beams are shown in Figure 1. The BFRP bars used to cast beams were of 10 mm diameter with ultimate tensile strength of 680 MPa, ultimate strain of 3.75% and Young's Modulus of 50 GPa.

2.3 Test set-up

The beams were tested over a span of 1200 mm. Two ends of the test beams were supported at 150 mm distance from the beam ends. Each specimen had a pure bending region of 400 mm at midspan achieved by a two-point loading as shown in Figure 2. A displacement controlled loading was applied at a rate of 0.75 mm/min through a 500 kN actuator. During testing, the midspan deflection was measured using an LVDT. The load and displacements data were collected using data logger.

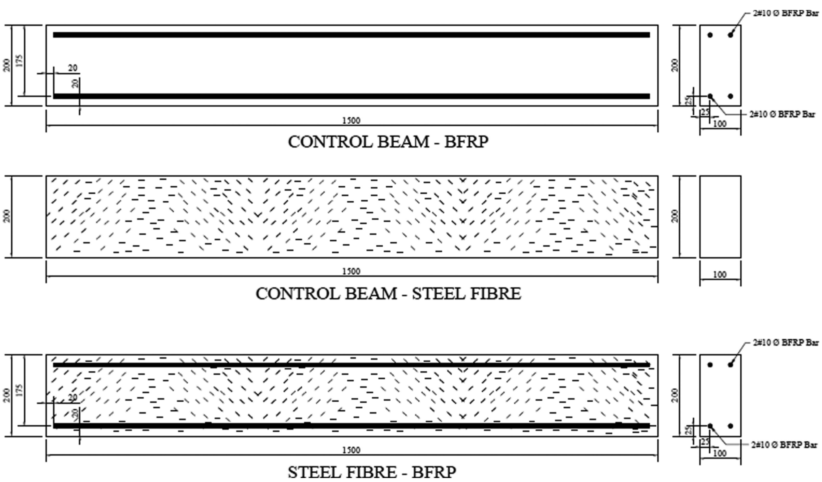


Figure 1: Description of Test Beam.

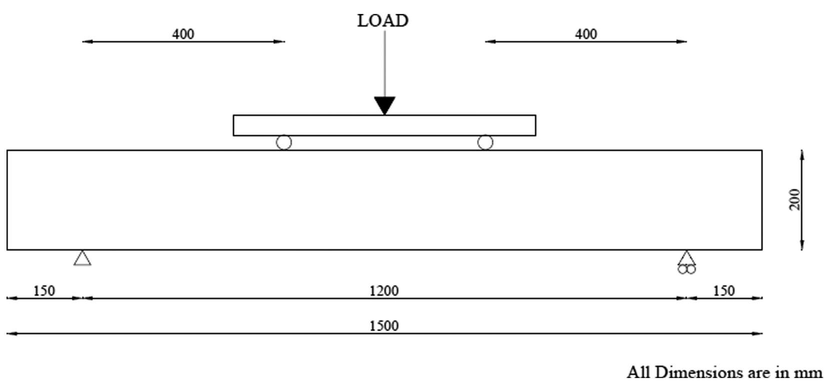
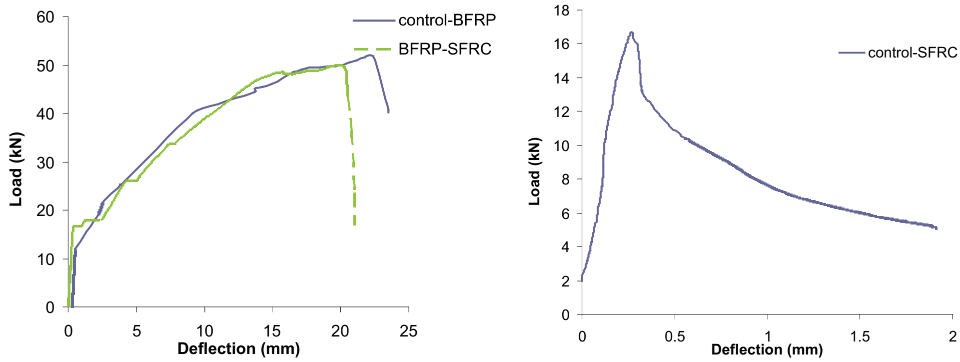


Figure 2: Two Point Loading Setup.

2.4 Results and observations

2.4.1 Load-deflection behaviour

The typical load vs deflection behaviour of various beams are shown in Figures 3(a) and (b). It is observed that for control BFRP reinforced beam, the ultimate load carrying capacity is 51.7 kN and corresponding deflection is 22.92 mm. For the SFRC reinforced beam, the ultimate load carrying capacity is 16.7 kN and corresponding deflection is 0.268 mm. While combining steel fibers along with BFRP, the ultimate load carrying capacity is 49.93 kN, which is almost same as that of BFRP reinforced beam and the corresponding deflection is 19.81 mm. It is found that the first cracking load of concrete beam with steel fiber and BFRP reinforcement is 54% higher than BFRP reinforced beam.



(a) (b)

Figure 3: Load vs Deflection. (a) BFRP reinforced beams & SFRC-BFRP reinforced beam; (b) SFRC reinforced beams.

2.4.2 Failure pattern

The final failure pattern of Control Beam - BFRP is shown in Figure 4(a). The final failure pattern of BFRP reinforced beam was in the region of constant bending moment zone and the shear cracks were formed. In addition, a bond-slip crack (horizontal) was seen in this zone. This gives an indication that BFRP beams should not be used without stirrups and there is a need to ensure the bond performance of such beams.In the case of steel fiber reinforced beams, the final failure pattern is shown in Figure 4(b). A single crack has been developed and its widening caused the final failure of the beam. However, after reaching the ultimate load, the beam failed gradually due to widening of crack. The final failure pattern of Steel Fiber-BFRP beam is shown in Figure 4(c), wherein shear cracks are absent and the final failure is due to flexural crack widening. Number of cracks that are developed in the constant bending moment zone is more in this case compared to BFRP reinforced beam.

3 Analytical modelling

In order to develop a shear strength prediction model for concrete beams where both BFRP and steel fibers are used as reinforcement, an extensive review was car-

(a) BFRP

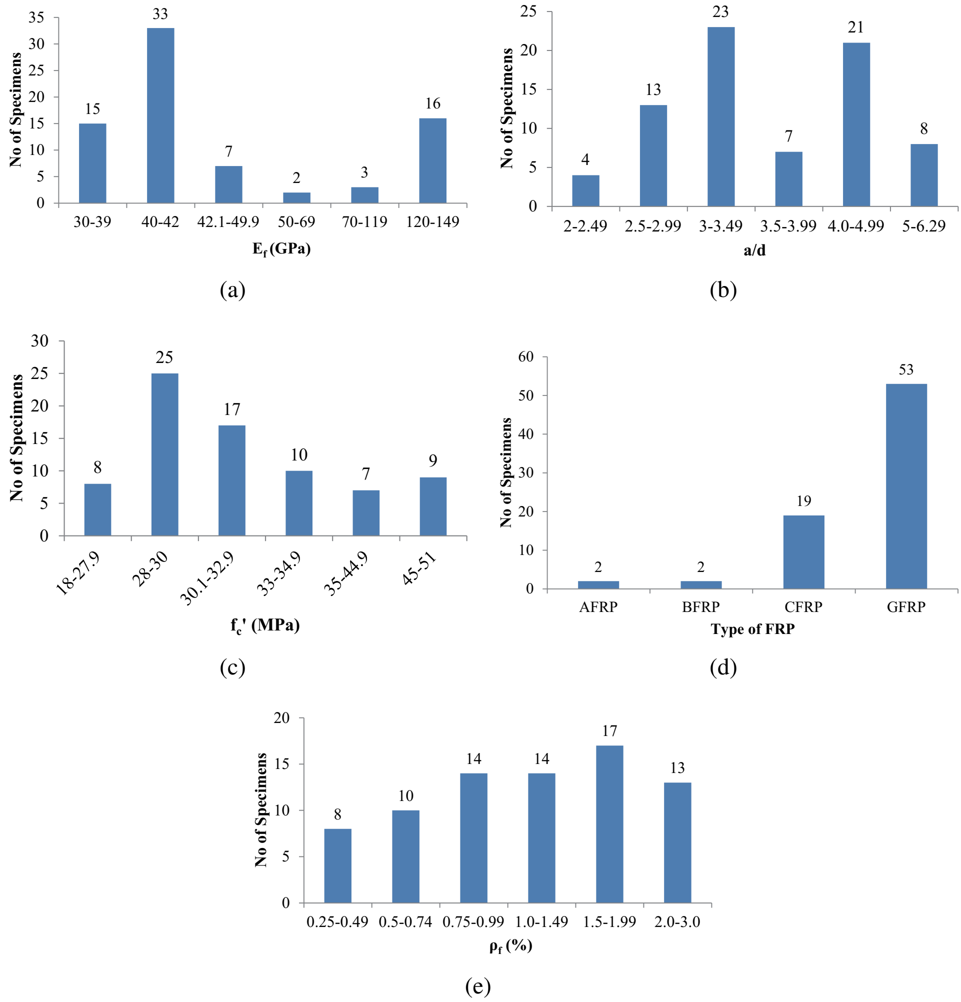
(b) SFRC

(c) SFRC-BFRP

Figure 4: Failure patterns of beams.

ried out to assess the existing shear strength prediction models for FRP reinforced beams and steel fiber reinforced beams.

Shear strength obtained from experiments reported in literature for 76 specimens are considered to assess the existing shear strength prediction models for FRP reinforced beams [Yost, Shawn, and David (2001); El-Sayed, Ehab, and Brahim (2006); Razaqpur et al. (2004); Ashour (2006); Tureyen, Koray, and Robert (2002); Alkhrdaji, Wideman, Belarbi, and Nanni (2001); Duranovic, Pilakoutas, and Waldron (1997); Evan et al. (2010); Alam and Hussein (2013); Tomlinson et al. (2015)]. All specimens were simply supported and were tested under two-point, three-point or four-point loading. These specimens were reinforced with FRP bars in which two specimens with aramid FRP bars, two specimens with basalt FRP bars, 19 specimens with carbon FRP bars and 53 specimens with glass FRP bars. All the specimens had no transverse reinforcement and exhibited shear failure. The concrete compressive strength f_c' , of the test specimens were between 24.1 and 63.0 MPa. The reinforcement ratio, ρ_f ranged between 0.25 and 2.63; the Young's modulus of FRP, E_f ranged between 32 and 145 GPa; the shear span to depth ratio ranged between 2.4 and 6.29; and the effective depth, d ranged between 158.9 and 937 mm. The detailed description relating the number of specimens are shown in Figures 5(a)–(e).



(a) (b) (c) (d) (e)

Figure 5: (a)–(e) Number of Specimens to five major parameters.

3.1 Review of models for FRP reinforced beams

Most of the shear design incorporated in codes for the FRP reinforced concrete beams have focused on modifying shear equations of steel reinforced concrete

Table 2: Shear Design equations for FRP reinforced concrete beams without stirrups.

ACI 440.1 R-03	$V_{cf} = \frac{\rho_f E_f}{90\beta_1 f''_c} V_c \leqslant V_c$ V_c is calculated using ACI 318-11 $\beta_1 = 0.85 - 0.05\frac{f'_c - 28}{7} \geqslant 0.65$
ACI 440.1 R-06	$V_{cf} = \frac{2}{5}\sqrt{f'_c}\, b_w C$ $C = kd$ $k = \sqrt{2\rho_f n_f + (\rho_f n_f)^2} - \rho_f n_f$ $n_f = \frac{E_f}{E_c}$ and $\rho_f = \frac{A_f}{b_w d}$
ISIS Canada-01	$V_c = 0.2\, b_w d \sqrt{f'_c \frac{E_f}{E_s}} \lambda \varnothing_c$ for $d \leqslant 300$ mm $V_c = \frac{260}{1000+d} \lambda \varnothing_c \sqrt{f'_c \frac{E_f}{E_s}} b_w d$ for $d > 300$ mm
CSA S 806-02	$V_{cf} = 0.0035\, b_w d (f'_c \rho_f E_f \frac{V_f d}{M_f})^{1/3}$ $0.1\, b_w d \sqrt{f'_c} \leqslant V_{cf} \leqslant 0.2 b_w d \sqrt{f'_c}$ for $d \leqslant 300$ mm $V_{cf} = \frac{130}{1000+d} \sqrt{f'_c} b_w d \geqslant 0.08\, b_w d \sqrt{f'_c}$ for $d > 300$ mm and $\frac{V_f d}{M_f} \leqslant 1$
JSCE-97	$V_{cf} = \frac{\beta_d \beta_p \beta_n f_{vcd}}{\gamma_b} b_w d$ $\beta_p = 3\sqrt{\frac{1000\rho_f E_f}{E_s}} \leqslant 1.5, \beta_d = 4\sqrt{\frac{1000}{d}} \leqslant 1.5$ $f_{vcd} = 0.23\sqrt{f_{cd}} \leqslant 0.72$ MPa γ_b and β_n are factors to account for strength reduction and axial forces respectively

Note: f'_c = Compressive strength of concrete, ρ_f = Longitudinal reinforcement ratio, V$_c$ = Nominal shear strength provided by concrete, E_c, E_s and E_f = Modulus of elasticity of concrete, steel and FRP longitudinal bars, respectively, b_w = Width of the Beam, d = Distance from extreme compression fiber to centroid of tension reinforcement, C = Distance from extreme compression fiber to the neutral axis, V_f, M_f = Shear force and Moment at critical section respectively.

beams (Table 2). These codal provisions are generally based on parallel truss model with 45° constant inclination of diagonal shear cracks. These provisions identify the shear strength of a reinforced concrete flexural member as the sum of the shear capacity of the concrete component V_{cf} and the shear reinforcement component V_s. The shear design guidelines namely, the American Concrete Institute (ACI 2003; ACI 2006), the Canadian Standards Association (CSA 2002), the Japan Society of Civil Engineers (JSCE 1997) , and the Canadian Network of Centres of Excellence on Intelligent Sensing for Innovative Structures (ISIS 2001) were used. It is found that there are mainly six main parameters that affect the shear strength (V_{cf}) of FRP-reinforced concrete members, such as the concrete compressive strength (f_c'), beam width (b_w), effective depth (d), shear span-to-depth ratio (a/d), reinforcement ratio (ρ_f) and modular ratio (E_f/E_s).

3.1.1 Relative comparison of models

The shear strength was calculated for various models based on the expressions given in Table 2. All the results obtained from the experimental studies (for FRP reinforced beams) and predicted by the models are shown in Figures 6(a)–(e).

It is observed that the shear strength predicted using JSCE-97 is closer to the experimental values. The CSA S 806-02 is also capable of predicting the shear strength with reasonable accuracy. However, it is found that the ACI and ISIS under predicts the results compared to experimentally observed values. The main parameters that influence the shear strength of FRP reinforced concrete beams are the longitudinal reinforcement ratio, concrete compressive strength and shear span to depth ratio. Hence these are discussed in detail in the following section.

3.1.2 Effect of concrete compressive strength on shear strength

The shear design method provided by ACI 440.1-03 assumes that the shear strength of FRP-reinforced concrete beams without stirrups decreases as f_c' increases, whereas all other methods assume that the shear strength of FRP-reinforced concrete beams increases with an increase of concrete compressive strength. The results obtained from experimental to calculated shear strength versus concrete compressive strength are given in Figures 7(a)–(e).

3.1.3 Effect of shear span-to-depth ratio on shear strength

ACI 440.1 and JSCE-97 shear design provisions do not consider the effect of a/d on the shear strength of reinforced concrete beams, CSA S 806-02 exhibits a slight influence of a/d on the shear strength of FRP reinforced concrete slender beams ($a/d > 2.5$). The results obtained from experimental to calculated shear strength versus shear span to depth ratio are given in Figures 8(a)–(e).

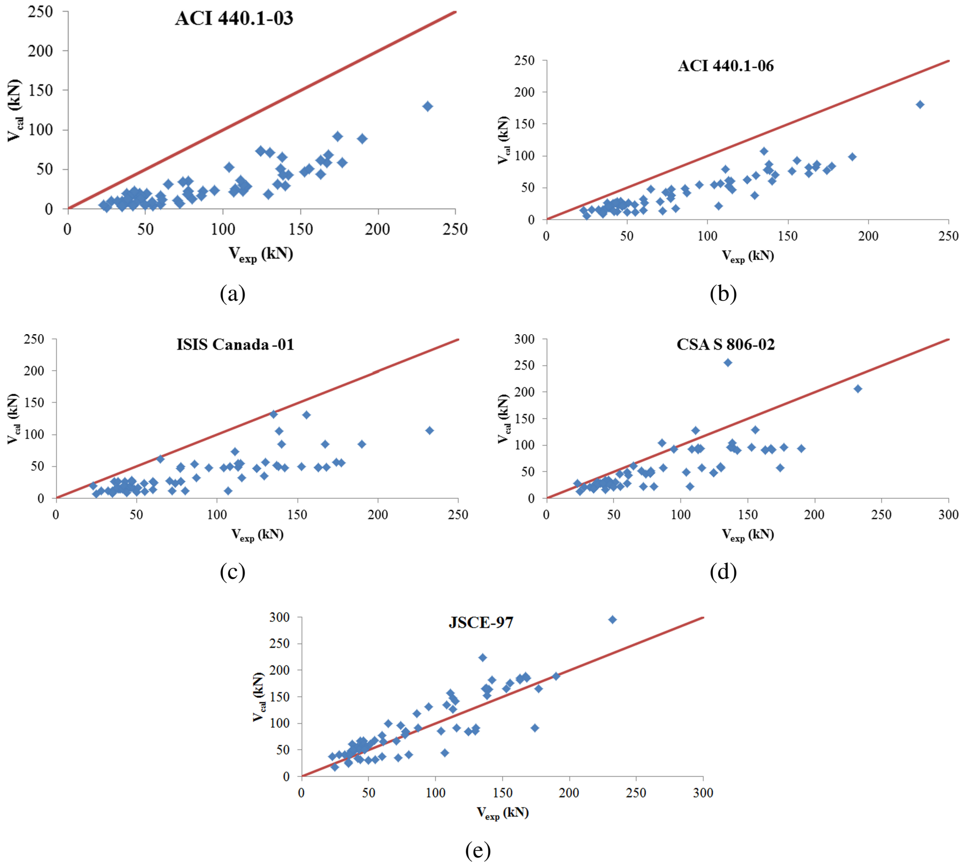


Figure 6: (a)–(e): Comparison of calculated and experimental shear capacity.

3.1.4 *Effect of longitudinal reinforcement ratio on shear strength*

The effect of longitudinal reinforcement ratio on the shear strength of FRP - reinforced concrete beams without stirrups is a prime factor. It is seen that ACI 440.1-03 assumes ρ_f is directly proportional to shear strength. Whereas its effect is inversely proportional in all other codal provisions. The results obtained from experimental to calculated shear strength versus Axial stiffness of reinforcing bars ($\rho_f E_f$) are given in Figures 9(a)–(e).

Experimental results are used to validate the codal provisions. It is concluded more accurate and consistent predictions were obtained using JSCE-97 and also gives a practical way for the prediction of concrete shear strength of beams reinforced with FRP bars. The prediction of CSA S 806-02 is also closer to experiment to great extent. However, ACI and ISIS predictions are not all conservative to use for design applications.

3.1.5 Validation

The shear strength was determined for the BFRP reinforced beam tested in the present study and comparative predictions by various models are shown in Figure 10. It is very clear that the JSCE-97 shows a closer prediction with the experimental value. While examining the remaining models, it can be concluded that the

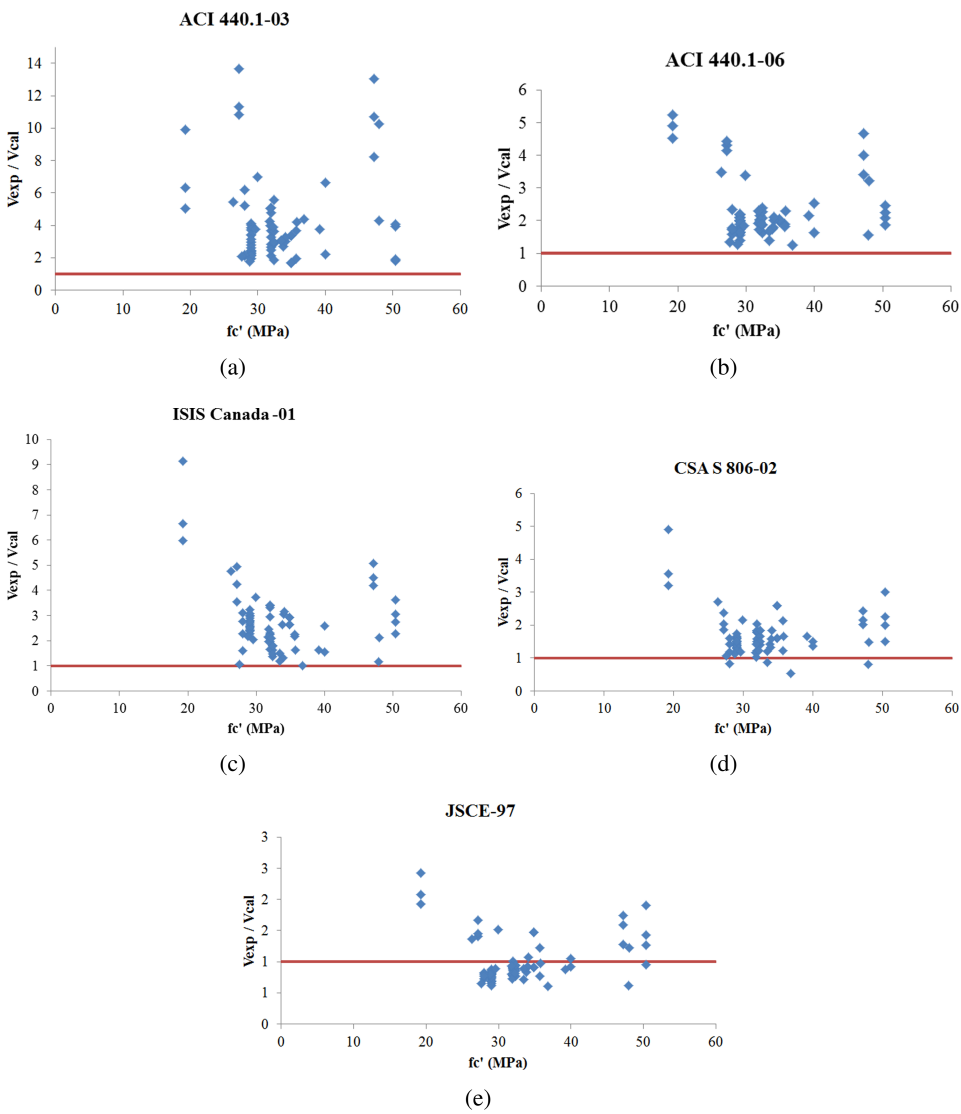


Figure 7: (a)–(e): Experimental to calculated shear strength versus concrete compressive strength.

remaining shear strength prediction models are highly conservative in estimating the shear strength of BFRP reinforced beams without shear reinforcement. The ACI 440 equation for the FRP stirrups contribution to shear capacity, V_c is more for FRP materials having low modulus of elasticity. However, it overestimates the capacity of FRP stirrups with high modulus of elasticity. Standards of JSCE-97 provided good estimation of the shear capacity provided by BFRP reinforcement for low shear capacity beams. However, such standards are highly conservative for

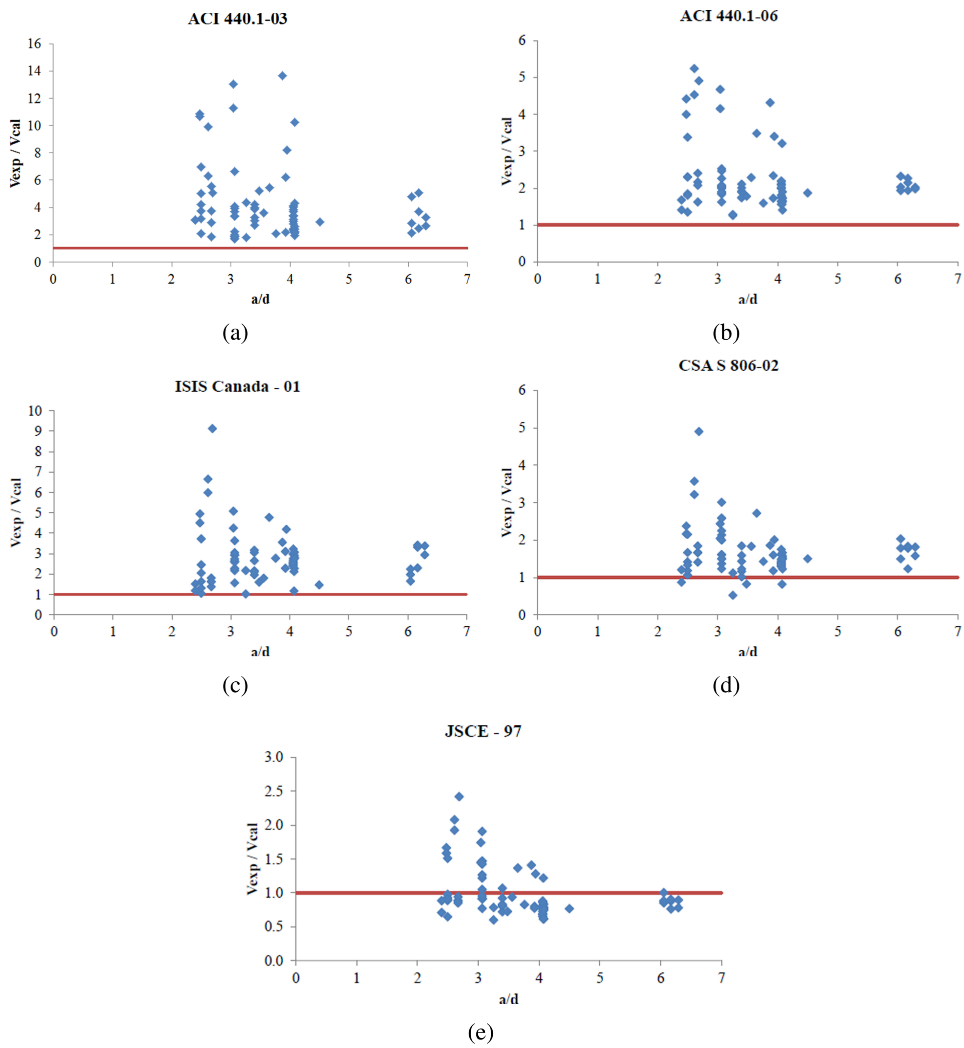


Figure 8: (a)–(e): Experimental to calculated shear strength versus shear span to depth ratio.

beams having high shear capacity. The CSA S806 method reasonably estimated shear strength of concrete beams having relatively low shear reinforcement ratio, yet overestimated the shear capacity of highly reinforced beams with FRP stirrups of high tensile strength. The effect of the axial rigidity of FRP longitudinal reinforcement on the shear capacity of FRP-RC beams is better captured by a cubic root.

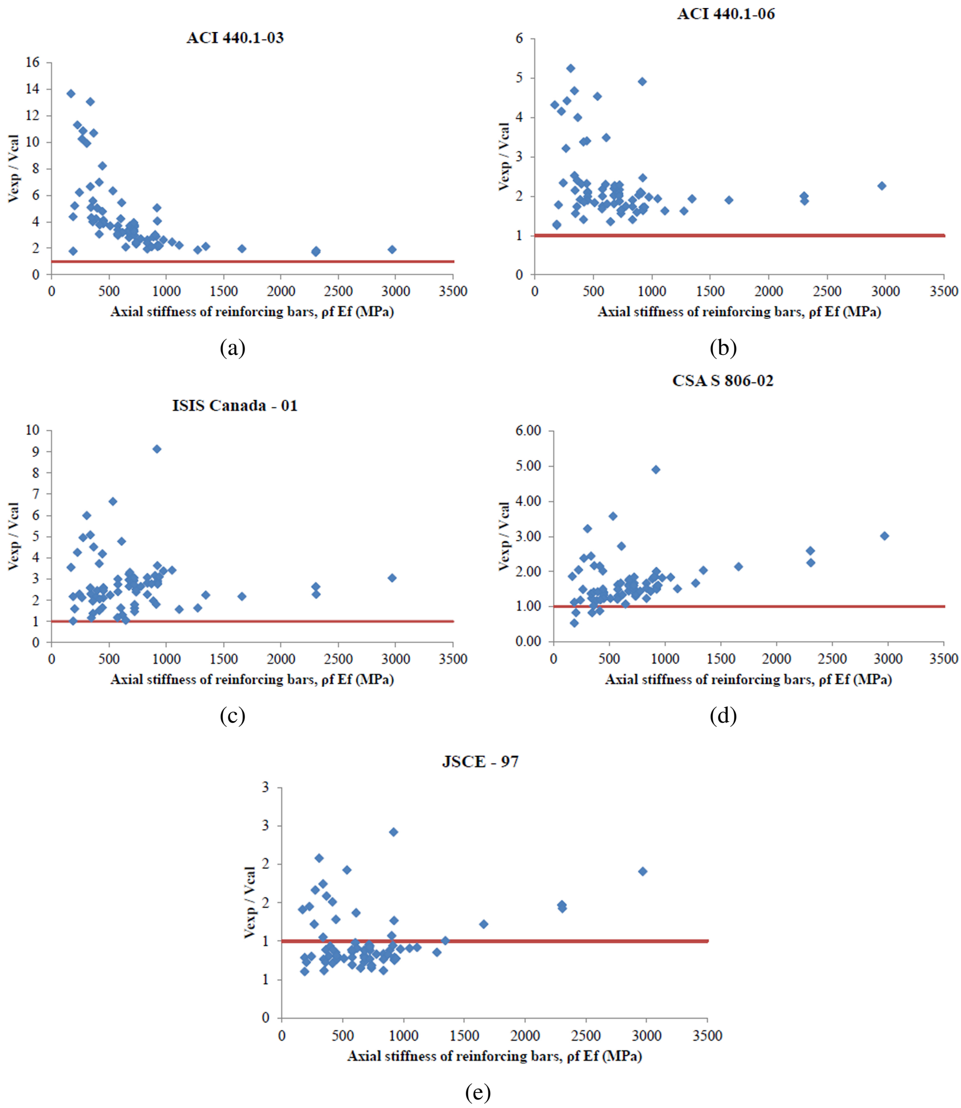


Figure 9: (a)–(e): Experimental to calculated shear strength versus Axial stiffness of reinforcing bars, $\rho_f E_f$.

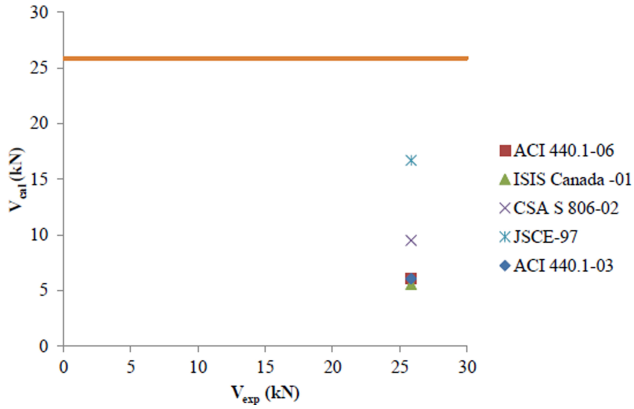


Figure 10: Comparison of calculated and experimental shear capacity for BFRP reinforced beams.

3.2 Review of models for steel fiber reinforced beams

The use of steel fibers in concrete mixtures has not yet been fully utilized by the concrete industry for several reasons: steel fibers are often considered expensive and the shear behavior of concrete containing steel fibers is still not fully understood. It is important to better understand and predict the shear behavior of SFRC for its wider applications in the concrete industry. Many researchers have developed analytical and numerical tools for predicting the shear strength of SFRC beams [Zhang, Nie, and Wu (2014)]. Present study utilizes previous experimental data to develop shear strength prediction models for SFRC beams without stirrups. It is seen that several equations were developed to predict the shear strength of SFRC beams based on span-depth ratio, concrete compressive strength and fiber shape, which were found to produce precise and accurate results. Extensive experimental investigations are required on the shear strength testing of SFRC beams with more variability in their identified parameters that affect their shear strength. This will help understand the shear behavior better and develop more precise numerical tools considering a larger database. As identified in the literature, more data points are required for SFRC beams having $a/d < 3$ with plain fiber type.

A number of investigators have proposed empirical equations for estimating the average shear stress at shear failure v_u of fiber reinforced concrete beams. The majority of the proposed equations contain the fiber factor (F), which illustrates the combined effect of the fiber aspect ratio and fiber content on the shear strength of SFRC beams. It can also be noticed that the inverse of the span depth ratio is used in most equations. In order to produce accurate equations for modeling the shear behavior of SFRC beams, the most important parameters affecting their shear strength of SFRC must be investigated. The parameter schosen for the development of shear strength equations were those observed from the previous studies on the shear strength of SFRC. These parameters are the concrete compressive strength (f'_c), tensile reinforcement ratio (ρ), span-depth ratio a/d, fiber aspect ratio (l_f/d_f) and the amount of fiber in concrete (Vf) [Narayanan and Darwish (1987)]. The influence of each parameter on the shear strength of SFRC beams has been observed from previous studies conducted by Baston and Jenkins (1972); Sharma (1986); Narayanan and Darwish (1987); Ashour, Hasanain, and Wafa (1992); Imam et al. (2008).

In order to predict the shear strength of SFRC beams a collection of 10 experimental test results from 2 previous studies were compiled into a database. The database contains only the test results involving the shear strength of SFRC beams without stirrups. The experimental data collected has been summarized in Table 3. The studies varied with the type of steel fiber, size of the beams tested as well as the amount of fiber in the concrete. Other than the concrete compressive strength, reinforcement ratio, span-depth ratio, fiber aspect ratio and the fiber volume, several other parameters such as effective beam depth (d), nominal maximum aggregate size (d_a), concrete flexural and splitting tensile strength (f_f and f_{sp}, respectively). Although these parameters were used in the shear strength prediction equations previously proposed models in the equations by Imam et al. (2008); Sharma (1986). It was, therefore, necessary to include these parameters in the database to enable the comparison of these existing models. However, upon gathering these extra parameters, it was discovered that in some previous studies not all of these parameters were reported. As a result, approximations were made to include the missing parameters in the database. The various shear strength prediction models existing for FRC reinforced concrete beams are given in Table 4.

Table 3: Summary of previous tests on SFRC beams without stirrups.

Reference	b_w (mm)	d (mm)	Fiber type	Fiber volume	f'_c (N/mm^2)	a (mm)	$V_{\exp}$ (kN)
[14]	200	265	Plain-50 mm	0.5	45.3	800	231
[14]	200	265	Plain-50 mm	0.75	44	800	288
[14]	200	265	Plain-50 mm	1	39.9	800	294
[14]	200	265	Plain-30 mm	0.5	44.4	800	213
[14]	200	265	Plain-30 mm	0.75	42.4	800	246
[14]	200	265	Plain-30 mm	1	41.7	800	303
[22]	100	175	Plain-40 mm	0.5	80	525	50.9
[22]	100	175	Plain-40 mm	1	80	525	63

Table 4: Shear Design equations for SFRC beams.

Sharma	$v_u = kf'_t(d/a)^{0.25}$ $k = 2/3;\ f'_t = 0.79\ (f'_c)^{0.5}$
Narayanan and Darwish	$v_u = e\left[0.24 f_{spfc} + 80\rho\dfrac{d}{a}\right] + v_b$ $f_{spfc} = \dfrac{f_{cup}}{\left(20-\sqrt{F}\right)+0.7+1.0\sqrt{F}}$ $e = 1.0$ for $a/d > 2.8$ and $2.8\ d/a$ for $a/d \leq 2.8$ $d_f = 0.5$ for round fiber; 0.75 for crimped fiber; 1 for indented fiber
Ashour, Hasanain and Wafa	$v_u = (2.11\sqrt[3]{f'_c} + 7F)\left(\rho\dfrac{d}{a}\right)^{1/3}$ for $a/d \geq 2.5$ $v_u = [(2.11\sqrt[3]{f'_c} + 7F)\left(\rho\dfrac{d}{a}\right)^{1/3}]\dfrac{2.5}{a/d} + v_b\left(2.5 - \dfrac{a}{d}\right)$ for $a/d < 2.5$
Imam and Vandawalle	$v_u = 0.6\psi\sqrt[3]{\omega}\left[(f'_c)^{0.44} + 275\sqrt{\dfrac{\omega}{(a/d)^5}}\right]$ $\Psi = \dfrac{1+\sqrt{5.08/d_a}}{\sqrt{1+d/(25d_a)}}$ $d_f =$ Bond Factor: 0.50 for smooth fibers, 0.90 for deformed fibers and 1.00 for hooked fibers
Zsutty	$v_u = 11.4e\left(f'_c\,\rho\dfrac{d}{a}\right)^{1/3}$ $e =$ Arch action factor: 1.0 for $a/d > 2.5$ and $2.5\ d/a$ for $a/d \leqslant 2.5$

Note: v_u = Average shear stress at shear failure; a/d = Shear span to depth ratio; f_t = Split cylinder tensile strength of concrete; f'_c = Concrete cylinder compressive strength; f_{spfc} = Computed value of split cylinder strength of fiber concrete; ρ = Flexural reinforcement ratio; F = Fiber Facto $r = (L_f/D_f)V_f d_f$; f_{cuf} = Cube strength of fiber concrete; L_f = Fiber Length; D_f = Fiber Diameter; V_f = Volume fraction of steel fibers; d_f = Bond Factor; $v_b = 0.41\tau F$; τ = Average fiber matrix interfacial bond stress, taken as 4.15 MPa, based on the recommendations of Swamy, Mangat, and Rao; Ψ = Size effect factor; ω = Reinforcement factor $\rho(1+4F)$; d_a = maximum aggregate size.

3.2.1 Relative comparison

Based on the result of his own tests and those of Baston and Jenkins (1972); Sharma (1986) proposed a simple empirical equation for predicting the shear strength of fiber reinforced concrete beams. Sharma's model is attractive, but this equation does not explicitly account for factors that are known to significantly influence the shear strength, including the fiber volume, the shape of the fibers, and the flexural reinforcement ratio. In addition, it underestimates the effect of a/d and is excessively conservative for low values of a/d and non conservative for higher values of a/d. Narayanan and Darwish (1987) proposed an empirical equation for the average shear stress at shear failure vu. According to the authors, the first term in the brackets accounts for the fiber contribution in terms of the split cylinder strength, the second term accounts for dowel action, and the third term accounts for the contribution of fibers across an inclined crack. The fiber factor F accounts not only for the fiber volume and aspect ratio but, with the bond factor df, also accounts for variations in anchorage conditions of the fibers. The non- dimensional factor e which accounts for arch action is similar to the factor in the shear equation proposed by Zsutty (1971) for conventional beams without fibers. Narayanan and Darwish equation considers the key parameters affecting shear strength, including the volume and shape of fibers, a/d, the concrete strength and the flexural reinforcement ratio. It provided reliable but conservative estimates of shear strength. Ashour, Hasanain, and Wafa (1992) tested 18 beams made of high strength fiber reinforced concrete. Based on these test results, they proposed two equations for predicting the strengths of such beams. The first set was similar to Zsutty's (1971), but was modified to account for the fibers. Ashour, Hasanain and Wafa Equation include the same parameters that were included in Narayanan and Darwish equation. Imam et al. (2008) modified an expression that Bazant and Sun had developed to predict the shear strength conventional concrete beams. The Bazant and Sun expression was developed based on the results of non linear fracture mechanics, which indicate that the shear capacity varies with maximum aggregate size d_a and the ratio of beam depth to maximum aggregate d/d_a. The Iman et al. equation differs from the Bazant and Sun equation only in that reinforcement factor ω was substituted in place of the flexural reinforcement ratio ρ and the constants were adjusted as the result of statistical analysis. Imam model incorporates the key factors of other models and adds the size effect. All the results obtained from the experimental studies and predicted by the equations are given in Figure 11.

It is observed that the shear strength predicted using Sharma model is closer to the experimental values. The Ashour et al. model is also capable of predicting the shear strength with reasonable accuracy. However, it is found that the Narayanan and Darwish model under predicts the results compared to experimentally observed values.

Table 5: Comparison of shear strength of various models for SFRC reinforced beams.

Sharma		Narayanan and Darwish		Ashour, Hasanain and Wafa		Iman and Vandewalle	
V_{cal} (kN)	V_{exp}/V_{cal}	V_{cal} (kN)	V_{exp}/V_{cal}	V_{cal} (kN)	V_{exp}/V_{cal}	V_{cal} (kN)	V_{exp}/V_{cal}
142.53	1.62	699.45	0.33	78.41	2.94	59.99	3.85
140.47	2.05	745.82	0.39	81.88	3.52	62.35	4.62
133.76	2.19	770.69	0.38	83.80	3.50	62.46	4.70
141.10	1.51	676.43	0.32	76.77	2.78	58.50	3.65
137.89	1.78	709.38	0.35	79.26	3.10	60.07	4.09
136.75	2.21	752.31	0.40	82.43	3.67	62.12	4.87
62.64	0.81	233.68	0.22	18.99	2.68	16.78	3.03
62.64	1.01	241.12	0.26	19.36	3.25	17.28	3.65

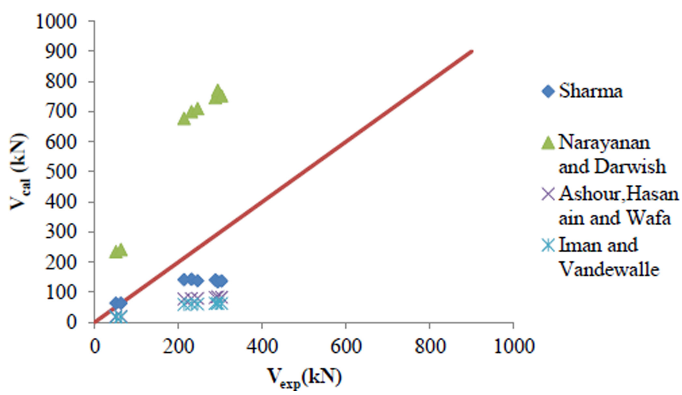


Figure 11: Comparison of calculated and experimental shear capacity.

3.2.2 *Validation*

From Figure 12 it is observed that the models by Ashour et al. predictgood results which are closer to experimental values. It is concluded that this model can be modified to incorporate the combined effect of steel fiberalong with BFRP reinforcement to predict the shear strength of concrete beams.

3.3 *Analytical model for SFRC-BFRP reinforced beams*

From the review of analytical models for FRP reinforced beams, it is concluded that JSCE-97 shows good results relating the calculated and experimental values. The concrete shear capacity of the flexural members using FRP as main reinforcement

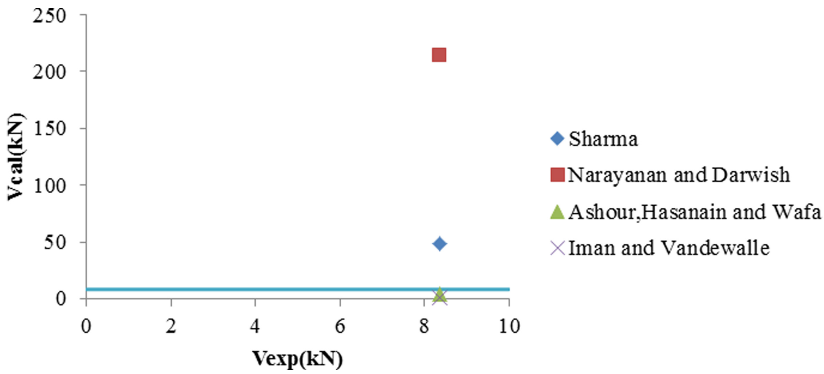


Figure 12: Comparison of calculated and experimental shear capacity for steel fiber reinforced beams.

can be evaluated as per this committee is

$$V_{cf} = \frac{\beta_d \beta_p \beta_n f_{vcd}}{\gamma_b} b_w d$$

For steel fiber reinforced beams, it is concluded that Ashour, Hasanain and Wafa model shows good results relating the calculated and experimental values. The concrete shear capacity of the flexural members for the effect of fibers is described in the following equations.

For $a/d \geq 2.5$

$$v_u = (2.11\sqrt[3]{f_c'} + 7F)\left(\rho\frac{d}{a}\right)^{1/3} \quad \text{(MPa)}$$

For $a/d < 2.5$

$$v_u = [(2.11\sqrt[3]{f_c'} + 7F)\left(\rho\frac{d}{a}\right)^{1/3}]\frac{2.5}{a/d} + v_b\left(2.5 - \frac{a}{d}\right) \quad \text{(MPa)}$$

The shear strength of concrete beams reinforced with BFRP and steel fibers can be calculated as given in the following equation.

$$V_{\text{BFRP+SF}} = [V_{\text{BFRP}} + V_{\text{SF}}]^{0.91}$$

where

$V_{\text{BFRP}} =$ Shear capacity of BFRP reinforced beams without stirrups
$V_{\text{SF}} =$ Shear capacity of Steel fiber reinforced beams

$V_{\text{BFRP+SF}} =$ Combined shear capacity of Steel fiber and BFRP reinforced beams

For the combined effect of fiber and FRP Reinforced beams, the proposed equation is:

$$V_{\text{BFRP+SF}} = \left\{ \frac{\beta_d \beta_p \beta_n f_{vcd}}{\gamma_b} b_w d + \left[\left(2.11 \sqrt[3]{f'_c} + 7F\right) \left(\rho \frac{d}{a}\right)^{1/3} \frac{2.5}{\frac{a}{d}} + v_b \left(2.5 - \frac{a}{d}\right) \right] b_w d \right\}^{0.91}$$

Table 6 gives a comparison between the experimentally obtained value and calculated shear capacity.

Table 6: Comparison of experimental and calculated shear capacity for the Present Study.

	Experimental Shear Capacity (kN)	Calculated Shear Capacity (kN)	$\frac{V_{\text{exp}}}{V_{\text{cal}}}$
V_{BFRP}	25.9	16.70	1.55
V_{SF}	8.4	4.76	1.76
$V_{\text{BFRP+SF}}$	24.965	16.248	1.54

3.4 Summary and concluding remarks

Experimental and analytical investigations are reported on three types of concrete beams reinforced with BFRP, steel fibers and combination of BFRP and steel fibers. It is observed that incorporation of steel fibers along with BFRP could change the shear failure mode of BFRP reinforced beam to flexural mode. From the relative comparison of various shear strength prediction models available in literature for FRP reinforced beams and fiber reinforced beams were reviewed and compared. It is found that the existing model needs modification for incorporating the effect of steel fibers into BFRP reinforced beams. Hence, a modified model has been proposed to predict the shear strength of concrete beams with steel fiber and BFRP as reinforcement.

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