SHEAR STRENGTH OF FIBER REINFORCED CONCRETE BEAM-COLUMN JOINTS UNDER SEISMIC LOADING

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ABSTRACT:

Existing reinforced concrete frames constructed before the 1970s and some present buildings are often characterized by an inadequate seismic resistance: beam-column connections in a ductile reinforced concrete frame is a critical region, especially under the action of earthquake loading. These structures were designed for gravity loads and are often inadequately detailed to resist to severe seismic loads. Different methods have been used and studied by several researchers for strengthening and increasing the resistance of reinforced concrete beam-column joints. Among these the use of fiber-reinforced concrete has shown to permit connections to satisfactorily perform under large shear reversals with excellent damage tolerance. In this paper several experimental studies, done by other researchers on beam-column joints both without and with fiber reinforcements, have been taken into account. On the basis of the studies conducted by the author on interior and exterior beam-column joints, it is here proposed a new formula that predicts the shear strength of fiber-reinforced concrete beam-column joints. The shear strength values obtained with this formula have been compared to those derived by the experimental tests. It has been found that the here proposed expression gives an accurate and uniform prediction of the shear resistance, as it properly estimates the tests results.

KEYWORDS: beam-column joints, fiber, shear, strength

1. INTRODUCTION

During earthquakes, structural elements must be able to dissipate a great amount of energy to ensure the structural integrity of the building and avoid collapse. One of the most critical regions of a framed structure is the beam-column area, because high shear forces acting.

To dissipate the earthquake induced energy, joints are usually designed with stirrups having decreased spacing, and hence increased reinforcement percentage. However, with a reduced spacing of the joint hoops, during construction the concrete is not able to flow properly around the reinforcing bars, not providing an adequate bond between steel and concrete. Several test results and researches [Bayasi and Gebman (2002), Filiatrault et al. (1994), Filiatrault et al. (1995), Gefken and Ramey (1989)] have illustrated that the use of fiber reinforced concrete in the joint area leads to better ductility, increased energy-dissipation capacities, and hence increases the joint shear strength and can diminish requirements for closely spaced hoops.

Fiber reinforced concrete is found to represent a good solution for providing more cost-effective ductile beam-column joints for structures built in seismic areas. This can be achieved by reducing the percentage of transverse reinforcement in the joint region and by compensating the required shear strength by fibers in the reinforced concrete.

Although several researchers have published their results using steel fibers in RC beam-column joints, the method of designing them has not been reported, and only one expression [Jiuru et al. (1992)] has been nowadays proposed.

In this paper a formula for computing the ultimate shear strength of a fiber reinforced concrete (FRC) joints is proposed and compared with the results of the most numerous collection of FRC tested joints, 37 joints.

2. CALCULATION OF JOINT SHEAR STRENGTH

The here presented model for calculating the joint shear strength is based, as done by the author for interior and exterior reinforced concrete (RC) joints [Russo and Somma (2002), Russo and Somma (2004)] and by Jiuru et al. (1992) for FRC joints, on the superposition of shear strength contributions. Those here considered are: 1) concrete contribution to shear strength, $v_{j,c}$, 2) beam longitudinal reinforcement contribution to shear strength, $v_{j,l}$, and 3) stirrup-fiber contribution to shear strength, $v_{j,h\text{-}f}$. The ultimate shear strength of an FRC joint, v_j, is here proposed to be calculated as:

$$v_j = v_{j,c} + v_{j,l} + v_{j,h-f} \tag{2.1}$$

Now the single three contributions to shear strength are explained and an expression is given for them.

2.1. Concrete contribution to shear strength

The so called "concrete contribution" is that provided by concrete and by the two vertical stresses, σ_a and σ_v, respectively due to the axial load applied to the column and to the vertical reinforcement vertical stresses transmitted by column. Hence in this contribution the effect of axial load and of column longitudinal vertical reinforcement is taken into account too.
The calculation of this shear strength contribution has already been done in previous author's papers [Russo and Somma (2006), Somma (2007), Somma (2008)]. In this paper only the final expression is given, as it has been kept unchanged.

$$v_{h,c} = \bar{p}_t \sqrt{1 + \frac{|\sigma_a - f_v|}{\bar{p}_t}} \tag{2.2}$$

where σ_a = N/A_j (A_j is the area of the joint transverse section), and f_v is the maximum value of the vertical stress σ_v, obtained when the longitudinal bars are yielded:

$$f_V = \frac{\lambda_0 f_{yv} A_v}{A_j} \tag{2.3}$$

where f_{yv} and A_v are respectively the yielding strength and cross section area of the vertical column longitudinal reinforcement, and λ_0 is the over-strength factor usually assumed equal to 1.25.
In Eqn. 2.2 $\bar{p}_t$ is the principal tensile stress expressed as:

$$\bar{p}_t = f'_c \sqrt{26 + 10\,\frac{\sigma_a - f_v}{f'_c}} - 5\, f'_c - \sigma_a + f_v \tag{2.4}$$

where f'_c is the concrete compressive strength.
Eqn. 2.4 has been obtained [Russo and Somma (2006)] by considering the biaxial tensile-compressive stress state in the joint panel and the diagram proposed by Kupfer et al. (1969).

2.2. Beam longitudinal reinforcement contribution to shear strength

This contribution is difficult to be evaluated because of the large alternate cyclic actions making non linear steel behavior.
It is assumed that the joint shear resistance due to the confinement action provided by beam longitudinal reinforcement, should be proportional to the steel yielding strength, f_{yl}, and to the area of the beam bottom longitudinal reinforcement, A_{sl}, which is always not greater than the top one, and hence able to provide a greater bond force. Consequently the shear strength due to beam reinforcement is

$$v_{j,l} = \frac{\lambda_0 f_{yl} A_{sl}}{A_j} \tag{2.5}$$

where λ_0 is the over-strength factor (= 1.25).

2.3.Stirrup-Fiber contribution to shear strength

The addition of steel fibers to seismic joints, without changing joint design is noted to improve the resistance to earthquake loading. Because of the advantaging confining effect of fibers, transverse reinforcement in the joint can be reduced (increasing hoop spacing) and the same shear strength can be obtained.
It is demonstrated in several tests that the use of fiber reinforced concrete in the joint region is effective in increasing shear strength, even allowing the total elimination of the joint transverse reinforcement [Parra-Montesinos et al. (2005)].
In this paper the stirrup contribution to shear strength has been considered together with the one provided by fibers. The expression of this "double" contribution is:

$$v_{j,f-h} = 5 f_{yh} \left(\rho_h + \rho_f\right)^4 \tag{2.6}$$

where f_{yh} is the transverse reinforcement yielding strength, ρ_h is the area ratio of stirrups and ρ_f is the volume fraction of fiber in the concrete mix.
As it can be noticed, this expression is suitable to be used also if fibers are not present in the joint core ($\rho_f = 0$).

2.4. Ultimate shear strength

On the basis of Eqns. 2.1, 2.2, 2.5 and 2.6, the ultimate shear strength of FRC joints is:

$$v_j = \overline{p}_t \sqrt{1 + \frac{\left|\sigma_a - f_v\right|}{\overline{p}_t}} + \frac{1.25 f_{yl} A_{sl}}{A_j} + 5 f_{yh} \left(\rho_h + \rho_f\right)^4 \tag{2.7}$$

To evaluate the reliability of this expression, the results of 37 FRC joints tested by various authors from 1989 until 2005 have been considered. It must be stressed that it is the most numerous collection of test results nowadays published. The average value (AVG), the standard deviation (STD) and the coefficient of variation (COV) of the experimental to calculated shear strength ratios have been computed, and the obtained values are: AVG = 0.7, STD = 0.32 and COV = 0.46. The COV value indicates the uniformity in the prediction, and the lower it is, the more reliable the shear strength calculation. The AVG value gives the accuracy in the prediction: the closer to the unity it is, the more accurate the expression. The expression in Eqn. 2.7 has been multiplied by the factor 0.4 to obtain the exact mean equality between experimental and calculated shear strength (AVG = 1), and by the factor 0.33 to obtain a design formula which provides AVG = 1.2, hence safe, because the experimental results are meanly greater than the calculated ones. The just mentioned expressions are the following:

$$v_{ju} = 0.4\left[\bar{p}_t\sqrt{1+\frac{|\sigma_a - f_v|}{\bar{p}_t}} + \frac{1.25 f_{yl} A_{sl}}{A_j} + 5 f_{yh}(\rho_h + \rho_f)^4\right] \tag{2.8}$$

where v_{ju} is the ultimate shear strength providing in the calculation AVG = 1 and COV = 0.46, and

$$v_{jd} = 0.33\left[\bar{p}_t\sqrt{1+\frac{|\sigma_a - f_v|}{\bar{p}_t}} + \frac{1.25 f_{yl} A_{sl}}{A_j} + 5 f_{yh}(\rho_h + \rho_f)^4\right] \tag{2.9}$$

where v_{jd} is the design shear strength providing in the calculation AVG = 1.2 and COV = 0.46.

3. RELIABILITY OF THE PROPOSED MODEL OF SHEAR STRENGTH CALCULATION

With the here proposed expressions (Eqns. 2.8 and 2.9) a COV value of 0.46 has been obtained. In the following it is verified if this model is reliable and hence the expressions are better than those previously proposed by other authors and provided by Codes. Three authors expressions and two Codes formulas have been taken into account.

3.1. Authors expressions

The expressions proposed by Jiuru et al. (1992), by Attaalla (2004), and by Hegger et al. (2004) have been considered.

3.1.1. Jiuru et al. (1992)

The ultimate shear strength of FRC joints are proposed to be calculated as:

$$v_j = v_c + v_f + v_s \tag{3.1}$$

where v_c is the shear strength carried by concrete, v_f is the shear strength carried by fibers, and v_s is the shear strength carried by the joint stirrups. These shear strengths have the following expression:

$$v_c = 0.1 f'_c\left(1+\frac{\sigma_a}{f'_c}\right) \tag{3.2}$$

$$v_f = 2\frac{l_f}{d_f}\rho_f \tag{3.3}$$

where l_f is the length of the fibers and d_f is the diameter of the fibers, and

$$v_s = \frac{f_{yh} A_{sh}}{A_j s_h}(h_0 - a'_s) \tag{3.4}$$

Where A_{sh} and s_h are the stirrup area and spacing, h_0 is the effective beam depth, and a'_s is the distance from extreme compressive fiber to centroid of compressive reinforcement.

This expression (Eqn. 3.1) is the first providing the shear strength of fibers. The shear strength values calculated with this expression have been compared with the experimental outcomes from the 37 considered FRC joints, and the following values of AVG and COV of the experimental to calculated shear strength ratios have been obtained: AVG = 0.62, COV = 0.76.
It can be noticed that the here proposed expression (providing a COV = 0.46) is 40% more reliable than the Jiuru et al. one.

3.1.2. Attaalla (2004)

He proposed the following expression:

$$v_j = 0.45\,\eta\,\zeta_h\,f'_c\left[\frac{\sqrt{(\rho_t\,f_{yt}-\sigma_b)(\rho_v\,f_{yv}-\sigma_a)}}{\rho_t\,f_{yt}+\rho_l\,f_{yv}-(\sigma_b+\sigma_a)}\right] \tag{3.5}$$

where σ_b is the axial stress in the beam, η = 0.79 for exterior joints and 1 for interior joints,

$$\zeta_h = 0.4\left[1+\left(\frac{110-f'_c}{69}\right)^3\right]\le 1 \tag{3.5}$$

$$\rho_t\,f_{yt} = \rho_h\,f_{yh} + \frac{1}{3}\rho_l\,f_{yl} \tag{3.6}$$

$$\rho_v = \rho_{jl} + \frac{1}{3}\rho_c \tag{3.7}$$

where ρ_l is the reinforcement ratio of beam flexural bars, ρ_{jl} is the reinforcement ratio of intermediate column bars, and ρ_c is the reinforcement ratio of column bars at the two faces of the joint.
The shear strength values calculated with this expression (Eqn. 3.5) have been compared with the experimental outcomes from the 37 considered FRC joints, and the following values of AVG and COV of the experimental to calculated shear strength ratios have been obtained: AVG = 0.83, COV = 0.59.
It can be noticed that the here proposed expression (providing a COV = 0.46) is 22% more reliable than the Attaalla one.

3.1.3. Hegger et al. (2004)

They proposed the following expression:

$$v_j = v_c + v_s \le v_{\max} \tag{3.8}$$

where v_c is the shear resistance of the concrete, v_s is the shear resisted by the stirrups, and v_{max} is the maximum shear resistance of the connection, and are calculated as following:

$$v_c = \alpha_1\left(2.4-0.6\frac{h_b}{h_c}\right)\left(1+\frac{\rho_c-0.5}{7.5}\right)f'^{\,1/3}_c \tag{3.9}$$

where $0.75\le h_b/h_c\le 2$, α_1 is a factor reflecting the efficiency of the anchorage of the beam reinforcement to be taken as 0.85 for 180-degree bend bars and 0.95 for 90-degree bend or headed bars, and $0.5\le\rho_c\le 2$

$$v_s = \alpha_2 \frac{A_{sh}\ f_{yh}}{A_j} \tag{3.10}$$

where α_2 is a shear reinforcement efficiency factor, to be taken as 0.6 for 180-degree bend bars and 0.7 for 90-degree bend or headed bars

$$v_{\max} = 0.25\,\gamma_1\,\gamma_2\,\gamma_3\,f'_c \le 2\,v_c \tag{3.11}$$

where γ_1 is a coefficient to account for the anchorage efficiency of the of the beam reinforcement to be taken as 1 for bend bars and 1.2 for headed bars, $\gamma_2 = 1.5 - 1.2\,\sigma_a / f'_c \le 1$, and $\gamma_3 = 1.9 - 0b\,h_b / h_c \le 1$.
In this case the following values of AVG and COV of the experimental to calculated shear strength ratios have been obtained: AVG = 0.77, COV = 0.58.
It can be noticed that the here proposed expression (providing a COV = 0.46) is 21% more reliable than the Hegger et al. one.

3.2. Codes formulas

In this paper the formulas provided by the New Zealand Standard (1995) and by the ACI Code 318M-05 have been considered and compared with the experimental results.

3.2.1. New Zealand Standard (1995)

This code provides the following expression for calculating the joint shear strength

$$v_j = \frac{f'_c}{6\alpha_j} \cdot \frac{f_{yh} A_{sh}}{f_{yl} A_s^*} \tag{3.12}$$

where A_s^* is the greater of the area of top or bottom beam reinforcement, and

$$\alpha_j = 1.4 - 1.6 \frac{\sigma_a}{f'_c} \ge \frac{1}{15} \cdot \frac{f'_c\, A_j}{f_{yl} A_s^*} \tag{3.13}$$

The shear strength v_j must be such as $0.14\, f'_c \le v_j \le 0.20\, f'_c$.
In this case the following values of AVG and COV of the experimental to calculated shear strength ratios have been obtained: AVG = 1.16, COV = 0.61.
It can be noticed that the here proposed expression (providing a COV = 0.46) is 25% more reliable than this one.

3.2.2. ACI Code 318M-05

This code provides the following expression for calculating the joint shear strength

$$v_j = \beta \sqrt{f'_c} \tag{3.12}$$

with β equal to 1.7 for interior joints and 1.2 for exterior joints.
In this case the following values of AVG and COV of the experimental to calculated shear strength ratios have been obtained: AVG = 0.63, COV = 0.52.

It can be noticed that the here proposed expression (providing a COV = 0.46) is 11% more reliable than this one.

4. CONCLUSIONS

In this paper the author has collected the greatest number of interior and exterior FRC joints tested by other authors under seismic loading, and has concluded that the effective application of steel fibers in the joint concrete mix results in significantly improved joint behavior under seismic loading, in particular with an increased shear resistance.

This is also evident in Figure 1, where the experimental shear strength of joints having the same ρ_h (and also the same geometrical and mechanical characteristics), but different ρ_f are represented: it is clearly shown that an increase in fibers percentage leads to increased shear strengths. This permits to reduce the amount of transverse reinforcement in the joint region, hence limiting steel congestion in joints.

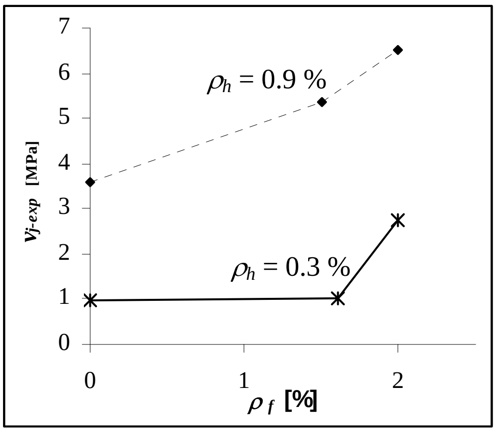

Figure 1: Experimental shear strength depending on ρ_h and ρ_f

In this paper a new expression for predicting the shear strength of FRC joints has been proposed. It takes into account the contribution of the fibers together with the transverse reinforcement one.

This expression has been compared with the outcomes from the experiments on 37 FRC joints subjected to earthquake loading, and with others expressions provided by Codes and authors. It has results that the here proposed expression (from it a design formula has been also obtained) leads to the lowest COV, even 40% lower than previous expressions (Table 1).

Table 1: AVG and COV values of experimental to calculated shear strength ratios

Authors	AVG	COV
Jiuru et al. (1992)	0,62	0,76
Attaalla (2004)	0,83	0,59
Hegger et al. (2004)	0,77	0,58
Proposed expression	**1,00**	**0,46**

Codes	AVG	COV
NZS (1995)	1,19	0,61
ACI 318M-05	0,63	0,52
Proposed design formula	**1,20**	**0,46**

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