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EVALUATION THE SHEAR STRENGTH OF FIBROUS REACTIVE POWDER CONCRETE BEAMS STRENGTHENED WITH CFRP STRIPS

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Abstract

A new expression for estimating the ultimate shear strength of steel fibers reinforced high strength concrete **(SFRHSC)** beams strengthened with **CFRP** strips based on previous researches is proposed in this research. The proposed expression covers different characteristics and principal parameters such as concrete compressive strength, shear span to effective depth ratio, volume fraction of steel fibers, **CFRP** amount and distribution, **CFRP** stiffness, deep beam effect, as well as the end anchorage state of the **CFRP** strips with the beam. A comparison between computed values and experimentally observed values (with a low COV of about 3.58 %) shows the validation of the proposed theoretical treatment.

Keywords: High Strength Concrete, Steel Fiber, Reactive Powder Concrete, CFRP Strips, End Anchorage Effect, Deep Beam Effect.

حساب مقاومة القص لأعتاب خرسانة المساحيق الفعالة المقواة بأشرطة الياف الكاربون

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الخلاصة

تعبير رياضي جديد لتخمين مقاومة القص القصوى للأعتاب الخرسانية المسلحة عالية المقاومة والمسلحة بألياف الحديد والمقواة بأشرطة الياف الكاربون البوليمرية وبالاعتماد على البحوث السابقة تم تقديمه في هذه الدراسة. التعبير المقترح يغطي خصائص و متغيرات اساسية مختلفة مثل مقاومة انضغاط الخرسانة، نسبة فضاء القص الى العمق الفعال، حجم الياف الحديد في الخلطة، كمية وتوزيع اشرطة الياف الكاربون البوليمرية، صلادة اشرطة الياف الكاربون البوليمرية، تأثير العتب العميق، اضافة الى حالة تثبيت النهايات لاشرطة الياف الكاربون البوليمرية مع العتب. مقارنة بين قيم نتائج التعبير الرياضي الجديد و القيم المحصلة مختبرياً (وبمعامل تغير واطيء مقداره 3.58%)تُبين امكانية استخدام التعبير النظري المقترح.

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1.Introduction

Jungwirth (2002), showed that metallic fibers have a significant role in improving flexural and tensile resistance of concrete by carrying the load well after first cracking. **Gao et al. (2005),** showed that the steel fibers are important to control the crack extension and to improve the ductility of RPC beams. It was concluded that for RPC beams without reinforcement, only one main crack occurred during the failure process, and for RPC beams with reinforcement there were many subordinate cracks created near the main cracks, and if the amount of reinforcement is increased, the number of subordinate cracks will also increase. **Voo et al. (2006),** showed that the quantity and type of fibers in the concrete mix did not significantly affect the initial shear cracking load of the fibrous RPC prestressed girders without stirrups, while increasing the volume of fibers leads to an increase in the failure load. **Ridha (2010),** showed that the amount of fibers in RPC mixture did not significantly affect the shear cracking load but did have an influence on the rate of crack growth and on crack width. Fibers also changed the mode of failure to a more ductile one, instead of the catastrophic type of failure for nonfibrous RPC beams. **Narayanan and Darwish (1987)**, concluded that, based upon the use of crimped steel fibers as web reinforcement, there was a steady rate of increase in ultimate shear strength when higher strength concretes were used. They found that there is an increase in shear strength of fiber concrete beams when smaller a/d ratios are used, also when the fiber factor is increased from 0.5 to a little over 1.0, a steady increase in the shear stress is observed with the increase in main steel ratio. They also concluded that the effectiveness of dowel resistance increases with an increase in the fiber factor (F). This indicated that the presence of fibers improves the tensile strength of concrete in the splitting plane along the reinforcement. **Kani (1964),** reported that in the region of low values of shear span to depth ratio (a/d), the shear capacity of the structure is determined by the strength of remaining tied arch (arch action), whereas in the region with medium value of a/d, the capacity of teeth of cracked concrete determines the shear capacity of the beams (beam action). **Sarsam and Al-Musawi (1992),** concluded that, the HSC beams are likely to be more slender than NSC beams. **Oh and Shin (2008),** concluded that, at a lower a/d ratio, deep beams with high strength concrete (without steel fibers) fail abruptly without any warning, which could be seen in deep beams with normal-strength concrete. The concrete strength has a significant effect on the ultimate shear strength. Addition of horizontal shear reinforcement does not improve the ultimate shear strength with decreasing (a/d) ratio in a deep beams of high strength concrete. **Madan et al (2007),** found that inclusion of short steel fibers in the concrete mix provides effective shear reinforcement in deep beams and provides better crack control and deformation characteristic of the beams. They supported the idea of using steel fibers as an alternative to conventional web reinforcement in deep beams. **Al-Delfi (2013),** concluded that the effect of steel fibers on capacity of HSFRC deep beams can be accounted for by multiplication of the concrete shear strength part (V_c) by the term ($1+0.4F$) where (F) is the steel fiber factor. The present study concerns with derivation a new expression for estimation the shear strength of SFRHSC beams strengthened for shear with U-wrapping CFRP strips instead of the conventional steel stirrups, as well as compared the theoretical results with an experimental strengths to confirms validation of the proposed expression. Effects of many parameters such as (a/d) and the deep beam effect, compressive strength of SFRHSC, the steel fiber factor, longitudinal reinforcement ratio, CFRP amount and distribution, and the anchorage of the ends for the CFRP strips are included in the proposed expression.

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2. Shear Strengthening of Beams Using FRP

The strains in the stirrups and the FRP are different even at the same locations. This is because a stirrup stretches evenly over its length while the FRP strip, which is adhered to concrete, stretches over a limited area across the shear crack **[Uji (1992)]. Taerwe et al. (1997),** concluded that the position and the distribution of the FRP plays important roles on the shear strengthening of beams. **Izzet (2008),** concluded that the end anchor system proved its effectiveness in carrying the applied shear force whether the **CFRP** strips were bonded or not to the beam sides. The CFRP strain (and, therefore, resistance to loading) only starts after diagonal cracking. Also the use of CFRP is significantly influenced by the spacing of the strips and the shear span-to-depth ratio (a/d). FRP is only effective in a limited area within the effective development length, while outside this area, it has no influence to shear**[Maeda et al. (1997)].**

3. Experimental Work

In the work of **Al-Habbobi (2014),** nine shear tests of SFRHSC beams without steel stirrups and strengthened with CFRP strips are reported. Beams were designed to have extra strength in flexure to ensure shear failure. The beam details are presented in **Figure 1 and Table 1.**

For all beam specimens, the cross section was 100 mm wide and 180 mm in depth. The overall length was 1250 mm, with clear span 1150 mm. The longitudinal reinforcement ratio (ρ_w), shear span to effective depth ratio (a/d) and the deep beam effect, CFRP amount and distribution were varied. Method of anchorage CFRP strips also changed.

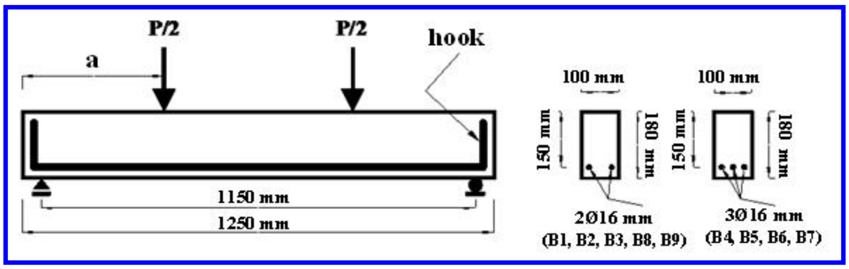

Fig.1: Details of Typical Tested Beams [Al-Habbobi 2014].

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Table 1: Details of the reinforcement and U-wrap strips [Al-Habbobi 2014].

Beams	a/d	Reinforcement amount	ρ_w	CFRP Width (mm)	CFRP Spacing (mm)	CFRP ends anchorage status
B1	2.5	2Ø16 mm	0.0268	**….**	**….**	**….**
B2	1.5	2Ø16 mm	0.0268	40	100	Anchored
B3	1.5	2Ø16 mm	0.0268	75	200	Anchored
B4	3	3Ø16 mm	0.0402	75	200	Anchored
B5	3	3Ø16 mm	0.0402	40	100	Anchored
B6	3	3Ø16 mm	0.0402	75	200	Without
B7	3	3Ø16 mm	0.0402	40	100	Without
B8	1.5	2Ø16 mm	0.0268	75	200	Without
B9	1.5	2Ø16 mm	0.0268	40	100	Without

Only the first specimen (B1) was kept without strengthening as control specimen, whereas the other eight beam specimens were strengthened with externally applied CFRP strips with or without end anchorage. The following different schemes illustrate the technique of this strengthening as shown in **Figures 2 to 5**. The strengthened beams were divided into two groups according to the anchorage of the CFRP strip end or not, and these groups were subdivided into two subgroups according to shear span to effective depth ratio, namely : a/d =1.5 (deep beam) and 3, the longitudinal reinforcement ratio (ρ_w) and the amount and distribution of the CFRP strips.

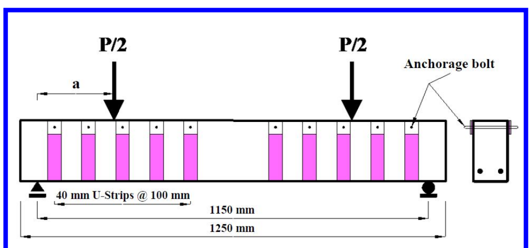

Fig. 2: Shear Strengthening with End Anchoring B2 and B5 [Al-Habbobi

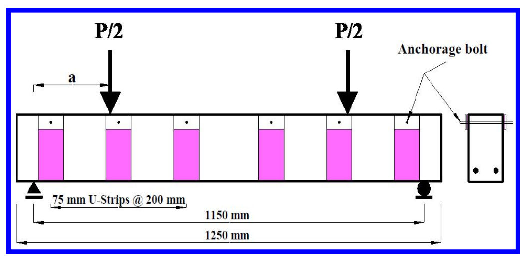

Fig. 3; Shear Strengthening with End Anchoring B3 and B4 [Al-Habbobi 2014],

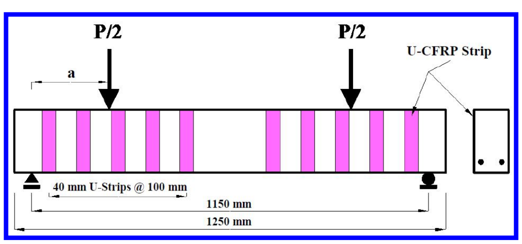

Fig. 4: Shear Strengthening without End Anchoring B7 and B9 [Al-Habbobi 2014].

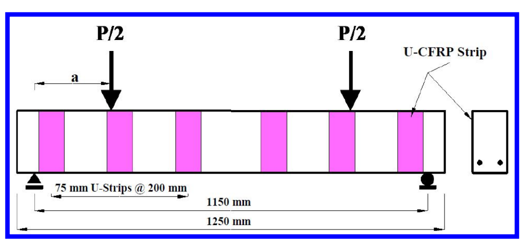

Fig. 5:Shear Strengthening without End Anchoring B6 and B8 [Al-Habbobi 2014].

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4. Proposed Expressions for Shear Capacity of SFRHSC Beams

Several empirical equations are available in the literature to predict the shear capacity of high strength steel fiber reinforced concrete beams. **Ridha (2010),** proposed an expression for shear capacity of RPC beams reinforced with steel fibers. Depending on the well known ACI-Code provision for shear capacity with adding the effect of steel fibers to the proposed expression.

The shear force V of SFRHSC Beams (without CFRP contribution) may be resisted by [1] the shearing forces across the compression zone, V_{cz} which sum up to; [2] the transverse force induced in the main flexural reinforcement by dowel action V_d; [3] vertical component V_{fi} of the steel fiber pullout forces along the inclined crack as shown in **Figure 6 [Fenwick and Paulay (1968)]**. Since the individual contribution from each of internal shear components V_{cz} and V_d are difficult to estimate, they are commonly lumped together and denoted by the term V_c, the contribution of the concrete thus;

$V = Vc + V_{fi}$ ……………………………………..………eq.(1)

The shear stress (v) was obtained by dividing the shear strength (V) by ($b_w d$). However, one of the proposed expressions for the steel fiber contribution was **[Ridha (2010)]**:

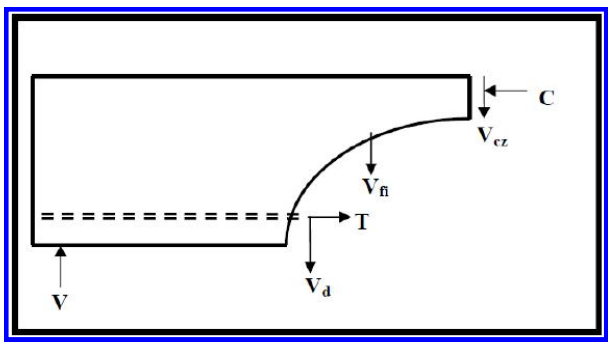

Fig. 6 : Free Body Diagram of Part of the Shear Span of a Simply Supported SFRHSC Beam [Fenwick and Paulay (1968)].

$v_{fi} = 2.82\left(f'_{cf}\,F\right)^{0.418}/(a/d)$ …………………………eq.(2)

Where:
v_{fi} :The shear stress carried by steel fiber reinforcement.
f'_{cf} : compressive strength for fiber reinforced concrete.
a/d :shear span to effective depth ratio
F :fiber factor, given by:

$F=(L_f/D_f)V_f\,B_f$ ……………………..……………..…. eq.(3)

Where: B_f is the bond factor that accounts for bond characteristics of the fibers. Based on a large series of pullout tests by **Narayanan and Kareem Palanjian (1986),** B_f was assigned a relative value of 0.5 for round fibers, 0.75 for crimped fibers, and 1.0 for indented fibers.

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After this stage, the proposed expression for predicting v_{fi}, [Eq.(2)], will be added to the expression of v_c of the reinforced concrete beams given by **ACI-Code (2008),** stated as following :

$$v_c = 0.16\sqrt{f'_{cf}} + 17\rho_w \, {}^{d}/_{a} \text{ ....eq.(4)}$$

Where ρ_w : longitudinal reinforcement ratio.

5. Evaluation of FRP Contribution to Shear Strength capacity

Based on the observations **Khalifa et al. (1999)** rewrote the ACI expression for computing the FRP contribution to the shear capacity of an RC beam, V_f as:

$$V_f = \frac{A_f f_{fe}(\sin\beta + \cos\beta) d_f}{s_f} \text{ ....eq.(5)}$$

Where:

$A_f = 2t_f w_f$ area of CFRP shear reinforcement.

β = is the angle between principal fiber orientation and longitudinal axis of the beam.
d_f = effective depth of FRP reinforcement.
f_{fe} = FRP effective average stress calculated as:

$$f_{fe} = R\, f_{fu} \text{ ....eq.(6)}$$

Where:

f_{fu} = FRP ultimate stress.

R = stress reduction coefficient, computed as **[Khalifa et al. (1999)]:**

$$R = 0.56(\rho_{FRP} E_{FRP})^2 - 1.22(\rho_{FRP} E_{FRP}) + 0.78 \text{..........eq.(7)}$$

For the Reduction coefficient R, based on CFRP debonding failure, **Khalifa et al. (1999)** used some experimental considerations:

6. Effective Bond Length and Ultimate Load Capacity

Miller (1999) showed that the effective bond length increases as CFRP stiffness ($t_f . E_{FRP}$) increases. However, he suggested a conservative value for L_e equal to 75mm. His experimental results indicated that the bond stress at failure is a function of the CFRP stiffness and the average bond strength, τ_{bu} may be computed from the following Eq.(8):

$$\tau_{bu} = \left[119.06\left(t_f . E_{FRP}\right) - 0.654\left(t_f . E_{FRP}\right)^2\right] \times 10^{-6} \text{ ....eq.(8)}$$

where, τ_{bu} is the average bond stress in GPa, t_f is the thickness of the CFRP strip in mm. Finally, considering an active bonded area equal to the effective bond length L_e times the width of the bonded strip w_f, the ultimate load capacity of the CFRP strips P_{max} may be computed from Eq.(9):

$$P_{max} = L_e . w_f . \tau_{bu} \text{ ....eq.(9)}$$

Where, Eq.(9) is applicable for CFRP stiffness $t_f . E_{FRP}$ ranging from 20 to 90.

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7. Effect of Concrete Strength

Horiguchi and Saeki (1997) showed that the bond strength between the CFRP strip and the concrete surface is a function of $(f'_c)^{2/3}$. So they suggested that Eq.(8) may be modified by multiplying by $(f'_c/42)^{2/3}$, where f'_c in MPa.

8. Effect of Bonded Surface Configuration.

Khalifa et al. (1999) suggested to replace the width of the FRP strip w_f with an effective width w_{fe} in Eq.(9) for the strip is in the form of a U-wrap without end anchor.

Zheng et al. (2005) modified Khalifa's equation for calculating the stress- reduction coefficient by using the same way Khalifa has used to derive this expression in his design approach but with defining the failure mode of the CFRP strips:

(For rupture failure mode)

$R = -2.3156(\rho_{FRP}E_{FRP})^2 + 1.5098\,(\rho_{FRP}E_{FRP}) + 0.3505$ ……eq.(10)

(For debonding mode)

$R = 0.1466(\rho_{FRP}E_{FRP})^{-0.8193}$ ………..………………………..eq.(11)

Where:

ρ_{FRP} : is the FRP area fraction and equal to $(2t_f/b_w)(w_f/S_f)$.

E_{FRP} : is the elastic modulus of FRP.

Effect of the end anchorage of the CFRP strips to the shear capacity of the beams can be theoretically estimated. However, the presence of the end anchorage increases the effective bond length (L_e) of the CFRP strips which are included in the calculations. The effective length of CFRP L_e=75mm. In case of presence of the end anchorage the effective length may be taken as the overall fixed length of **CFRP [Izzet (2008)].**

9. Proposed Expression of the Shear Capacity for The SFRHSC Beams Strengthened in Shear With CFRP Strips

By following the previous works, one can conclude the following equation to estimate the shear capacity of the SFRHSC beams strengthened in shear with CFRP strips tested in the present work. If one makes a superposition for the equation of estimation the SFRHSC beam shear capacity the Eq.(4) after adding the effect of the steel fibers from Eq.(2), and after the result being multiplied by (b_w.d), with the equation of evaluation the CFRP contributions the Eq.(5), as the following main expression:

$V_{theo} = 0.85\ V_{HSFRC} + 0.7\ V_f$ ……………………………….………..eq.(12)

Where:

$V_{HSFRC} = \{v_C\ [Eq.(4)] + v_{Fi}\ [Eq.(2)]\}.b_w.d$ …………………………eq.(13)

V_f : contribution of the CFRP strips to the shear strength of the beams calculated using Eq.(5).

The constants 0.85 and 0.7 are the reduction factor for the shear strength contributions of the SFRHSC and the CFRP respectively [Izzet (2008)].

The calculated results are compared with experimental results as illustrated in Table 2. The average value of (V_{exp}/V_{theo}) = 1.0125 and standard deviation SD = 0.0363 producing COV = 3.58%. The small value of the COV illustrates acceptability of the proposed expression.

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10. Evaluation of the Proposed Expression

The accuracy of the present proposed expression [Eq.(12)] can be examined through a comparison with the experimental tests based on the results tabulated in **Table 2.**

Table 2: Results of the Proposed Equations of the Shear Strength of SFRHSC Beams Strengthened with CFRP Strips [Al-Habbobi 2014].

Beam No.	V_{exp} (kN)	L_e (mm)	P_{max} (kN)	R	V_{fcalc} (kN)	V_f (kN)	V_{HSFRC} (kN)	V_{theo} (kN)	$(\frac{V_{exp}}{V_{theo}})$%
B2	202.5	165	36.92	0.579	38.84	36.92	196.46	192.8	1.05
B3	185	165	62.9	0.573	36.03	36.03	185	182.5	1.01
B4	125	165	65.69	0.573	36.03	36.03	108.2	117.2	1.07
B5	115	165	34.94	0.579	38.84	34.94	108	116.3	0.99
B6	112.5	75	32.1	0.499	31.38	31.38	113.1	118.1	0.95
B7	107.5	75	16.27	0.473	31.73	16.27	109.7	104.6	1.03
B8	180	75	30.3	0.499	31.38	30.3	191.9	184.3	0.98
B9	178	75	16.17	0.473	31.73	16.17	191.9	174.4	1.02
								$\overline{m}$	1.0125
								SD	0.0363
								COV	3.58%

11. Comparison with Experimental Results

From **Figure 7**, it can be seen that proposed [Eq.(12)] gives satisfactory predictions for shear strength capacity of the SFRHSC beams strengthened with U-wrapping CFRP strips as illustrated through the value of the relative shear strength ($V_{test}/V_{proposed}$) based on the present proposed expression **[Al-Habbobi 2014].**

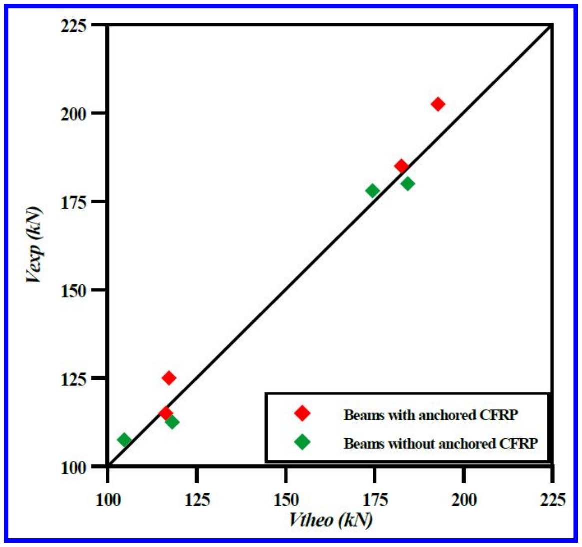

Fig. 7: Experimental versus Predicted Values of the Shear Strength Capacity [Al-Habbobi 2014].

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12. Influence of Major Parameters

The proposed expression is simultaneously conservative for all tests $(V_{exp.}/V_{theo.} \approx 1)$ with relatively low COV value. Thus, for all tested beams the ratio $(V_{exp.}/V_{theo.})$ is plotted against the four major parameters f'_{cf}, ρ_w, a/d and ρ_{FRP}. **Figure 8** reveals that V_{theo} predicted by the proposed Eq.(12) is slightly less than V_{exp} observed experimentally for the majority of the beams tested in this work. However, varying parameters results a difference between V_{exp} and V_{theo} for the strengthened SFRHSC beams not exceeding 7%. Therefore, Eq.(12) can safely be used in design and analysis within the ranges of the parameters values **[Al-Habbobi 2014].**

13. Deep Beam Effect

If the deep beam effect includes for beams B2, B3, B8 and B9 through multiplying the contribution of SFRHSC V_{HSFRC} by the factor $(1+0.4F)$, a theoretical shear capacity may be concluded at about 235, 223, 226 and 216 kN respectively with a ratio (V_{exp}/V_{theo}) about 86.2%, 82.9%, 79.6% and 82.4 respectively.

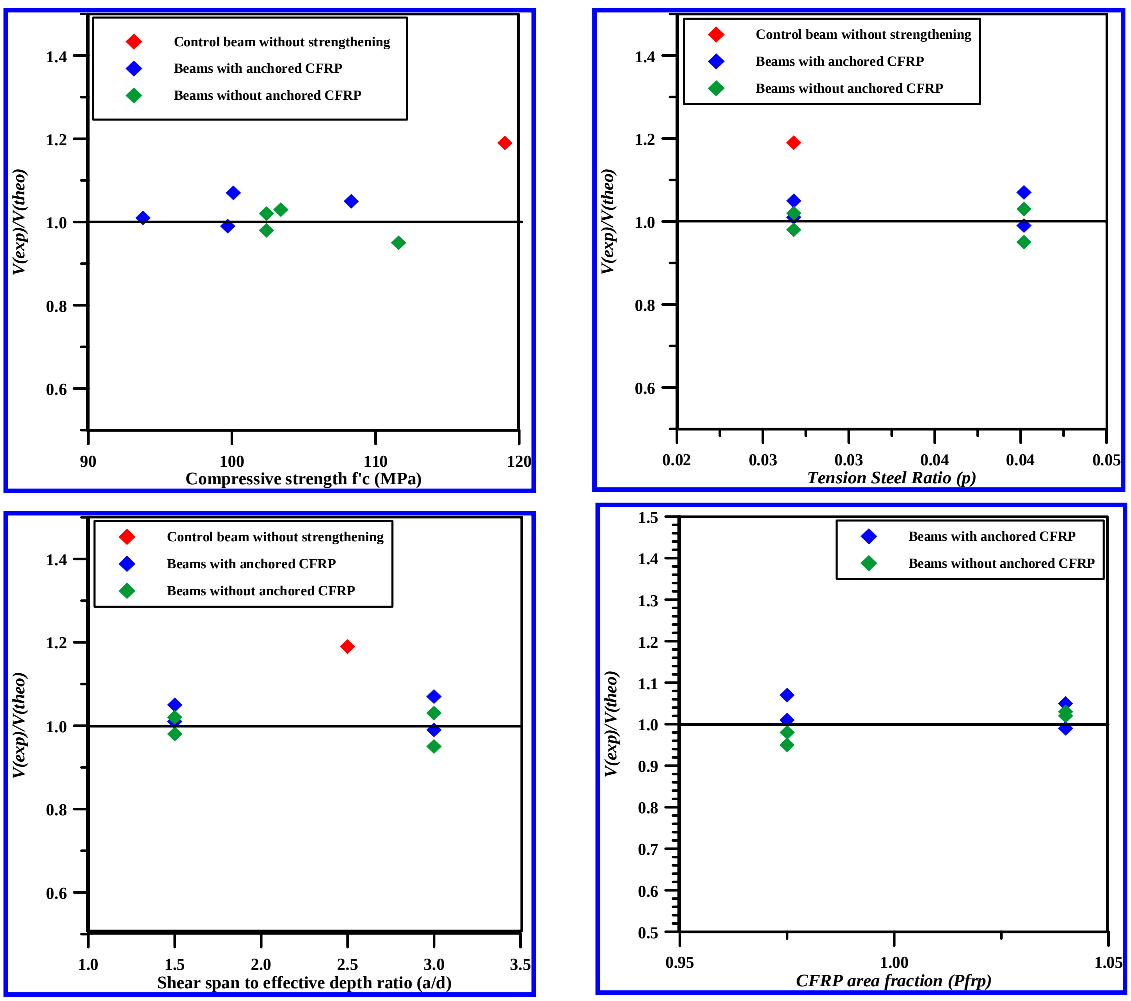

Fig. 8: The Ratio (Vexp/Vtheo) Versus Different Factors (f'_{cf}, ρ_w, a/d and ρ_{FRP}) Respectively [Al-Habbobi 2014]

14- Conclusions

1. Comparisons with experimental data indicate that the proposed expression properly estimates the shear strength of SFRHSC beams strengthened in shear with CFRP strips. This expression can be applied for a wide range of specimens with varying compressive strength (f'_c), shear span to effective depth ratio (a/d), steel fiber factor (F), longitudinal reinforcement ratio (ρ_w), and the U-wrapping CFRP strengthening with different width, spacing, stiffness and thickness of strips, with and without the effect of end anchorage. The proposed expression, [Eq.(12)] have a low COV value about 3.58% for the ratio (V_{exp}/V_{theo}).
2. Deviancy of the theoretical results when including the deep beam effect from the experimental results leads to support the idea states that SFRHSC deep beam tend to be slender in its behavior.

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