Shear Strengthening Reinforced Concrete Beams with Externally bonded Fiber-Reinforced Polymer: Updated Data Base

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Abstract: - This paper deals with the shear strengthening of reinforced concrete (RC) beams with externally bonded fiber reinforced polymer (EBFRP) composite. Its objectives are to update the existing data base related to the shear strengthening of RC beams with EBFRP from the published literature. Investigate the different parameters that affect the shear strength of EBFRP reinforced concrete beams and capture better interaction among various influencing parameters. About seven hundred tests of beams with EBFRP were collected from the published literature and tabulated in an updated database. The interactions among the parameters related to the type and properties of the FRP, fiber orientation as well as the strengthening scheme, the shear and the longitudinal steel reinforcement ratios, the shear span ratio, and the geometry of the member that influence the shear behavior of these members are investigated. As a result of this investigation the collected database is refined and the existing design model (*ACI 440.2R-08)* is reviewed and conclusions are drawn.

Key-Words: - beam; FRP; reinforced concrete; shear; strength.

1 Introduction

As The tremendous studies in recent years that have been directed toward understanding the behavior of concrete structures strengthened with externally bonded fiber-reinforced polymer (EBFRP) have resulted in valuable findings that incorporated into various national design guidelines such as ACI 440.2R-08, 2008, Canadian CSA-S806-02, 2002, and European *fib-TG9.3, 2001,* Bulletin14, 2001; CNR-DT 200/2004, 2004. However and despite of this large number of research studies for EBFRP members strengthened in shear, the theoretical calculations using the developed models and the experimental results are not in a good agreement and scarce and sometimes controversial. The behavior of strengthened RC members in shear is complicated and affected by several interacting parameters such as, type and properties of the FRP, fiber orientation as well as the strengthening scheme, the strength and composition of the concrete, the shear and the longitudinal steel reinforcement ratios, member geometry and size, the shear span ratio, the type of applied loading, and FRP linear behavior in tension up to failure versus concrete and steel nonlinear behavior. Also, the complexity of the RC shear problem is increased by the addition of FRP composite strengthening materials that introduces a new set of variables related to the FRP composite, properties, behavior, systems and configurations. The aim of the research presented in this papers is to better understand the behavior in shear of EBFRP reinforced concrete beams. To achieve this aim three individual objectives are defined as follows: a) to update the existing data bases related to the shear strengthening of RC beams with EBFRP from the published literature, b) to bring together the most used existing models and investigate the different parameters that affect the shear strength of EBFRP reinforced concrete beams, c) to Develop using MRA models that predict the shear strength of beams with EBFRP and capture better interaction among various influencing parameters.

2 Research Significance

The extensive experimental studies on EBFRP shear strengthened beams that have been carried out during the last three decades and focused on exploring the effectiveness of EBFRP shear strengthening systems and configurations, have provided interesting findings and conclusions with regard to the effect of the aforementioned parameters. But, the observed relatively large scatter between the theoretical models and the experimental results indicates that other parameters that may influence the EBFRP shear resistance are not yet captured and many parameters interactions are still not fully discovered.

The complexity of shear behavior of RC beams is quite high and is further increased in the presence of FRP strengthening systems. This paper attempts to identify and assess the most important factors that influence the shear failure of EBFRP strengthened RC beams by compiling and analyzing previously reported experimental data in the literature. These data are compiled in an updated database described herein.

3 Database of experimental result

Numerous experimental studies have been conducted on EBFRP RC beams strengthened in shear. The previously published databases presented by Triantafillou and Antonopoulos [6], Bousselham & Chaallal [3], Chen [4], Gabriel [5] among others have been updated, enriched and cross checked for completeness, redundancy and consistency, (refer to Table 2). The new database was subsequently updated and now contains data on 698 EBFRP RC beams and covers the time span from 1990 to 2016.

The upgraded database gathers all key variables that are known to have significant influence on the shear behavior of EBFRP RC beams such as: (i) the concrete strength, (ii) the shear and the tensile steel reinforcement ratios, (iii) the shear span to depth ratio (*a/d*), (iv) the cross section geometry and size, (v) the geometric, elastic and mechanical properties of the FRP and the strengthening configurations. In addition to this the mode of failure, load at failure V_{total}, and the contribution of the FRP to the shear resistance V_f are also reported.

The upgraded database contains information on 698 experimental tests. The span length (L) of the tested beams is distributed as follows: 256 (37%) are with (L<2 m), 325 (47%) are with (2 m < L< 4m), and 81 (12 %) are with (L> 4m); no dimensions are specified for the remaining 36 beams (5%). The majority of the tested beams 524(75%) are of rectangular (R) cross-sections; the remaining 174 (25%) are of (T) cross-sections which are more widely used in practice. The information on concrete compressive strength (f'_c) of the tested EBFRP strengthened RC beams covers a wide range. 24% of beams has f'_c < 25 MPa, 68% has 25<f'_c<50, and 8% has f'_c>50 MPa. When needed the concrete tensile strength (f_{ct}) and modulus of elasticity (E_c) are obtained from the relevant specification in the (ACI-11). About 75% of the data came from studies examining strong EBFRP RC beams with (f'_c>25MPa) to simulate the strengthening of relatively new structures The rest of the data (25%) came from studies using relatively weak concrete to simulate the rehabilitation of old structures.

The shear response of RC beam is closely related to the shear span to depth ratio (a/d). 30% of beams (208) are deep beams (a/d ≤ 2.5), 69% (482) are with (a/d > 2.5); no (a/d) values are reported for the rest 1% (8) of beams. 52% of beams (363) are with shear reinforcement. Of them 107 beams are deep beams (a/d ≤ 2.5) and 256 are regular beams. Of the 335 beams in the database that did not have shear reinforcement, 101 are deep beams and 234 regular beams. 96% of beams have tensile reinforcement. As shown in Fig.1, the types of fibers used for strengthening the EBFRP RC beams are Carbon FRP 85% (596), Glass FRP 11% (74) and Aramid FRP 4% (28). 320 of beams in the database are U wrapped, 207 Side (S) bonded, 135 W wrapped, 35 anchored U+ wrapped, and 1 anchored W+ wrapped (see Fig.2).

583 of beams in the database, the FRP is applied with 90° angle to longitudinal axis, 101 beams with 45°, and 14 beams with different angles. The tests database has limited experimental data on the behavior of pre-damaged RC beams strengthened in shear with the EBFRP.

The database has information on data regarding beams that failed by diagonal shear cracking, beams that failed in flexure (FL) and beams for which no failure mode was reported (NA). Only, two modes of failure of the tested EBFRP beams related to the bond behavior at the concrete/FRP interface are considered. These modes are the debonding (DB) and rupture (RT) of the FRP composite at ultimate load. Of the beams in the database, DB failure occurred in 364 beams and RT failure in 201 beams, the rest failed in different modes.

4 Refinement of the database

Since the focus of this work is to study the shear behavior of EBFRO RC beams, the database is refined by applying certain filters in order to have the most relevant information. Specifically:

1. Size of cross-section: Previous studies have showed that, to develop the bond resistance of the FRP composites, a minimum length of about 200mm is required. Therefore, data on beams with a height h<200mm are not included in the refined database.
2. Shear gain: Data on EBFRP strengthened beams that did not gain an increase in their shear capacities by more than 10% relative to the reference beams are also removed from the database. This is done to exclude the possibility that theses beams have failed due to other unseen factors not related to the use of FRP
3. Failure mode: Data on beams that failed in mode different than diagonal shear cracking (DB or RT) are disregarded.

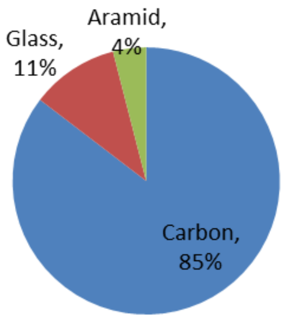

Fig.1. Distribution of Type of Fibers used in EB FRP Beams

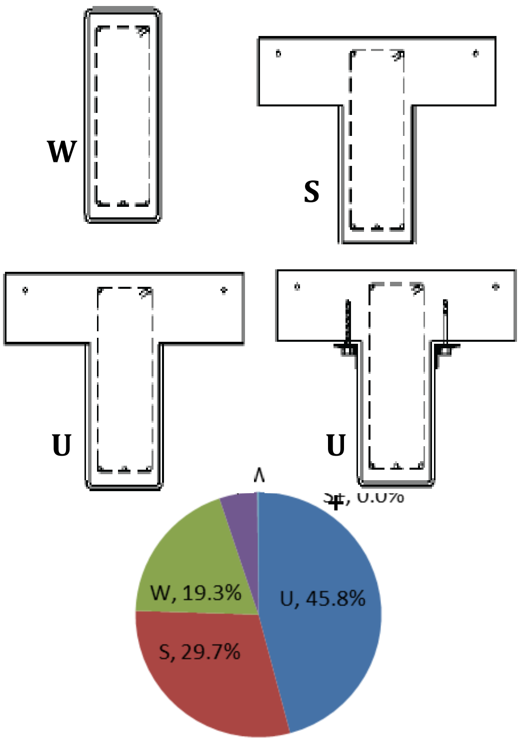

Fig.2. Shear Strengthening of EBFRP Beams: a) Configurations b) Distribution

After applying these filters, 152, 49, and 25 are removed from the database based on the first, second and third criterion, respectively. Data on 472 different beams remained for analysis in the refined database. Table 1 presents the distributions of the remaining database based on different criteria.

Table 1 Distributions of Various parameters in the refined Database

Span Length (m)	L<2	2<L<4	L>4	NA
	39%	48%	15%	5%
shear span depth ratio	a/d ≤ 2.5	a/d > 2.5	NA	
	27%	72%	2%	
Section height (mm)	h =200	h>200		
	8%	92%		
Section Shape	R	T		
	80%	20%		
Concrete Strength (MPa)	*f'c*<25	25<*f'c*<55	*f'c* >55	
	22%	71%	7%	
Shear Stirrups	a/d≤ 2.5 and stirrups	a/d≤ 2.5 and no stirrups	a/d> 2.5 and stirrups	a/d> 2.5 and no stirrups
	13%	13%	35%	37%
FRP Configuration	U	S	W	U+
	44%	23%	23%	5%
FRP Type	Carbon	Glass	Aramid	
	86%	10%	4%	
Shear Crack Angle	90°	45°	other	
	86%	12%	2%	
Failure Mode	DB	RT		
	63%	37%		

5 The ACI Shear Design Model

All of the design models rely on the approach where shear strength of a strengthened member is attained by the sum of the contributions from the concrete, V_c, reinforcing steel, V_s, and FRP, V_f. In ACI-318 and ACI 440, the total shear strength can be calculated as:

$$V_n = V_c + V_s + V_f \quad (1)$$

$$V_c = 0.17\sqrt{f_c'}\, b_w d \quad (2)$$

$$V_s = \frac{A_{sw} f_y}{s}(\sin\alpha + \cos\alpha)d \quad (3)$$

Where, fc' is the specified concrete compressive strength, b_w and d are the width of the web and its effective depth, respectively. A_{sw} = area of the stirrups, f_y = Yield stress of the stirrups, s = spacing of the stirrups and α = inclination of the stirrups.

$$V_f = \frac{A_{frp} \cdot f_{frp,e} \cdot (\cos\alpha + \sin\alpha) \cdot d_{frp}}{s_{frp}} \quad (4)$$

$$A_{frp} = 2 \cdot n \cdot t_{frp} \cdot w_{frp}$$

$$f_{frp,e} = \varepsilon_{frp,e} \cdot E_{frp}$$

$$\varepsilon_{frp,e} = \begin{cases} 0.004 \le 0.75\varepsilon_{frp,u} & \text{for full wrapping} \\ k_v \varepsilon_{frp,u} \le 0.004 & \text{for sideor U jacketing} \end{cases}$$

$$k_v = \frac{k_1 \cdot k_2 \cdot L_e}{11900 \cdot \varepsilon_{frp,u}} \le 0.75$$

$$L_e = \frac{23300}{(n \cdot t_{frp} \cdot E_{frp,u})^{0.58}} \qquad k_1 = \left(\frac{f_c}{27}\right)^{2/3}$$

$$k_2 = \begin{cases} \dfrac{d_{frp} - 2 \cdot L_e}{d_{frp}} & \text{for side bonding} \\ \dfrac{d_{frp} - L_e}{d_{frp}} & \text{for U jacketing} \end{cases}$$

Many studies revealed that the additive contribution models should be modified to account for the interaction among different parameters. For example the shear steel reinforcement and applied FRP contributions to the total shear strength are additive but interacting. This interaction might depend on different factors.

6 Analyses of Data

The analyses in this section are presented in terms of the shear force gain for different failure modes of the EBFRP strengthened beams. The shear force gain is defined as the ratio of the shear force increase due to the EBFRP composites and the shear force resisted by the reference unstrengthened beam.

The database will be analyzed in terms of the following parameters: a) the properties of the FRP composite; b) the influence of the FRP configuration (U-W-S-U+); c) the influence of the cross section (R-beams vs T-beams); d) the shear span to depth ratio *a/d*; e) the shear steel reinforcement ratio; f) the longitudinal steel reinforcement ratio; and g) the beam size effect.

Each of the parameters will be discussed in terms of the shear force gain for different failure modes (debonding versus fracture) of the EBFRP beams. The shear force gain is defined as the ratio of the shear force increase due to the EBFRP composites and the shear force resisted by the unstrengthened beam, (*Shear gain* = V_f / V_{total}).

6.1 The influence of the FRP Configuration (U-S-W-U+)

Fig.3 shows that the side bonded and U-wrapped configurations are more likely to fail by debonding, while the W-wrapped and U+ -wrapped by rupture. It is interesting to note that 63% of the tested beams failed by debonding and only 37% by fiber rupture.

The presence of the shear stirrups in the beams will affect the effective strain in fibers depending on the FRP configuration.

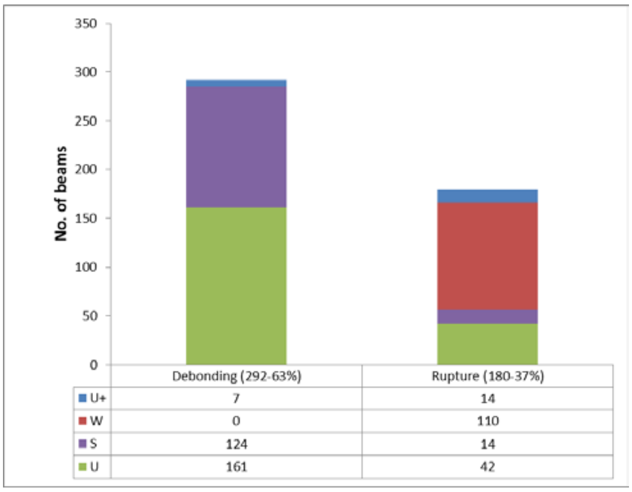

Fig.3 Modes of failure in beams using different FRP configurations

Fig.4 shows how the FRP strengthening systems influence the shear force gain in beams with and without stirrups. The efficiency of the strengthening configuration is different for beams with and without stirrups. As the $E_f\rho_f/fc^{2/3}$ ratio increases, the shear force gains decrease for all strengthening configurations, but at low $E_f\rho_f/fc^{2/3}$ ratios, the W-wrapped and U-wrapped beams performed better than S-bonded. The increases in the shear force capacities are more when FRPs are used on beams without stirrups (Fig.4b). However for the same type of FRP configuration, the scatter of the shear force gain versus the values of $E_f\rho_f/fc^{2/3}$ is quite large.

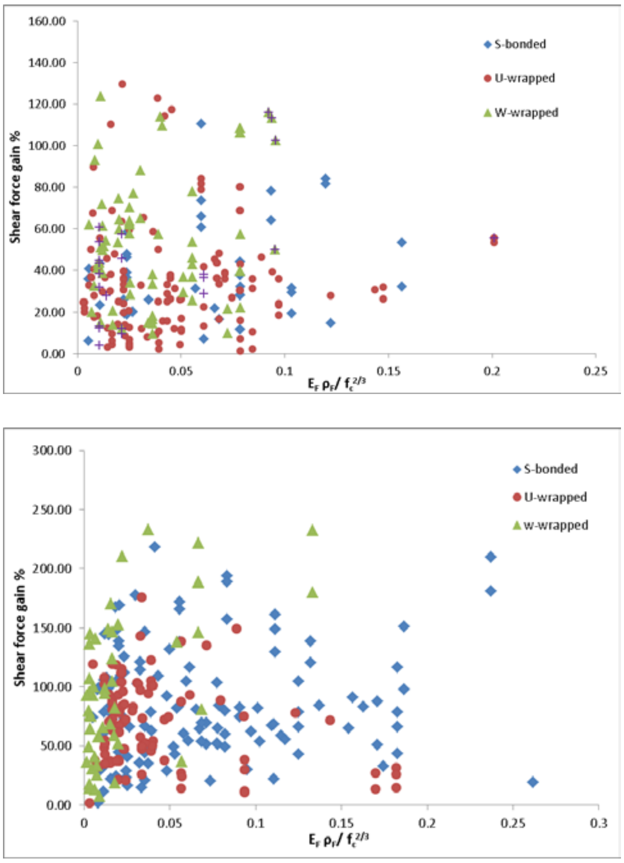

Fig.4 Shear force gain versus $E_f\rho_f/fc^{2/3}$ ration for different FRP configurations a) With stirrups, b) Without Stirrups

6.2 Influence of the cross section R-beams vs T-beams

The type of cross section (R or T) has a considerable effect on the gain of the shear of strengthened EBFRP beam. Fig.5 shows the shear force gain in R and T-section beams with and without stirrups, for debonding and rupture failure mode of the FRPs. It is clear that the shear force gain in R-beams is higher than that in T-beams for both failure modes.

6.3 The shear span to depth ratio (a/d)

Fig.6 presents the measured shear gain versus the shear span to depth ratio *a*/*d*. Beams with and without stirrups are considered separately. In general, for beams both with and without stirrups, the shear gain with the use of FRP increases with the *a*/*d* ratio until the latter reaches about 4.5; after this point, the gains are relatively small. It also seems that for deep beams (a/d ≤ 2.5) without and with stirrups, the predominant failure modes are debonding and rupture, respectively.

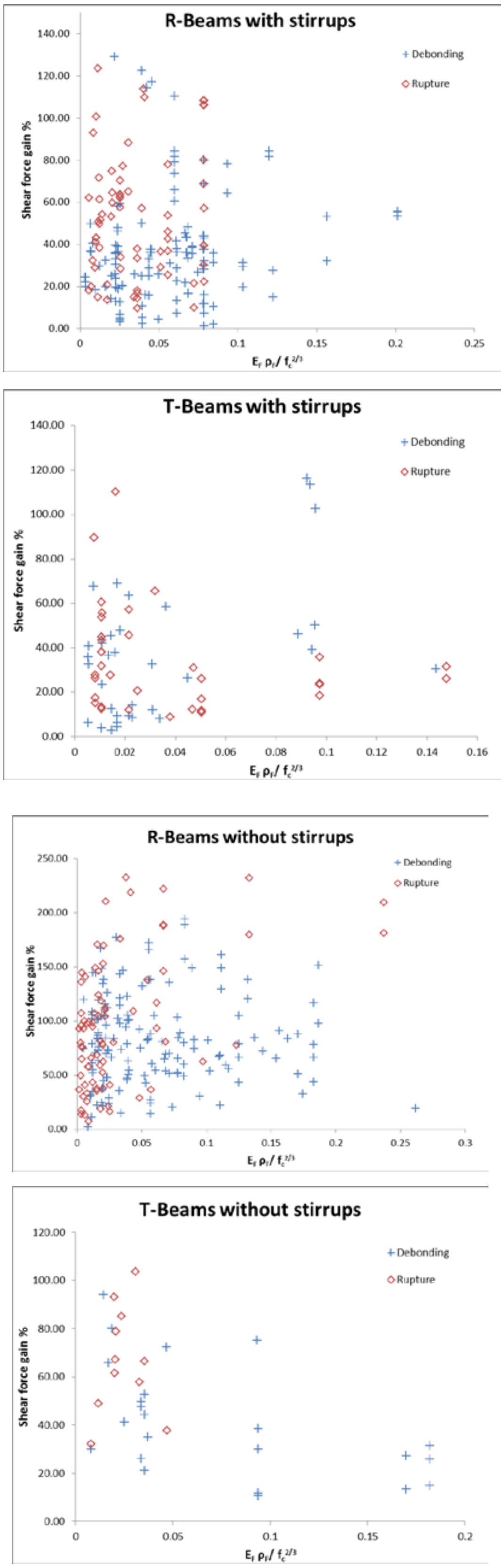

Fig.5 Shear force gain versus $E_f\rho_f/fc^{2/3}$ in beams with and without stirrups for different cross section types

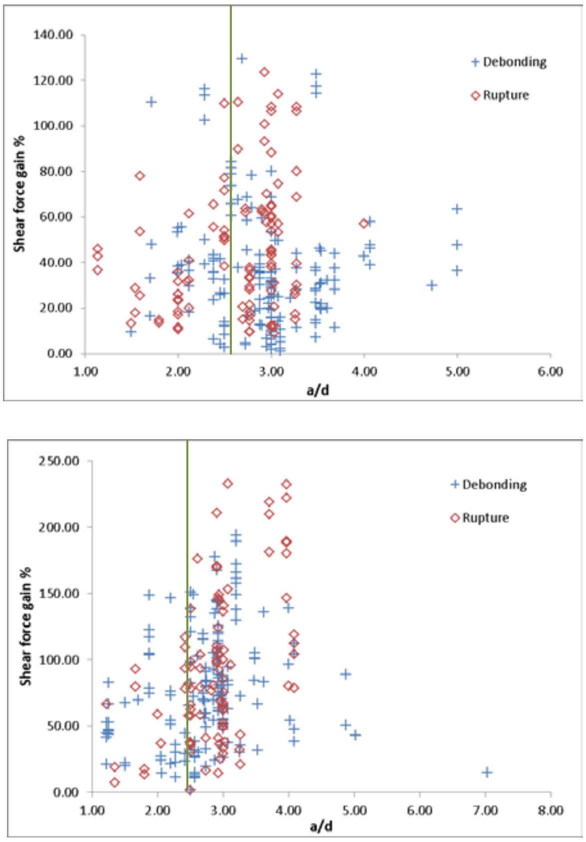

Fig.6 Shear force gain versus the shear span to depth ratio (a/d) for (a) beams with stirrups and (b) without stirrups

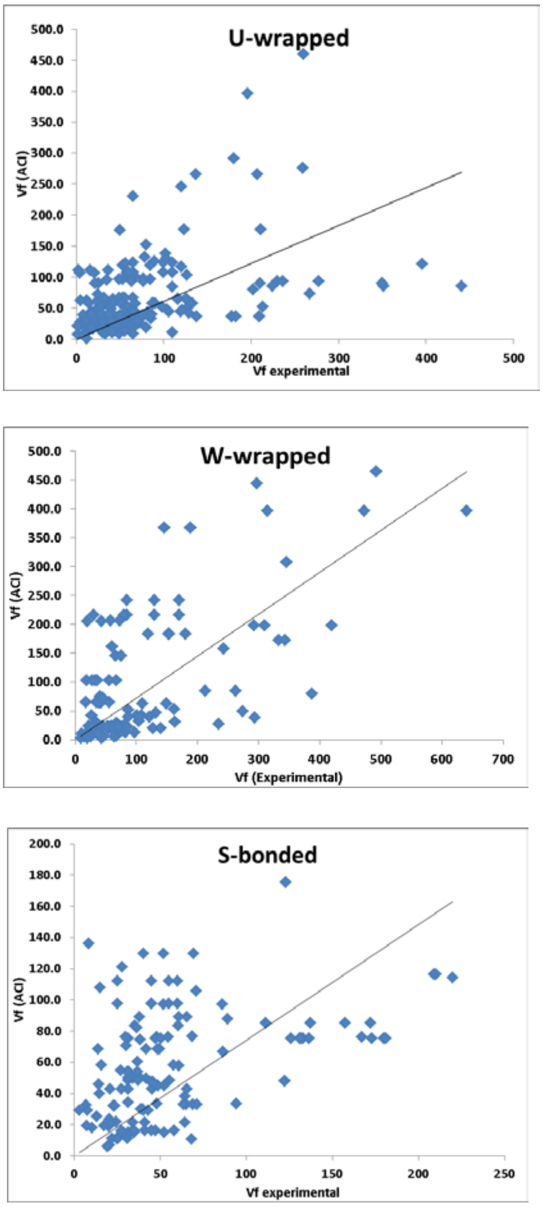

Fig.7 Predictions of the ACI design model for S-bonded, U-wrapped and W-wrapped EBFRP RC beams.

6.4 The predictions of the ACI model

The predictions of the ACI model are compared with the experimental results obtained from the refined database (472 data tests). The comparisons between the ACI predicted V_f and experimental FRP shear force (V_{exp}) are shown in Fig.7 for beams with different strengthening configurations. In general, the predictions of the ACI model are safe for the majority of the experimental values but with large scatters around the equality lines.

7 Conclusions

It is evident that a lot of research on the shear of EBFRP strengthened RC beams has been conducted and valuable data is available. Therefore, it is useful to compile all data in one database. This makes it easier to study and analyze the parameters that most influence the shear behavior of RC members strengthened with EBFRP. The initially compiled data base contained 698 tests, but in many cases, the data obtained from such tests are unreliable, and incomplete that led to a refined database with 472 tests. The analysis of this available data confirmed that the shear problem involves a number of parameters, which are related and interacting such as the properties of FRP and the existence of the internal shear reinforcement among others. It must be noted that the data was gathered from different experimental tests. It follows that the data analysis and the interpretation of the results should be handled with great caution. The ongoing investigations by the authors are aiming at reducing the scatter in the prediction of the ACI design models presented above (Equations 1 to 4) by analyzing the refined database.

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