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Contribution of CFRP to the shear strength of retrofitted lightly-reinforced concrete panels

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Abstract

Low-rise buildings with thin Reinforced Concrete (RC) walls that do not comply with the minimum web shear reinforcement prescribed by current earthquake-resistant codes can be found in some Latin American countries. Previous experimental studies evidence that Carbon Fiber Reinforced Polymers (CFRP) strips may be used to retrofit RC walls for shear forces. The two models available in the literature to predict the contribution of CFRP to the shear strength of RC walls exclude key variables for assessing the seismic performance of lightly-reinforced concrete walls retrofitted with CFRP. In this research, a model for predicting the contribution of CFRP to the shear strength of lightly-reinforced concrete panels is initially developed. A model to correlate the contribution of CFRP to shear strength of lightly-reinforced concrete panels with that of thin and lightly-reinforced concrete walls is also proposed. The experimental program includes cyclic diagonal compression tests on fourteen lightly-reinforced concrete panels: one plain concrete panel and thirteen panels reinforced internally with web shear reinforcement-ratio equal to 0.11%; twelve retrofitted with CFRP, and one RC panel retrofitted with a concrete overlay conventionally reinforced with a welded-wire mesh. The CFRP configuration were diagonal or horizontal with one strip, and diagonal or horizontal with three strips. Three volumetric ratios of CFRP were studied in this research: 0.02%, 0.06% and 0.09%. The effectiveness of the configuration and volumetric-ratio of CFRP on performance of retrofitted panels was evaluated in terms of cracking patterns, failure modes, shear strength and energy dissipation capacity obtained from shear-strain curves measured during cyclic diagonal compression tests. The model proposed to predict the contribution of CFRP to the peak shear strength of retrofitted lightly-reinforced concrete panels depends on the properties, volumetric ratio and configuration of CFRP on the panel.

Keywords: retrofit, CFRP, lightly-reinforced panels, low-rise buildings, diagonal compression test.

1. Introduction

A significant number of buildings in Latin America, Europe and Asia that are built with thin (80 to 100 mm) and concrete walls reinforced internally with web shear reinforcement-ratios of 0.11% as the main structural system are susceptible to severe damage or collapse during moderate and strong earthquakes [1, 2]. Causes of this inadequate behavior can be related to one or more reasons; namely, the use of inadequate materials and structural system, the lack of code-based specifications at the construction or design stage, unsuitable earthquake-resistant requirements or simply, the deterioration effects on materials such as steel corrosion causing loss of rebar area. For instance, the first earthquake-resistant code in Colombia (CCCSR-84) [3] was just published in 1984. This code was motivated by important damages on buildings that were registered during the Popayan earthquake in 1983. CCCSR-84 code [3] established a minimum shear-reinforcement-ratio for RC walls of 0.16%. However, the code was updated in 1998 with the building code for earthquake-resistant

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construction in Colombia, NSR-98 [4], which incremented the shear-reinforcement-ratio for RC walls setting the value at 0.20%. The minimum shear reinforcement ratio for RC walls prescribed by the version 2010 of NSR [5] is equal to that prescribed by the version 2008 of ACI 318-08 [6]. This same requirement is valid for the version 2019 of ACI 318-19 and NSR-10 [5] when welded wire mesh are used. Therefore, there are low-rise buildings in Colombia built before 1998 with shear-reinforcement-ratio for RC walls that do not comply the last version of NSR-10 [5].

A review of the state-of-the-art shows that main retrofitting techniques for RC walls are the concrete jacketing conventionally reinforced [7, 8], jacketing with Steel Fiber Reinforced Concrete (SFRC) [9], jacketing with steel plates [10, 11] and steel bracings [12, 13]. GangaRao *et al*. [14] reported a state-of-the-art review on RC structures retrofitted with Carbon Fiber Reinforced Polymers (CFRP) in the US, Japan and Europe. Galal and El-Sokkary [15] argue that the FRP increases the shear and the flexural strength of the RC walls retrofitted with FRP. Hube *et al*. [8] reported two cases of buildings with RC walls that were retrofitted with CFRP after the Chile earthquake in 2010. Lombard *et al*. [16] presented a model to predict the peak shear strength of flexural-controlled RC walls retrofitted with CFRP. Some models are available in the literature to predict the contribution of FRP to the shear strength of different structural elements, which have been proposed by Triantafillou and Antonopoulos [17], Machado [18], Alcaino and Santa María [19], Babaeidarabad *et al.* [20] and Lombard [21], and by some codes and guidelines such a ACI 440 [22], AC 125 [23] and FIB-14 [24]. The models by ACI 440 [22], FIB-14 [24] and by Triantafillou and Antonopoulos [17] evaluate the contribution of FRP to the shear strength of RC beams. The models by Machado [18], Alcaino and Santa María [19] and by Babaeidarabad *et al*. [20] evaluate the contribution of CFRP to the shear strength of masonry walls. The two models by AC 125 [23] and Lombard [21] are proposed for predicting the shear strength of RC walls retrofitted with CFRP. The model by AC 125 [23] is intended for rectangular cross-sectional walls retrofitted with CFRP strips on both sides of the wall. This model depends mainly on thickness, tensile stress and inclination of the CFRP strips. The model by Lombard [21] is planned for flexural-controlled thin (t_w =0.1 m) RC walls with height-to-length ratio (h_w/l_w) of 1.2. This model depends primarily on the number, tensile stress and thickness of the horizontal FRP sheets. However, these models exclude the FRP reinforcement ratio and the number FRP reinforcement strips. Moreover, these two models are proposed for RC walls with properties and retrofitting configurations different to those of the thin and lightly-reinforced concrete walls typical for low-rise buildings in Latin America. The model proposed in this study is aimed at correlating the contribution of CFRP to the peak shear strength of shear-controlled thin RC panels and RC walls (t_w = 75 mm) with h_w/l_w = 1 and retrofitted with CFRP strips. In addition, there are not available studies in the academic literature that correlate the contribution of CFRP to the shear strength of lightly-reinforced concrete panels with that of thin and lightly-reinforced concrete walls. This relationship could be useful for new experimental programs, given that the cost associated with the experiments with RC walls is significantly higher than that with RC panels.

The aim of this paper is to develop a model to estimate the contribution of CFRP to the peak shear strength of lightly-reinforced concrete panels, and a model to correlate the contribution CFRP to the peak shear strength of RC panels with that of thin RC walls. The model for predicting the contribution of CFRP to the peak shear strength is initially developed for panels because the influence of the variables affecting the structural response can be efficiently assessed using a significant number of panels rather than full scale walls during the experimental program. The experimental program comprises the construction and testing of fourteen (14) panels. The variables under study were the reinforcement volumetric-ratio and the configuration of the CFRP (four different retrofitting configurations including one or three strips placed diagonally or horizontally). Thus, twelve (12) panels were retrofitted with CFRP strips with three different CFRP volumetric-ratios. Each retrofitting configuration is studied with three CFRP reinforcement volumetric-ratios. One plain concrete (PC) panel and one RC panel retrofitted with a concrete overlay conventionally reinforced with web shear reinforcement-ratio equivalent to 50% of the minimum ratio specified by NSR-10 [5] (ρ_{min} = 0.20%) and using welded-wire mesh were studied as benchmark panels. Although the reinforcement-ratio used in old buildings was found to be 80% the minimum ratio of today's standard, a lower value of 50% of the minimum was used for assessing the contribution of CFRP retrofitting on the performance of panels with lower critical values of web reinforcement. Measured behavior of panels is discussed in terms of cracking patterns, failure modes, peak shear strength, contribution of CFRP to the peak shear strength and energy dissipation. The effectiveness of the reinforcement volumetric-ratio and configuration of the CFRP were also assessed in the study. The functional form of the model proposed to predict the contribution of CFRP to the shear strength of RC panels is established considering not only the experimental response of the panels, but also the functional form of the related-models proposed in the academic literature. The response calculated with the proposed prediction-model is compared with that computed using the models available in the literature. A model to correlate the contribution of CFRP to the shear strength of lightly-reinforced concrete panels with that of thin and lightly-reinforced concrete walls is also developed. The ratios of the predicted to the measured values of the contribution of CFRP to the shear strength were used to compare the measured results with those computed with the proposed model and with the AC 125 [23] and Lombard [21] models for RC walls.

2. Experimental campaign

The experimental program included the construction of fourteen (14) panels which were subjected to cyclic diagonal compression. The measured dimensions, reinforcement details and the main measured-parameters of the panels are shown in Table 1. The panels were square-shaped with 600 mm length and 75 mm thickness. Except the Plain Concrete (PC) panel, all panels were reinforced internally with web shear reinforcement-ratio equivalent to 50% ($\rho_{h,v}$= 0.11%) of the minimum ratio specified by NSR-10 [5] (ρ_{min} = 0.20%) and the same web steel ratio at horizontal and vertical directions. The web steel ratio ($\rho_{h,v}$= 0.11%) was provided using welded wire mesh (WWM) with steel wires of 4mm diameter and with spacing of 150 mm at horizontal and vertical directions. Fig. 1 shows the CFRP configurations of all the twelve retrofitted panels. Four (4) types of CFRP configurations were arranged externally on one side of the panels: one or three strips arranged horizontally (*H1* and *H3*, respectively) and, one or three strips arranged diagonally (*D1* and *D3*, respectively). Horizontal, vertical and diagonal refer to the direction of CFRP strips and steel wires of the panels placed in its original location (see Fig. 1). Three different CFRP reinforcement volumetric-ratios $\rho_{f\text{-}vol}$ (0.02%, 0.06% y 0.09%) were used for each CFRP configuration, this is twelve panels retrofitted with CFRP. One plain concrete (PC) panel and one RC panel retrofitted externally with a concrete overlay conventionally reinforced with web shear reinforcement-ratio equivalent to 50% of ρ_{min} and using WWM were also tested as benchmark panels.

Table 1. Dimensions, reinforcement details and main measured response of panels

Internal and external reinforcement	ID	Geometry				Measured response				
		h_w	l_w	t_w	A_w	$V_{max\text{-}m}$	$v_{max\text{-}m}$	$V_{f\text{-}m}$	$v_{f\text{-}m}$	E_{max}
		mm	mm	mm	mm^2	kN	MPa	kN	MPa	J
PC panel	P	601	600	76	45886	223	4.85	-	-	-
Panels with 50%ρ_{min}	P50	601	600	76	45886	154	3.35	-	-	255
Panels with 50%ρ_{min}, retrofitted with CFRP	P50-02H1	600	600	77	46414	188	4.05	34	0.74	47
	P50-02H3	601	600	76	45880	224	4.88	70	1.53	50
	P50-02D3	602	602	72	43638	195	4.46	41	0.93	27
	P50-02D1	599	600	79	47653	225	4.72	71	1.48	60
	P50-06H1	602	606	74	45144	179	3.98	25	0.56	26
	P50-06H3	600	599	77	45987	210	4.55	56	1.21	61
	P50-06D3	602	601	78	47106	206	4.37	52	1.11	31
	P50-06D1	600	600	77	46414	224	4.82	70	1.50	42
	P50-09H1	600	599	77	45987	191	4.16	37	0.81	412
	P50-09H3	601	600	76	45564	216	4.74	62	1.36	62
	P50-09D3	602	602	72	43638	231	5.30	77	1.77	47
	P50-09D1	600	600	78	46778	192	4.11	38	0.82	29

In table 1, h_w, l_w, t_w and A_w ($l_w \times t_w$) are the height, length, thickness and cross sectional area of the panel, $V_{max\text{-}m}$ and $v_{max\text{-}m}$ are the measured peak shear force and peak shear strength of the panels, respectively; $V_{f\text{-}m}$ and

$v_{f\text{-}m}$ are the measured contribution of CFRP to the peak shear strength of the panels in terms of shear load and stress, respectively, and E_{max} is the energy dissipated at peak shear strength. The specimens were identified using the alphanumeric character PX-YZ, where P is a panel test, X is the percentage of the minimum web steel ratio specified by NSR-10 (ρ_{min}), i.e., 50 = 50% ρ_{min}, and no value means a Plain Concrete (PC) panel; Y indicates the volumetric-ratio of CFRP external reinforcement ($\rho_{f\text{-}vol}$), i.e., 02 = 0.02%, 06 = 0.06%, 09 = 0.09%, and Z characterizes the CFRP configuration , i.e., *D1*, *D3*, *H1* o *H3;* when letters YZ are omitted, the panels were not retrofitted (externally).

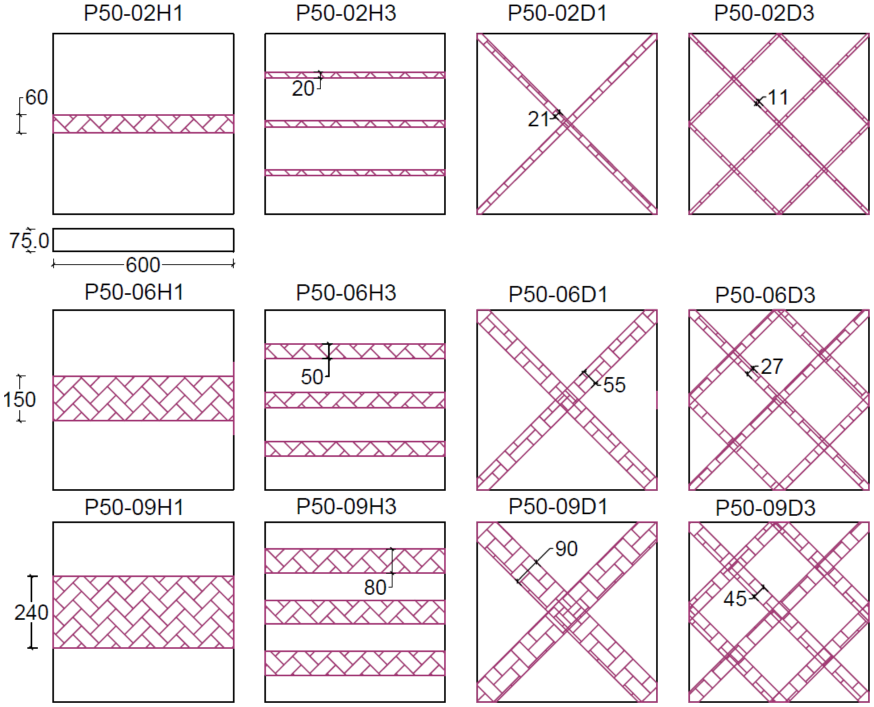

Figure 1. CFRP retrofitting arrangement, dimensions in mm.

2.1 CFRP retrofitting

The models proposed by FIB-14 [24] and Triantafillou and Antonopoulos [17] estimate the contribution of CFRP to the shear strength (v_f) using the CFRP ratio (ρ_f) that is computed using Eq. (1).

$$\rho_f = \left(\frac{2t_f}{t_w}\right)\left(\frac{w}{s_f}\right) \tag{1}$$

As shown in Fig. 2, t_f is the thickness of CFRP strip (mm), w is the width of the CFRP strip that is perpendicular to its longitudinal axis (mm), s_f is the horizontal spacing measured between longitudinal axis of CFRP strips or or the vertical spacing measured between longitudinal axis if CFRP strips are horizontally arranged. In this study, the CFRP volumetric-ratio ($\rho_{f\text{-}vol}$) computed using Eq. (2) is proposed to consider the standardized influence of CFRP configuration.

$$\rho_{f\text{-}vol} = \frac{Vol_f}{Vol_c} = \frac{c\ t_f\ w_f\ sen\beta\ \ l_f}{t_w\ s_f sen\beta\ \ l_f} = \frac{c\ t_f w_f}{t_w\ s_f} \tag{2}$$

where Vol_f is the volume of a CFRP strip on the panel, Vol_c is the volume of a concrete block that contains a CFRP strip, c is the number of orientations along which the strips are arranged; for instance, there are strips oriented along both 45° and 135° with respect to the horizontal line in Fig. 2, therefore $c = 2$; w_f is the vertical width of the CFRP strips when they are horizontally arranged; otherwise, w_f is the horizontal width of the strips, β is the angle between the strips and the horizontal axis of the panel, and, l_f is the length of the CFRP strips.

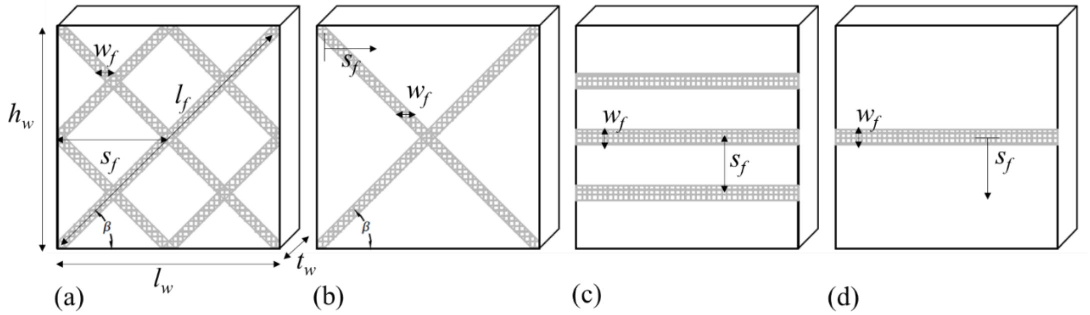

Figure 2. Parameters to calculate $\rho_{f\text{-}vol}$: (a) dimensions on retrofitted panel, (b) concrete block on a panel that contains a CFRP strip.

2.2 Materials properties

Concrete and WWM

A ready mixed-concrete with a specified compressive strength f_c' = 21 MPa was used for casting the panels. The measured values of f_c' and the modulus of elasticity of concrete (E_c) were 24.1 MPa and 19,146 MPa, with a coefficient of variation (*CV*) of 1.3%. ASTM A1064 [25] standard specifies that the nominal values of the yielding strength (f_y) and ultimate strength (f_u) of the 4 mm wires of the WWM are 485 MPa and 550 MPa, respectively. ASTM A1064 does not require ductility requirements in terms of elongation or strain. However, it is widely known that the ductility capacity of the steel product is reduced as the ratio f_u/f_y decreases [26]. The measured values of f_y, f_u, yield strain (ε_y), strain associated with f_u (ε_u) and ratio f_u/f_y of the wires were 506 MPa, 525 MPa, 0.4%, 1.7%, and 1.04, respectively. Although the measured values of f_y, f_u of the wires fulfill the strength requirement prescribed by ASTM A1064, values of ε_y, ε_u and the ratio f_u/f_y () were extremely low, indicating the fragile behavior of this type of cold-drawn reinforcement.

CFRP

The carbon fibers are usually fabricated with three products: poliacrylonitrile fibers (PAN), rayon fibers and tar fibers (PITCH) [14]. Three types of resins can be used bonding the CFRP on RC elements, namely primers, surface regulators or saturators. Sika-Wrap 300C and Sikadur 301 were the CFRP strips and the saturator-type resin, respectively, selected for retrofitting the lightly-reinforced concrete panels of this study. Additional anchorage different to that of the epoxy was not provided because it can affect significantly the integrity of the elements in a real low-rise building. The specified properties of the CFRP Sika Wrap 300C are: t_f of 0.17 mm, tensile strength (f_{uj}) of 4,200 MPa, modulus of elasticity (E_f) of 240,000 MPa, and ultimate tensile strain (ε_f) of 1.5%. The measured properties of the CFRP Sika Wrap 300C were: f_{uj} of 4,047 MPa with a *CV* of 6.3%, E_f of 233,286 MPa with a *CV* of 3.9% and, ε_f of 1.73% with a *CV* of 11%.

2.3 Loading protocol

Fig. 3 shows the test setup for the cyclic diagonal compression test of the panels under study. The loading protocol adopted in the study was that proposed by Almeida *et al.* [27]. Both diagonals of the panels were externally instrumented with Tokyo Sokki linear variable displacement transducers (LVDTs) with a 100-mm stroke and accuracy of 0.01 mm. The compression loads on the panels were applied through a MTS 244.31 servo-hydraulic actuator with a 250 kN capacity. The test was force-controlled with a loading rate of 300 kg/min from the beginning to half of the maximum expected load. After reaching this load, the test was displacement-controlled with a loading rate of 0.01 mm/s. The loaded corners of the panels were reinforced with CFRP to avoid local failure due to stress concentration.

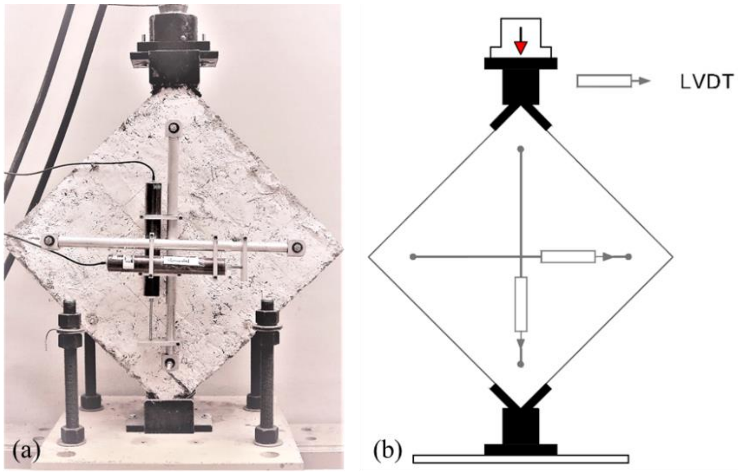

Figure 3. Testing of panels: (a) test setup, (b) external instrumentation.

3. Results and discussion

3.1 Cracking patterns and failure modes of the panels

Fig. 4 shows the final cracking patterns and failure modes observed after the diagonal compression testing of five (5) typical panels: the plain concrete (PC) panel (Fig. 4a) and four panels retrofitted with CFRP configurations *D1*, *D3*, *H1* and *H3* (Figs. 4b, 4c, 4d and 4e, respectively). Fig. 4 shows a main crack along the loaded diagonal of all the panels. As expected, the failure mode of the PC panel was governed by brittle diagonal compression stresses. Fig. 4a shows a crack at the right side of the PC panel, which initiates at the middle of the diagonal compressive crack and extends to on edge. Cracks in the panels retrofitted with CFRP strips arranged horizontally were smaller than those in panels with CFRP arranged diagonally. Debonding of the superior reinforced corner of load application was observed at the end of the tests of the panels strengthened with CFRP (Figs. 4b, 4c, 4d and 4e).

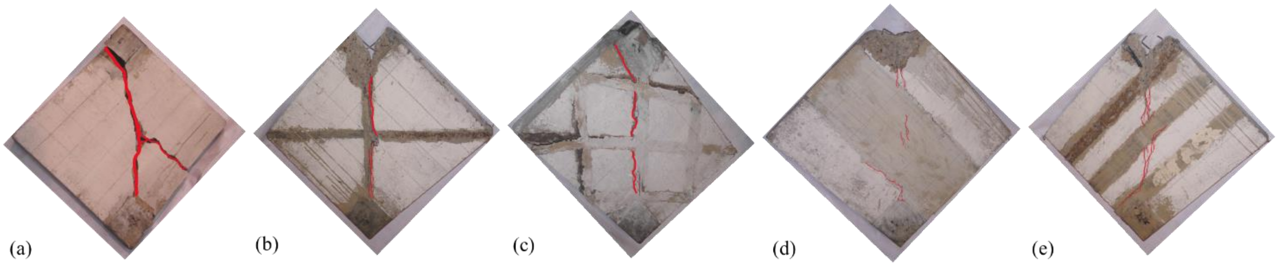

Figure 4. Typical cracking patterns of panels: (a) PC, (b) P50-02D1, (c) P50-06D3, (d) P50-09H1, (e) P50-06H3.

3.2 Shear strength

Fig. 5 shows the shear stress-strain curves measured during the diagonal compression tests of the lightly-reinforced concrete panels. The shear stress and the strain were calculated in accordance with the ASTM E-519 [28] standard. The measured values of the peak shear force ($V_{max\text{-}m}$), peak shear strength ($v_{max\text{-}m}$) and, the contribution of CFRP to the peak shear strength of the lightly-reinforced concrete panels in terms of force ($V_{f\text{-}m}$) and stress ($v_{f\text{-}m}$), are summarized in Table 1.

All the CFRP retrofitted panels were cast with the same concrete and were internally reinforced in the web with the same web shear reinforcement as the P50 panel (50%ρ_{min}), which is not a retrofitted panel. The strength measured in the panel P50 (v_{P50}) characterizes the contributions of the concrete and the internal steel reinforcement. Therefore, the measured contribution of the CFRP to the peak shear strength ($v_{f\text{-}m}$) of panels was obtained by subtracting the peak shear strength measured in the panel P50 (v_{P50}) from the peak shear strength measured in the CFRP retrofitted panels (v_{P50+f}). The results of the calculation of $v_{f\text{-}m}$ are shown in Table 1.

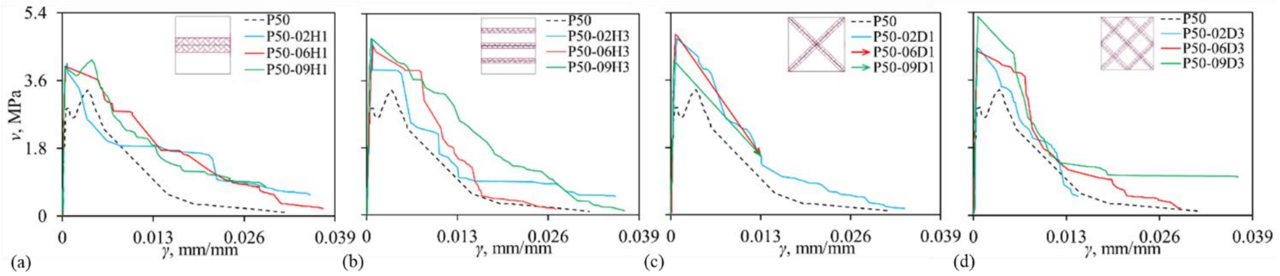

Figure 5. Shear stress-strain curves of panels with different configuration of CFRP strips: (a) H1, (b) H3, (c) D1, (d) D3.

4. Prediction of contribution of CFRP to the peak shear strength

A model for predicting v_f in lightly-reinforced concrete panels retrofitted with CFRP strips is developed in this section. Main variables used in the models proposed by ACI 440 [22], AC 125 [23], FIB-14 [24], Machado [18], Alcaino and Santa María [19], Babaeidarabad *et al.*[20], Triantafillou and Antonopoulos [17], and Lombard [21] were examined to develop the model. The measured values (v_{f-m}) are then compared with the values calculated (v_{f-c}) with the models available in the literature and with the model proposed in this paper.

In synthesis, the models available in the literature were developed to predict v_f of structural elements with behavior different to that of lightly-reinforced concrete panels; nevertheless, these models are useful to study the CFRP contribution to the shear capacity of RC panels (v_f). The main variables included in the available models were initially identified for developing the numerical model of v_f in lightly-reinforced concrete panels. The model proposed in this study also includes ρ_{f-vol} and the number of CFRP strips (N) along the height of the panel, given that the state of the art demonstrated that these parameters influence on the prediction of v_f. Iterative regression analyses were performed with different combinations of variables to reach the best combination that fits the measured values of v_f. Fig. 6a shows the calculated value of v_f using such combination of variables in the abscissa axis and, the measured value of v_f in the ordinate axis. The measured dimension and mechanical properties of materials were used to compute the peak shear strength. Fig. 6a also shows linear and power regression analyses for correlating the measured with the predicted data of the contribution of CFRP to the peak shear strength. Fig. 6a shows that correlation coefficients (r) associated to the linear and power regressions of the numerical model proposed in this study are 0.63 and 0.67, respectively. Rowntree [29] proposed a scale to categorize values of r; low, moderate, high and very high correlations for r between 0.21 to 0.40, 0.41 and 0.60, 0.61 and 0.80, and 0.81 and 0.99, respectively. Therefore, the correlations associated to the linear and power regressions of the numerical model proposed in this study are categorized as high.

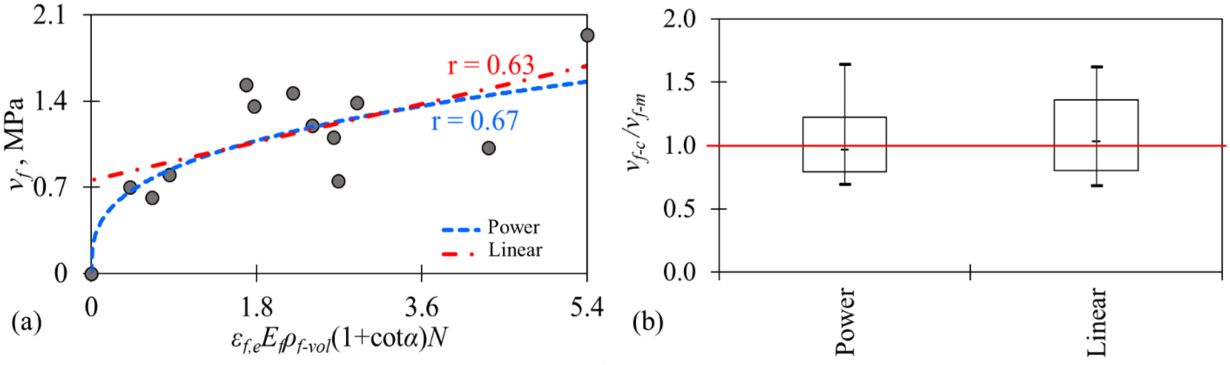

Figure 6. Regression analyses to predict v_f for panels: (a) calculated and measured v_f, (b) box-and-whisker plots of v_{f-c}/v_{f-m}.

A statistical analysis of the v_{f-c}/v_{f-m} ratios computed with the two regression analyses is performed to select the type of regression of the model of v_f proposed in this study. Box-and-whisker plots are performed to graphically show the main statistical parameters such as the mean (X), the coefficient of variation (CV), the interquartile range (*IQR*) and the over-prediction (*Op*) of the $v_{f\text{-}c}/v_{f\text{-}m}$ ratios. Fig. 6b shows the box-and-whisker plot of the ratio $v_{f\text{-}c}/v_{f\text{-}m}$ for the linear and power regressions of the numerical model proposed in this study. For a code-based and accurate numerical model of the peak shear strength of RC panels, the measured strength must be equal or slightly higher than the calculated strength; therefore, *X* must be as closest to 1.0 as possible but smaller than 1.0. The *CV* is an indicator of the homogeneity of *X* in the sample. The qualitative scale of *CV* proposed by Rustom [30] is considered in this study to assess the homogeneity of *CV*; slight, intermediate and high variation for *CV* values smaller than 5%, close to 20%, and higher than 50%, respectively. The *IQR* allows to describe the dispersion of data; for instance, the dispersion is higher as long as the *IQR* is greater. The *IQR* is calculated as the subtraction of the first quartile form the third quartile of data; thus, the value of *IQR* is not directly affected by the extreme values. The *Op* characterizes the predicted values that are higher than the measured data, in percentage.

The difference between the statistical parameters (*X*, *CV*, *IQR* and *Op*) of the box-and-whisker plots associated to the linear and power regressions in Fig. 6b are lower than 13%, showing that both models are statistically equivalent for predicting v_f. As previously discussed, the linear and power regressions are highly correlated as can be evidenced by the correlation coefficients. A model for predicting v_f using the linear regression is proposed in this study because the estimate of v_f using this model is more practical for code-based design purposes. The results of this numerical model of v_f is shown in Fig. 7 (best fit). The over-prediction (*Op*) associated with the best fit regression is 50%. To reduce this *Op*, the linear regression model associated with the percentile 83% (P83) of the calculated data is proposed in this study. The model proposed in this study is described by Eq. (3), characterizing that the 83% of calculated data are lower than the measured data, with an *Op* of 16.7%. The statistical parameters *X*, *CV*, *IQR* and *Op* of the linear regression associated with the best fit are 1.07, 26.8%, 0.56 and of 50%, respectively, and the corresponding values of the linear regression associated with the percentile 83% are 0.82, 27.4%, 0.34 and 16.7%. Hence, the proposed model (P83) in this study is conservative, practical and is associated with statistical parameters that are suitable to be used for code-based design.

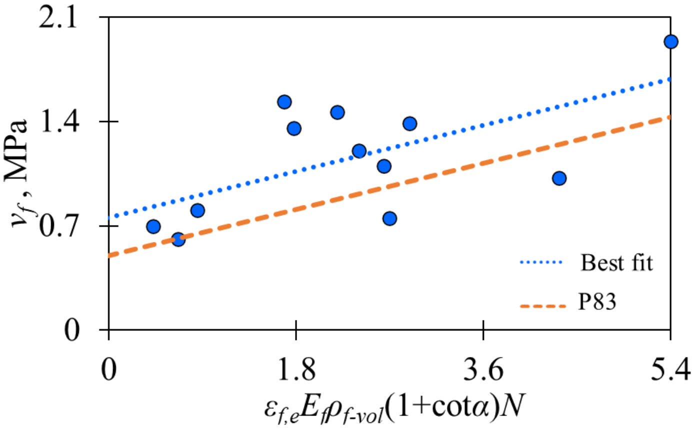

Figure 7. Best fit and P83 (proposed) numerical models of v_f.

$$v_f = 0.17\varepsilon_{f,e}E_f\rho_{f\text{-}vol}(1 + cot\alpha)N + A \text{ (MPa)} \tag{3}$$

where $\varepsilon_{f,e}$ is the effective CFRP strain along the main direction (mm/mm) and it is calculated with Eq. (4), which is recommend by FIB-14 [24]; $\rho_{f\text{-}vol}$ is the volumetric-ratio of the CFRP strips, which is calculated with Eq. (2); α is the angle between the strips and the longitudinal axis of the panels; *N* is the number of CFRP strips along the height of the panels, which is calculated as the ratio between the height of the panel (h_w) and s_f and; *A* is a regression coefficient. This constant is equal to 0.76 for the best fit and equal to 0.5 for the proposed model (P83) that is intended for code-based design.

$$\varepsilon_{f,e} = \min\left[0.65\left\{\frac{f'^{\frac{2}{3}}_c}{E_f\rho_f}\right\}^{0.56}\times 10^{-3},\ 0.17\left\{\frac{f'^{\frac{2}{3}}_c}{E_f\rho_f}\right\}^{0.30}\varepsilon_f\right] \tag{4}$$

Table 2 summarizes the main statistical parameters of the ratio between the calculated and the measured values of the contribution of CFRP to the peak shear strength ($v_{f\text{-}c}/v_{f\text{-}m}$) using the numerical models of v_f available in the academic literature and the model proposed in this study. The numerical models of v_f available in the literature were proposed for elements different to lightly-reinforced concrete panels. Nevertheless, they were used in this study as an indicator of the estimate, and to analyze the statistical parameters of the model proposed. Values of v_f computed with the model proposed by Machado [18] for panels retrofitted with horizontal CFRP strips are not included in Table 2 because this model does not consider the horizontal configuration of CFRP strips. Similarly, values of v_f computed with the model proposed by Lombard [16] for panels with inclined CFRP strips by because this model does not contemplate inclined CFRP strips.

Table 2. Summary of statistics for $v_{f\text{-}c}/v_{f\text{-}m}$ for panels

Structural element	RC beams				Masonry walls		RC walls		Panels - This study	
Specimen	ACI 440	FIB 14	Triantafillou and Antonopoulos	Machado	Alcaino and Santa-Maria	Babaeidarabad *et al.*	AC 125	Lombard	Best fit	P83
P50-02H1	0.11	0.85	0.85	-	0.15	4.54	2.26	2.53	1.18	0.82
P50-02H3	0.06	0.43	0.43	-	0.07	0.71	1.04	1.17	0.68	0.51
P50-02D3	0.04	0.57	0.41	1.49	0.23	0.60	0.77	-	1.10	0.86
P50-02D1	0.03	0.33	0.23	1.10	0.11	0.78	0.57	-	0.78	0.59
P50-06H1	0.32	1.67	1.67	-	0.44	13.99	2.60	3.00	1.42	1.00
P50-06H3	0.19	0.87	0.87	-	0.22	2.24	1.29	1.49	0.97	0.76
P50-06D3	0.09	0.83	0.59	1.49	0.57	1.37	0.74	-	1.47	1.21
P50-06D1	0.07	0.58	0.41	1.05	0.28	1.99	0.53	-	0.77	0.60
P50-09H1	0.38	1.67	1.26	-	0.53	16.11	1.93	2.23	1.12	0.80
P50-09H3	0.27	0.89	0.89	-	0.31	3.18	1.13	1.30	0.90	0.72
P50-09D3	0.09	0.57	0.40	0.85	0.54	1.40	0.42	-	0.87	0.73
P50-09D1	0.21	1.47	1.04	2.03	0.87	6.24	1.01	-	1.62	1.27
X	0.15	0.89	0.75	1.33	0.36	4.43	1.19	1.95	1.07	0.82
CV, %	72.9	49.9	54.0	64.6	62.4	113.6	57.1	74.8	26.8	27.4
IQR	0.19	0.75	0.60	0.62	0.37	4.89	1.16	1.38	0.56	0.34
Op, %	0.0	25.0	25.0	83.3	0.0	75.0	58.3	100.0	50.0	16.7

In a numerical model suitable for code-based design, the mean value (*X*) of the ratio $v_{f\text{-}c}/v_{f\text{-}m}$ must be close and slightly smaller than one (1.0), and the *CV*, *IQR* and *Op* must be lower than 25%, 0.25, and 20%, respectively [1]. The ratios $v_{f\text{-}c}/v_{f\text{-}m}$ in Table 2 evidence that the models showing values of *X* closest to one (1.0) are the models by FIB-14 [24], Triantafillou and Antonopoulos [17], and the models of this study associated to the best fit, and the P83, with *X* of 0.89, 0.75, 1.07 and 0.82, respectively. The models with the lowest *CV* are those proposed in this study (best fit and P83), with *CV* of 26.8% (best fit) and 27.4% (P83); the *CV* of the rest of the models varied between 49.9% and 113.6%. The values of *IQR* of the models proposed in this study are 0.53 (best fit) and 0.34 (P83), which are similar to the *IQR*-values of the models by Triantafillou and Antonopoulos [17] (0.60), Machado [18] (0.62) and, Alcaino and Santa-Maria [19] (0.37). The models developed in this study evidenced appropriate *IQR*-values given that are ranged between the mean values of *IQR* of the models analyzed. The values of *Op* for the models developed in this study are 50% (best fit) and 16.7% (P83), which are ranged from the mean values of *Op* registered by the models analyzed such as FIB-14

[24] (25%), Triantafillou and Antonopoulos [17] (25%) and, AC 125 [23] (58.3%). The values of X for the both models developed in this study (the best-fit and the P83) are statistically appropriated. Although the model associated to the best fit is the more accurate model for describing the experimental database, it may be unsafe for code-based design purposes given that it registered an X of 1.07 and Op of 50%. The model developed in this study that is associated with the percentile 83% is conservative given that it registered an X of 0.82 and Op of 16.7%, and therefore it is adequate for code-based design purposes.

5. Effect of CFRP on the structural response of panels

The effects of the ratio and configuration of the CFRP on the structural response of lightly-reinforced concrete panels were evaluated in this study in terms of $v_{f\text{-}c}$ and the energy dissipated at peak shear strength (E_{max}). The value of $v_{f\text{-}c}$ is computed with the model proposed in this study (P83) and defined in Eq. (3). The dissipated energy is the capacity of a structural element to dissipate the acting stresses without collapsing. The values of E_{max} measured on the lightly-reinforced concrete panels are shown in Table 1. These values were computed from the enclosed area in the load versus displacement curves for a same fraction of the peak shear load, namely 100%. The values of $v_{f\text{-}c}$ and E_{max} for the RC panels studied in this study are shown in Fig. 8. The trends of data in Fig. 8 evidenced that the volumetric-ratio and configuration of CFRP strongly influence the structural response of the lightly-reinforced concrete panels. Fig. 8a shows that $v_{f.c}$ increases as the $\rho_{f\text{-}vol}$ increases for all the CFRP configurations in this study (D1, D3, H1 and H3). Although the panels with D configuration of the CFRP presented debonding of the CFRP strips (see Fig. 4c), it is observed in Fig. 8a that the highest values of $v_{f.c}$ are associated to the CFRP with D3 configuration.

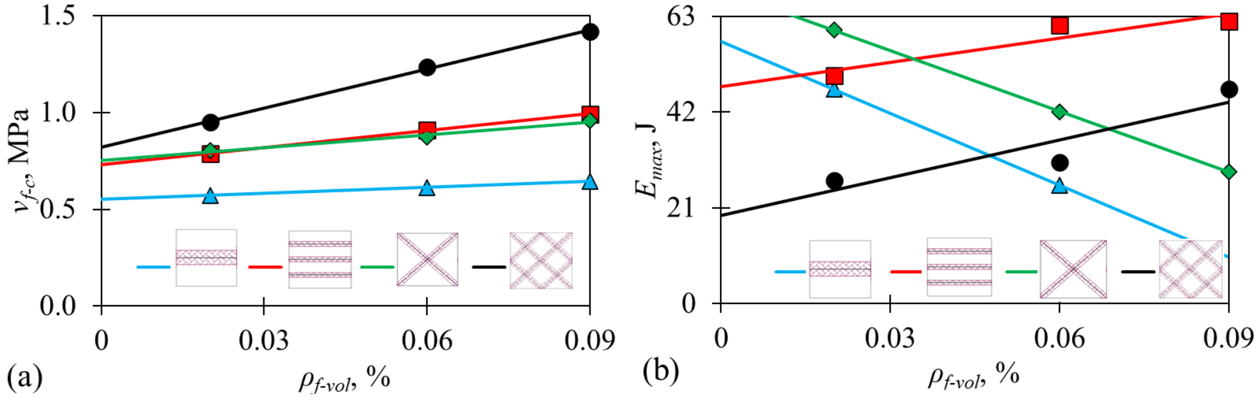

Figure 8. Effect of the volumetric-ratio and configuration of CFRP on: (a) $v_{f\text{-}c}$, (b) E_{max}.

Fig. 8b shows that E_{max} increases proportionally to $\rho_{f\text{-}vol}$ for *D3* and *H3* configurations of CFRP strips and, that E_{max} decreases proportionally to $\rho_{f\text{-}vol}$ for *D1* and *H1* configurations of CFRP strips. This reduction suggests that the efficient of $\rho_{f\text{-}vol}$ depends on the number of strips or the spacing of CFRP strips; that is, the more strips the higher efficiency of $\rho_{f\text{-}vol}$ for increasing E_{max}. Therefore, the number of CFRP strips along the height of the RC panels is also a variable that strongly influences the structural response of the panels. Fig. 8b also shows that the highest values of E_{max} for $\rho_{f\text{-}vol} \leq 0.03\%$ are associated to the CFRP with *D1* configuration otherwise, the highest values of E_{max} are reported for the RC panels retrofitted with three horizontal CFRP strips (*H3*). Values of E_{max} for PC and P50-09H1 panels are outliers because the shear strain values associated to the peak shear strength of these two panels are significantly higher than those of the other panels (see Fig. 5).

6. Correlation between the contribution of CFRP to the peak shear strength of panels and walls

There are no available studies in the academic literature that correlate the v_f of lightly-reinforced concrete panels retrofitted with CFRP with the v_f of thin and lightly-reinforced concrete walls retrofitted with CFRP. A model to correlate the v_f of panels with the v_f of walls is developed in this section. The correlation model proposed in this study is compared with models by AC 125 [23] and Lombard [21], which are oriented to RC walls. The model by AC 125 [23] is intended for rectangular cross-sectional walls retrofitted with CFRP strips on both sides of the wall. The model by Lombard [21] is planned for flexural-controlled thin (t_w =0.1 m) RC walls with height-to-length ratio (h_w/l_w) of 1.2. The model proposed in this study is aimed at correlating the peak shear strength of shear-controlled thin panels and lightly-reinforced concrete walls (t_w = 75 mm) with h_w/l_w = 1 and retrofitted with CFRP strips.

Four (4) thin and lightly-reinforced concrete walls tested under quasi-static cyclic loads and reported by Carrillo *et al.* [31] were considered to develop the correlation model in this study. The geometry, reinforcement and retrofitting of these four walls are similar to the geometry of the panels studied in this study. The height and length of walls tested by Carrillo *et al.* [31] is 900 mm (h_w/l_w = 1), and thickness is 75 mm. The walls were internally-reinforced for web shear with 50%$\rho_{min} \approx$ 0.11% using a WWM with steel wires of 4mm diameter and 150 mm of horizontal and vertical spacing (4×4-150/150). The walls were retrofitted with a $\rho_{f\text{-}vol}$ of CFRP of 0.06%, which are approximately equal to the mean of $\rho_{f\text{-}vol}$ used for the panels in this study. The CFRP configuration for the walls were *D1*, *D3*, *H1* and *H3*, which are the same CFRP configurations used for the panels in this study.

The contribution of CFRP to the peak shear strength of the panels and walls are summarized in Table 3 ($v_{f\text{-}m}$). Considering that no RC wall with 50%ρ_{min} (M50) was tested by Carrillo *et al.* [31] to obtain $v_{f\text{-}m}$ as it was done for the panels (see Section 3.2), the results of four 1:1.25 scaled RC walls reported by Carrillo and Alcocer [1] were used in this study. The lightly-reinforced concrete walls MCN50mC, MCL50mC, MCN50mD and MCL50mD reported by Carrillo and Alcocer [1] were internally-reinforced with WWM. The walls MCN50mC and MCL50mC were tested under quasi-static cyclic loading, and the walls MCN50mD and MCL50mD were tested under shaking-table excitations. Geometry and reinforcement characteristics of these walls are similar to those of the M50 wall. The mean value of the peak shear strength normalized to the root of the concrete compressive strength ($\tau_v/\sqrt{f_c'}$) of the walls MCN50mC, MCL50mC, MCN50mD and MCL50mD are of 0.299 MPa, 0.325 MPa, 0.295 MPa and 0.335 MPa, respectively. The mean value of $\tau_v/\sqrt{f_c'}$ for these four walls is 0.31 MPa with an associated *CV* of 5.4%. The mean value of $\tau_v/\sqrt{f_c'}$ (0.31 MPa) is transformed by $\sqrt{f_c'}$ to get the peak shear strength associated with the wall M50. In this way, the peak shear strength of the wall M50 is 1.54 MPa.

Table 3. Main characteristics and values of $v_{f\text{-}m}$ for panels and walls

Walls						Panels						Correlation v_f
Specimen	h_w mm	l_w mm	t_w mm	A_w mm^2	$v_{f\text{-}m}$ MPa	Specimen	h_w mm	l_w mm	t_w mm	A_w mm^2	$v_{f\text{-}m}$ MPa	v_{panel}/v_{wall}
M50-06H1	901	899	77	68774	0.99	P50-06H1	602	606	74	45144	0.56	0.56
M50-06H3	900	900	75	67500	1.36	P50-06H3	600	599	77	45987	1.21	0.89
M50-06D1	900	900	75	67500	1.18	P50-06D1	600	600	77	46414	1.50	1.27[a]
M50-06D3	900	900	75	67500	1.19	P50-06D3	602	601	78	47106	1.11	0.93
											X	0.79
											CV, %	20.8

[a] Outlier value not considered for calculating *X* and *CV*.

The model to correlate values of $v_{f\text{-}m}$ for panels and walls was developed considering the ratio v_{panel}/v_{wall}. The ratio v_{panel}/v_{wall} for the panel P50-06-D1 and the wall M50-06-D1 are not taken into account for assessing the correlation model given that is an outlier value when compared with the database. Table 3 shows that $v_{f\text{-}m}$ of panels are, on average, equal to 0.79 times $v_{f\text{-}m}$ of walls, with an associated *CV* of 20.8%. This variation is categorized as moderate variation according to scale proposed by Rustom [30]. The ratio v_{panel}/v_{wall} =0.79 suggests that the contribution of CFRP strips to the peak shear strength of the externally-retrofitted panel is equivalent to 79% of that of a full-scale externally-retrofitted wall.

The ratio $v_{f\text{-}c}/v_{f\text{-}m}$ computed with the models by AC 125 [23], Lombard [21] models, and the correlation model proposed for lightly-reinforced concrete walls in summarized in Table 4. The contribution of CFRP at peak shear strength of thin and lightly-reinforced concrete walls was obtained with the proposed correlation model, which consists on applying the mean of the ratio v_{panel}/v_{wall} of 0.79 (see Table 3) into the Eq. (3). In this equation, the properties of the panels are replaced by the properties of the walls. The prediction of the v_f of the walls retrofitted with diagonal CFRP strips using the model by Lombard [21] is not shown in Table 4, since this model does not consider diagonal CFRP strips.

Table 4 shows that the mean value (X) of the ratio $v_{f\text{-}c}/v_{f\text{-}m}$ associated with the correlation model proposed in this study is 0.93, while X of models by AC 125 [23] and Lombard [21] are 1.02 and 1.58, with an associated *Op* of 25%, 50% and 100%, respectively, and *CV* of 22.5%, 37% and 14.8% respectively. The *CV* associated with the model by Lombard [21] (14.8%) is 34% lower than the *CV* associated with the model proposed in this study (22.5%). Nevertheless, the *Op* of the model by Lombard [21] is 100%, while the *Op* of the model proposed in this study is 25%. The *CV* and *Op* associated to the model by AC 125 [23] (37% and 50%, respectively) are 64.4% and 100%, respectively, higher than the related values of the model proposed in this study (22.5% and 25%, respectively).

Table 4. Comparison between models available in the literature and the model proposed in this study

		AC 125		Lombard		This research	
Wall	$v_{f\text{-}m}$, MPa	$v_{f\text{-}c}$, MPa	$v_{f\text{-}c}/v_{f\text{-}m}$	$v_{f\text{-}c}$, MPa	$v_{f\text{-}c}/v_{f\text{-}m}$	$v_{f\text{-}c}$, MPa	$v_{f\text{-}c}/v_{f\text{-}m}$
M50-06H1	0.99	1.56	1.57	1.80	1.81	0.76	0.77
M50-06H3	1.36	1.59	1.16	1.83	1.34	1.05	0.77
M50-06D1	1.18	0.79	0.67	-	-	1.08	0.91
M50-06D3	1.19	0.79	0.67	-	-	1.52	1.28
		X	1.02		1.58		0.93
		VC, %	37.0		14.8		22.5
		Op, %	50.0		100		25.0

7. Summary and conclusions

The structural response of lightly-reinforced concrete panels retrofitted externally with CFRP strips, and subjected to cyclic diagonal compression was evaluated in this study. The cracking patterns, failure modes, the contribution of CFRP (v_f) to the peak shear strength and, the effect of the CFRP configuration on the shear behavior and the dissipated energy of the lightly-reinforced concrete panels were analyzed. A numerical model to estimate the contribution of CFRP to the peak shear strength ($v_{f\text{-}c}$) of the lightly-reinforced concrete panels was developed. Aiming at extrapolating the response of panels to that of walls, a model to correlate v_f of panels with that of thin RC walls is also proposed. The contribution of CFRP to the peak shear strength estimated with the model proposed in this study was compared with the contribution of CFRP computed using two models available in the academic literature for RC walls.

It was found that the structural response of the panels is influenced not only by the volumetric-ratio ($\rho_{f\text{-}vol}$) and configuration of CFRP but also by the number of CFRP strips (N). The model proposed in this study to predict v_f of thin RC panels retrofitted with CFRP strips depends mainly on the $\rho_{f\text{-}vol}$ and N, but also depends on the effective strain of the CFRP strips along the main direction ($\varepsilon_{f,e}$ and the angle between the strips and the longitudinal axis of the panels (α). The results of the model proposed in this study to predict v_f were compared to those of the models proposed for RC beams [17, 22, 24], RC walls [21, 23] and masonry walls [18, 19, 20]. The model proposed in this study is associated with the percentile 83% (P83). The analysis of the ratios between the calculated to the measured contribution of CFRP to the peak shear strength ($v_{f\text{-}c}/v_{f\text{-}m}$) evidenced mean ($X$) values of 0.82, the lowest *CV* value of 27.4% (P83 line), *IQR* values of 0.34 (P83), and *Op* values of 16.7% for the model of v_f proposed in this study for lightly-reinforced concrete panels. Thus, the comparison of the ratios between the calculated to the measured contribution of CFRP to the peak shear strength demonstrated that the proposed model in this study is conservative, practical and is associated with statistical parameters that are suitable to be used for code-based design.

The correlation of the measured contribution of CFRP to the peak shear strength of panels with that of walls evidenced that the strength of panels is, on average, equivalent to roughly 0.8 times that of walls, with an associated moderate *CV* of approximately 21%. Although more tests are deemed necessary to corroborate this factor, the correlation is a tool to extrapolate the v_f from panels to walls. The estimate of v_f of walls is obtained using the numerical model of v_f developed for panels and then multiplying by the correlation factor of 0.79 (v_{panel}/v_{wall}). The analysis of the statistical parameters of the ratios $v_{f\text{-}c}/v_{f\text{-}m}$ associated to the models by AC-125 [23] and Lombard [21], and to the model proposed in this study demonstrated that proposed correlation model is suitable for predicting the contribution of CFRP to peak shear strength of walls for code-based design. The model proposed in this study are based on a limited number of data points but in the absence of more data, they are indicative of the performance of thin and lightly-reinforced concrete panels retrofitted with CFRP similar to those tested and studied in the research program presented herein. Future cyclic and dynamic testing programs are necessary to adequately represent the performance of thin and lightly-reinforced concrete walls retrofitted with CFRP and subjected to characteristic ground motions. Proposed equations may be improved when more data becomes available.

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