Strengthening of square concrete columns with composite materials. Investigation on the FRP jacket ultimate strain

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ABSTRACT:

An accurate estimation of the effective ultimate strain of the FRP jacket is crucial to determine the values of strength and ultimate strain of FRP confined concrete. However, this is one of the main aspects not yet resolved by the theoretical models. Published design recommendations differ on this aspect, particularly in the case of non-circular sections. In this work, an experimental program carried out on 38 square section concrete specimens confined with FRP is presented. The results show a great influence of the radius of rounding of the corners on the behaviour of FRP confined square columns. The experimental values of effective ultimate strain are compared with the recommended values given by design guidelines.

KEYWORDS:

FRP-confined concrete; A. Polymer-matrix composites (PMCs); C. Mechanical properties; C. Strength; D. Mechanical testing

1. Introduction

FRP composite materials (fiber-reinforced polymers) are increasingly used in structural applications due to their excellent properties. One of the most attractive applications of FRP is the confinement of concrete columns to increase both strength and ductility. Numerous experimental studies have been carried out [1-10] and a large number of theoretical models have been proposed [11-21]. Several researchers have focused on the assessment of the performance of the models [22-23], concluding that the accuracy of the predictions still needs to be improved. Most of the experimental studies have focused on circular-section specimens and several empirical models have been proposed that have been adopted by the design guides published in various countries [24-27]. It is well known that the confinement of square or rectangular columns is less efficient than the confinement of circular columns, as it has been shown by several studies [28-32]. In the theoretical analysis of rectangular sections, models found in current design guides are usually based on models created for circular columns and then modified by a shape factor or ratio of the effective-confinement area and the gross area. The effective-confinement area is considered uniformly confined, even though the confining stress field is not uniform, as discussed in Nisticò and Monti [19].

A critical parameter for the fitting of the models is the strain efficiency factor, that is, the ratio of the effective ultimate strain or hoop rupture strain in the FRP jacket at tensile failure to the FRP ultimate strain in pure uniaxial tension tests. The FRP effective ultimate strain has been shown to be less than the ultimate tensile strain in uniaxial tension tests. There are a number of possible reasons for the premature failure of the FRP jacket, such as the multiaxial stress state, stress concentrations due to concrete failure, or the curved shape of the jacket.

The jacket curvature, especially at corners with low radius, may be an important factor for square or rectangular columns with rounded corners. However, most models do not take this aspect into account and they propose a single strain efficiency factor regardless of the shape of the section. So far, very few studies have focused on the study of FRP ultimate strain in square sections. In this paper the effective ultimate strain values obtained in an experimental program on square section concrete specimens confined with FRP are analyzed. The results of a previous study, summarized in section 3.1, motivated the authors to carry out a second phase of the experimental study, which is presented in more detail below.

2. FRP effective ultimate strain

The ultimate strength of FRP confined concrete is related to the FRP effective ultimate strain reached at the time of jacket rupture. Experimental studies have shown that this effective strain ϵ_{fe} is much less than the ultimate strain ϵ_{fu} obtained in standardized FRP tensile tests. The ratio between both values is usually called strain efficiency factor $k_\epsilon = \epsilon_{fe} / \epsilon_{fu}$.

There exist two types of tests for characterizing the tensile behavior of the FRP material: tensile testing of flat coupons [33-34], and split disk test specimens [35]. Chen et al. [36] observed that FRP ultimate strain obtained from a split-disk test is usually less than that obtained from a flat coupon test, due to geometric discontinuities at the ends of the FRP and to circumferential bending of the FRP ring at the gap of the two half disks. Flat coupon tests are more commonly used, and the technical data supplied by manufacturers are usually based on this type of tests.

Regarding the possible causes for the reduced value of the effective ultimate strain, the following have been indicated: the triaxial state of stress of the jacket, the quality of the execution, the curved shape of the reinforcement, size effects when applying multiple layers and inhomogeneous deformation and cracking of the concrete core that can lead to local stress concentrations.

The fib Bulletin 14 [24] indicates that proper design values for the effective ultimate strain should be justified by experimental evidence, due to the limited data available. Since the publication of fib Bulletin 14, in 2001, a large number of experimental studies on FRP confined concrete have been carried out, but the dispersion found in the effective ultimate strain data is very large. For example, in Xiao and Wu [37], effective ultimate strain values of approximately 50-80% of those obtained in flat coupons are indicated, but De Lorenzis and Tepfers [22] observed, based on a global review of FRP wrapped circular specimens, a strain efficiency factor ranging from more than 1 to less than 0,1. Similarly, Sadeghian and Fam [38] obtained from the analysis of a database formed by 454 cylindrical test tubes, values ranging between 1.22 and 0.12, with a mean value of 0.67. Other authors [13, 30, 39] also find similar average values, around 0.6, from their own tests and tests collected from the literature. However, they highlight the great dispersion in the results and even recommend to carry out a small number of tests to determine the strain efficiency factor for a given FRP in confinement applications. All these results show the difficulty to predict the effective ultimate strain and highlight the need for further investigations.

The curvature of the fibres in the jacket has been pointed out in several studies [39-41] as one of the causes of the reduced value of the effective ultimate strain, which is especially relevant in square and rectangular sections with rounded corners. It is well known that FRP confinement is much less effective for rectangular columns (including square columns as a special case) than for circular ones. In a circular column the jacket exerts a uniform confining pressure, while in a rectangular one the confining action is mostly concentrated at the corners. The predictive equations found in design recommendations are mostly based on approaches created for circular columns and then modified by a shape factor, usually defined as the ratio of the effectively confined area to the gross area of the column cross section. However, the models rarely take into account that the FRP effective ultimate strain may be smaller due to the jacket curvature at the corners. Most of the experimental studies carried out focused on cylindrical specimens. The experimental data available for square or rectangular columns are still limited and few studies have specifically addressed the issue of FRP failure strain.

Wang and Wu [41] conducted tests on square sections to investigate the effect of corner radius, finding that strength gain increases with corner radius, with a nearly linear tendency, but a reduction in FRP rupture strain was observed only for columns with sharper corners ($R_c < 15$ mm). Wu and Wei [42] performed tests on axially loaded short rectangular columns concluding that the FRP rupture strain was apparently unaffected by the aspect ratio.

Pham and Hadi [43] collected a test database of 190 FRP confined rectangular concrete columns, and from a small number of specimens in which the rupture strain at the corners of sections had been reported, they generated an equation to obtain the strain efficiency factor k_ϵ as a function of the corner radius R_c , length of the shorter side d and confinement stiffness ratio ρ_k :

$$k_\epsilon = 0.5 + 0.0642 \ln \frac{2R_c}{d\rho_k} \quad (1)$$

The confinement stiffness ratio was defined by Teng et al. [17] for a circular section as a function of its diameter D , the thickness t and elastic modulus E_f of the FRP and the properties of the unconfined concrete. For a rectangular section Pham and Hadi replace $D / 2$ with the corner radius:

$$\rho_k = \frac{tE_f}{\left(\frac{f_{co}}{\varepsilon_{co}}\right)R_c} \quad (2)$$

From the analyzed data they recommend that that the FRP strain efficiency factor be neither less than 0.4 nor greater than 0.7.

In view of these investigations, theoretical models have also included the concept of effective ultimate strain, which had not been initially taken into account. In the design guidelines in different countries, the generally accepted approach is to recommend a strain efficiency factor k_ε of approximately 0.60, for both circular and rectangular sections, based on the average value reported by several researchers. However, the Revised Concrete Society Technical Report TR55, 3rd Edition [25], recommends smaller values for k_ε in the case of rectangular sections. In section 4 the proposals of the different guides are reviewed and compared with the experimental results of this work.

3. Experimental program

Axial compression tests have been performed on specimens with a square cross section of 150x150 mm and a height of 600 mm. The experimental program has been developed in two phases:

- In the first phase, 26 reinforced concrete specimens strengthened with FRP and 2 unstrengthened specimens were tested. The preliminary results corresponding to the first 10 specimens tested and details of the experimental program were reported in [10]. In section 3.1, the results of 28 tested specimens are summarized. Concrete with low compressive strength (approximately 10 to 25 MPa) was used, given the lack of available data in the literature. The longitudinal reinforcement consists of 4 steel bars, 6 mm diameter with a yield stress of 500 N / mm², and steel stirrups (6 mm diameter) were spaced at 100 mm. The variables studied were the type of reinforcing fibre (glass or carbon) and the concrete strength. The corners of the section were rounded with a radius of curvature $R_c = 25$ mm.
- In the second phase, 14 plain concrete specimens were tested: 12 specimens strengthened with carbon FRP and 2 unstrengthened specimens. A medium strength concrete was used with a compressive strength of 41 MPa. The variables are the amount of FRP reinforcement (1, 2 and 3 layers of carbon fiber) and the corner radius R_c (20 and 40 mm).

3.1. Phase I

Table 1 shows a summary of the results from Phase I tests. Specimens are named as follows: the first letter indicates the type of fibre (C for carbon and G for glass) and the unconfined concrete compressive strength f_{co} (determined by testing 150 x 300 mm cylinders) is indicated below.

The confined concrete strength f_{cc} , strength enhancement ratio (f_{cc}/f_{co}), ultimate axial strain (ϵ_{cc}), ultimate transversal strain and strain efficiency factor k_ϵ are presented. Each value in the table is the average of two specimens with the same characteristics (average of 3 specimens in series C_16.5 and G_16.5).

Specimen	f_{co} [MPa]	f_{cc} [MPa]	f_{cc}/f_{co}	ϵ_{cc} [%]	ϵ_{fe}	$k_\epsilon = \epsilon_{fe}/\epsilon_{fu}$
C_8.8	8.8	21.7	2.46	1.72	-0.0033	0.22
C_13	13.0	23.2	1.79	3.44	-0.0045	0.30
C_16.3	16.3	31.4	1.93	2.35	-0.0057	0.38
C_16.5	16.5	28.4	1.72	1.97	-0.0053	0.35
C_16.7	16.7	29.6	1.77	2.49	-0.0044	0.29
C_17.5	17.5	25.8	1.48	2.86	-0.0041	0.27
C_26.4	26.4	41.3	1.56	1.34	-0.0065	0.50
G_8.8	8.8	20.8	2.37	2.98	-0.0051	0.15
G_13	13.0	20.3	1.56	2.88	-0.0075	0.22
G_16.5	16.5	24.6	1.49	2.13	-0.0107	0.31
G_16.7	16.7	25.3	1.51	2.33	-0.0084	0.25
G_17.5	17.5	24.6	1.40	2.93	-0.0098	0.29

Table 1. Phase I. Summary of results.

The results show that FRP confinement can enhance considerably the compressive strength and ductility of reinforced concrete square columns with rounded corners. As already known, the confinement effectiveness decreases with the increase of unconfined concrete strength.

Results regarding FRP effective ultimate strain are analysed in section 4.2, together with those obtained in Phase II.

3.2. Phase II

In view of the results obtained in the first part of the study, a second experimental program was conducted with the aim of further investigating the possible influence of the column shape on the FRP effective ultimate strain.

In this case, specimens were manufactured with a medium strength concrete, without internal steel reinforcement, and were externally strengthened with carbon fibre.

Test set-up and instrumentation are the same as those used for the previous tests. The axial and transverse strain is measured by LVDTs and electrical strain gauges, as shown in Fig. 1.

Fig. 1. Test set-up and instrumentation details.

The mechanical properties of FRP have been determined by tensile tests of flat coupons according to [34]. The average tensile strength, modulus of elasticity and rupture strain of single-layer CFRP were found 4161 MPa, 237 GPa and 1.776% respectively (average values, based on the net-fibre thickness, which is 0.129 mm).

Table 2 shows the results from the second phase of tests. The strengthened specimens are named as follows: the first number indicates the number of reinforcement layers (0, 1, 2 or 3)

followed by the corner radius in mm (20 or 40). Two specimens have been tested for each type, which are designated with the letters *a* and *b*. The average strength of concrete at 28 days is f_{co} = 41 MPa.

Specimen	f_{cc} [MPa]		f_{cc}/f_{co}		ε_{cc} [%]		ε_{fe}		$k_c = \varepsilon_{fe} / \varepsilon_{tu}$	
0_a	35.7	35.5	0.87	0.87	0.002 14	0.0021	-			
0_b	35.3		0.86		-					
1_20_a	41.2	43.0	1.01	1.05	0.008 08	0.0069	-0.0100	-0.0097	0.56	0.55
1_20_b	44.8		1.09		0.005 75		-0.0094		0.53	
1_40_a	52.5	52.0	1.28	1.27	0.010 66	0.0091	-0.0136	-0.0116	0.77	0.65
1_40_b	51.5		1.26		0.007 55		-0.0095		0.54	
2_20_a	51.4	55.2	1.25	1.30	0.008 26	0.0139	-0.0086	-0.0088	0.48	0.50
2_20_b	58.9		1.35		0.019 48		-0.0091		0.51	
2_40_a	77.0	76.0	1.88	1.85	0.021 14	0.0197	-0.0123	-0.0119	0.69	0.67
2_40_b	75.1		1.83		0.018 33		-0.0115		0.65	
3_20_a	84.1	78.6	2.05	1.92	0.020 89	0.0182	-0.0132	-0.0109	0.74	0.61
3_20_b	73.2		1.78		0.015 54		-0.0086		0.48	
3_40_a	94.6	93.6	2.31	2.28	0.013 53	0.0145	-0.0112	-0.0110	0.63	0.62
3_40_b	92.6		2.26		0.015 51		-0.0109		0.61	

Table 2. Phase 2. Summary of results

The confined concrete strength increases with the number of FRP layers and with the corner radius R_c . For specimens with a certain number of FRP layers, a very remarkable improvement is achieved by increasing the corner radius from 20 to 40 mm. In practical applications, the maximum achievable corner radius depends on the existing concrete cover. For the tested specimens, the strength improvement achieved by increasing R_c from 20 to 40 mm is practically equivalent to that achieved applying one more layer of reinforcement (Figure 2). In series 1_20 (specimens with a corner radius $R_c=20$ mm, strengthened with one FRP layer) there is practically no improvement of concrete strength, taking as reference the value of unconfined concrete obtained from tests of control cylindrical specimens ($f_{co} = 41$ MPa). However, a gain in strength of about 30% is achieved either increasing the radius of rounding to 40 mm or applying a further layer of reinforcement (series 1_40 and 2_20 respectively).

Fig. 2. Effect of number of FRP layers and corner radius.

The typical failure mode of FRP-confined concrete was observed (Fig. 3). All the specimens failed in a sudden and explosive way, due to the hoop tensile rupture of the FRP jacket. FRP rupture usually occurred at or near the corners.

Fig.3. Failure mode.

Fig. 4 to 6 show the experimental axial stress-axial strain and axial stress-lateral strain curves of all the tested specimens. For specimens strengthened with two and three FRP layers (Figs. 5 and 6) the typical bilinear behaviour with an ascending second branch is observed. In series 1_20 (specimens with $R_c = 20$ mm strengthened with 1 FRP layer) the stress-strain curve shows a plateau in the post-peak load part, but when the radius of rounding is increased to 40 mm, the ascending bilinear behavior is observed (Fig. 4).

Fig. 4. Stress-strain behaviour of specimens strengthened with 1 FRP layer.

Fig. 5. Stress-strain behaviour of specimens strengthened with 2 FRP layers.

Fig. 6. Stress-strain behaviour of specimens strengthened with 3 FRP layers.

4. Strain efficiency factor: proposals in the design guidelines and comparison with experimental results

4.1. Design guidelines

In this section, the proposals about the strain efficiency factor presented in some international design guidelines are reviewed.

In fib Bulletin 14 [24], published in 2001, it was already pointed out that the failure of the FRP wrapping reinforcement mostly occurs at strains lower than the ultimate strain obtained by standard tensile testing of the FRP sheet. The document indicates that proper design values for the effective ultimate strain should be justified by experimental evidence, due to the limited data available.

In ACI 440.2R-17 [26], a strain efficiency factor $k_\epsilon = 0.55$ is proposed, based on experimental calibrations by different authors [13, 30, 44]. For members subjected to combined axial compression and bending, the effective strain in the FRP should be further limited to a maximum value of 0.004 to ensure the shear integrity of the confined concrete.

CNR-DT 200 R1/2013 [27] propose a reduced FRP design strain computed as:

$$\epsilon_{fd,rid} = \min\left\{\eta_a \cdot \frac{\epsilon_f}{\gamma_f}; 0,004\right\} \quad (3)$$

Where η_a is an environmental conversion factor (with values between 0.85 and 0.95 for carbon/epoxy systems and between 0.50 and 0.75 for epoxy/glass FRP) and γ_f is equal to 1.1. This proposal should be equivalent to considering a strain efficiency factor k_ε around 0.45-0.68 for glass reinforcement and 0.77-0.86 for carbon reinforcement. But the maximum allowed strain is 0.004, although the reason for this limitation is to avoid excessive cracking in the concrete.

The UK Concrete Society TR55 [25] recommends for circular columns a strain efficiency factor $k_\varepsilon = 0.6$, also from the observations of experimental results collected in Lam and Teng. An important aspect is that, unlike the previous documents, the TR55 further limits the effective ultimate strain in the case of rectangular sections. For rectangular columns with rounded corners the rupture strain decreases as the ratio of the corner radius to side length decreases, and the strain efficiency factor is given by the following expression:

$$k_\varepsilon = 0,46\left(\frac{2R_c}{b}\right) + 0,14 \quad (4)$$

Where b is the length of long side, and R_c the radius of corner. Note that for practical corner radii, a factor k_ε around 0.2 is obtained.

Equation (4) is based on the variable strain efficiency equation proposed by Barrington et al. [45], assuming a linear relationship between column circularity ($2R_c/b$) and strain efficiency, and a maximum strain efficiency factor of 0,7:

$$k_\varepsilon = 0,54\left(\frac{2R_c}{b}\right) + 0,16 \quad (5)$$

In summary, the reviewed guidelines recommend an effective ultimate strain which lies between about 20 and 60% of the rupture strain in the FRP under uniaxial tension. It is striking that, despite its influence on the accuracy of the models, it is an unresolved issue that needs further research.

4.2. Experimental results

Table 1 gives the values of ultimate lateral strain or effective strain (ε_{fe}) and strain efficiency factor (k_ε) in the specimens from the first phase of the experimental program. Each value in the table represents the average of two specimens. The effective ultimate strain of each specimen is the average of the readings on the four strain gauges located at midheight, one on each side

of the specimen. The effective ultimate strain is lower than the ultimate tensile strain from tensile coupon tests.

In specimens strengthened with carbon FRP, the strain efficiency factor k_ϵ ranges from 0.22 to 0.51, with an average value of 0.33. In specimens strengthened with glass FRP, the efficiency factor k_ϵ ranges from 0.15 to 0.37, with an average value of 0.24. The value of k_ϵ is slightly lower than that of the specimens strengthened with carbon fibre. Although the limited number of tests does not allow to draw conclusions, a smaller value of k_ϵ has been obtained for specimens manufactured with low strength concrete.

The values of k_ϵ obtained in these tests are much lower than those obtained from literature databases and adopted by some design recommendations. A possible reason could be related to the shape of the cross section with the rounded corners since, as previously indicated, some studies have shown a decrease in the effective ultimate strain when the jacket corner radius decreases. TR55 is the only guide that recommends a smaller value of k_ϵ for rectangular sections. For the specimens tested in the Phase I, with $R_c = 25$ mm, a factor $k_\epsilon = 0.29$ is obtained according to equation (4), which is very similar to the average experimental values.

In order to clarify the influence of the corner radius on the effective ultimate strain, test samples with $R_c = 20$ and 40 mm were tested in the second part of the experimental work, and the results are shown in Table 2. In all the specimens tested in the second phase of the study, the effective ultimate strain is also lower than the tensile rupture strain determined from flat coupon tests ($\epsilon_{fu} = 1.776\%$). The strain efficiency factor k_ϵ ranges between 0.48 and 0.77, with a mean value of $k_\epsilon = 0.60$, which in this case coincides with the value proposed in TR55 for circular sections and generally proposed in other guidelines, despite being square section columns, and it is much higher than that obtained in phase I of the experimental program.

The results do not show a relationship between the effective ultimate strain and the amount of reinforcement. In series 1 and 2 of phase II (specimens strengthened with 1 and 2 carbon layers), it is observed that the effective ultimate strain increases with the corner radius. In series 3 (specimens with high confinement ratio, not used in practical applications) similar values of k_ϵ have been observed independently from the value of corner radius. The corresponding values from equation (4) are $k_\epsilon = 0.26$ for $R_c = 20$ and $k_\epsilon = 0.39$ for $R_c = 40$. However the experimental

values are $k_\varepsilon = 0.55$ for $R_c = 20$ and $k_\varepsilon = 0.65$ for $R_c = 40$. The approach of TR55 that recommends a smaller effective ultimate strain in the case of square or rectangular sections seems a valuable contribution, although the results obtained in this work do not agree with the formulation proposed in equation (4).

A modification of equation (5) which better fits the experimental results of phase II is proposed as follows:

$$k_\varepsilon = 0,54 \left(\frac{2R_c}{b} \right)^{0,25} + 0,16 \quad (6)$$

And in order to be congruent with the maximum value of $k_\varepsilon = 0.6$ for circular columns recommended by actual guidelines, equation (6) should be transformed into:

$$k_\varepsilon = 0,46 \left(\frac{2R_c}{b} \right)^{0,25} + 0,14 \quad (7)$$

The above proposed equation (7) should be applicable for square columns cast with medium strength concrete, and should be verified by testing full-size reinforced concrete columns.

In view of the results of phase II, it can be concluded that the very low values of effective ultimate strain obtained in phase I can not be solely attributed to the section shape, but could also be related with the buckling of the internal steel rebars. Local stress concentrations caused by lateral buckling of steel rebars might have caused the premature failure of the FRP jacket in the specimens of phase I. The specimens of phase II have no internal reinforcement, as the majority of results from the literature. More experimental work is needed to investigate the interaction between the internal steel reinforcement and external FRP jacket. Finally, it must be noted that, in phase I, specimens with a very low concrete strength have been tested, since most of the tests available in the literature have been carried out on cylindrical plain concrete specimens with an unconfined concrete strength greater than 30 MPa.

5. Conclusions

The following conclusions are drawn from this work:

- The test results show that the FRP confinement can increase the strength and ductility of concrete columns of square section with rounded corners. As is already known, the confinement effectiveness decreases with the increase of unconfined concrete strength.

- The strength gain achieved increases with the amount of reinforcement and, for a given amount, increases with the radius of curvature of the corners R_c . It has also been observed that the stress-strain behaviour depends on the corner radius, so it would be advisable to take into account this parameter in order to establishing a minimum confinement ratio for non-circular sections.
- The average value of the strain efficiency factor obtained in the medium strength concrete specimens strengthened with carbon FRP is $k_\epsilon = 0.60$, which coincides with the value obtained by some researchers based on the results of literature review. Within the scope of the studied parameters, and with the limitations derived from the small number of specimens, the test results show that the effective ultimate strain increases with increasing corner radius, for specimens strengthened with one or two FRP layers (common reinforcement ratios).
- In the tests on low strength concrete specimens, a much lower value of k_ϵ has been obtained: 0.24 in glass FRP confined specimens and 0.33 in specimens strengthened with carbon FRP. These results point to the influence of other factors besides the radius of curvature, such as the very low strength of the concrete or the buckling of the steel rebars. The interaction between the internal reinforcement and the FRP jacket is an aspect that requires further investigation.
- An accurate estimation of the FRP effective ultimate strain is needed to predict the compressive strength and ultimate axial strain of FRP confined columns. Despite its importance, this aspect is still unclear and there is no consensus among the reviewed design guidelines.
- The approach of TR55 that recommends a smaller effective ultimate strain in the case of square or rectangular sections seems a valuable contribution, although the results obtained in this work do not agree with the proposed formulation. A modification of the strain efficiency factor proposed in TR55 has been proposed.
- Further experimental research needs to be conducted on large-scale columns, very limited to date, to verify these findings.

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