Square and rectangular columns confined by FRP: experimental investigations *vs* ultimate strain prediction

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ABSTRACT: Ultimate stress and strain prediction is an important issue to be solved in order to define the performance of FRP confined section. In case of circular section, the task can be considered as partially solved thanks to the several studies carried out. In case of square and rectangular sections, the difficulties due to the non-uniform confinement stress distribution are delaying the problem solution. Furthermore, the well-known problem of an objective definition and characterization of the ultimate strain increased the difficulty level: the strain of the confinement device, as well as the confinement efficiency, depends on the corner radius and is not uniformly distributed along the boundary section. Regarding the ultimate strength definition, an analytical solution has been proposed in a companion paper, while in this paper an experiment-based expression is proposed and validated against a set of experimental values collected in a database that includes also the tests carried out by the authors.

1 INTRODUCTION

Research on FRP-confined concrete has reached a level that can be considered so satisfactory to be included in a design code. Different, but not several, codes have been developed and among them the Italian guidelines (National Research Council, 2004) can be considered as a good reference, even if further modification can be introduced in order to improve the predictive equations. In this framework the authors have been involved in the code update and, in order to improve the confinement models, focused their attention on: 1) ultimate axial strain and strength prediction, 2) Poisson modulus *vs* axial strain prediction, 3) stress *vs* strain law evaluation. Some of this problems, currently in evolution, have been proposed in other works; here the problem of the ultimate strain prediction has been focussed on, together with the ultimate strength evaluation proposed in a companion paper (Monti and Nisticò, 2008), where an analytical solution is presented.

2 EXPERIMENTAL RESULTS AND PHENOMENOLOGICAL ASPECTS

Experimental investigations on square sections date back to the tests proposed in (Mirmiran et al., 1998) where the effects of the corner radius were clearly described, influencing both strength and ultimate strain.
In that work compression tests were carried out on nine specimens (305 mm tall) of square (152.5×152.5 mm) concrete (f_{co} = 40.6 MPa) section confined by G-FRP. Three different confinement configurations have been considered, characterized by 6, 10 and 14 plies (wrapped with a ± 75° angle); for each configuration, three specimens have been tested. All specimens were characterized by rounded corners with curvature radius of 6.35 mm.
After the Mirmiran *et al*. work, other contributions focussed either on the prediction of ultimate parameters or on the development of constitutive models matched against tests on small specimens.

In (Rochette and Labossière, 2000) the authors presented the tests they carried out on three specimens of square (152.0×152.0 mm) concrete (f_{co} = 42.63 MPa, in average) section confined by C-FRP. Two specimens were characterized by a 25 mm rounded corners radius, while the remaining one by a 38 mm radius.
In (Parvin and Wei Wang, 2000) compression tests were carried out on nine specimens (305 mm tall) of square (108.0×108.0 mm) concrete (f_{co} = 21.4 MPa) section confined by C-FRP. Three different configurations have been considered: 1) unwrapped, 2) wrapped with one layer, and 3) wrapped with two layers. To prevent collapse of the specimen at the top and bottom parts (instead of the central part), one more layer has been applied at the specimens ends. All specimens were characterized by rounded corners with curvature radius of 6.35 mm. For each configuration the load has been applied with an eccentricity 0, 7.60 and 15.20 mm.
In (Wang and Restrepo, 2001) compression tests were performed on 6 reinforced concrete specimens (900 mm tall) of square (300x300 mm) and rectangular (300×450 mm) section. For each type of section three configurations have been considered: 1) unwrapped, 2) wrapped with 2 plies of carbon sheets, 3) wrapped with 6 plies of glass sheets. The longitudinal reinforcement (430 MPa nominal yield strength) consist of four 20 mm bars (square section) and of six 20 mm bars (rectangular section). The stirrups (300 MPa nominal yield strength, 10 mm diameter) were spaced at 180 mm to simulate older construction detailing, even if they were closed with 145° anchorage). The test procedure consists in loading and unloading phases, including tensile stress up to an axial strain of almost 0.4%.
In (Tastani et al., 2006) compression tests were performed on 31 reinforced concrete specimens (320 mm tall) of square (200x200 mm) section. The chosen height was consequent to the available loading frame, as reported by the authors. The longitudinal reinforcement consists of four 12 mm diameter bars (562 MPa nominal yield strength). Two typologies of stirrups (220 MPa nominal yield strength, 6 mm diameter) have been selected to simulate former (stirrups spaced 140 mm, with a 90° anchorage) and modern (stirrups spaced 75 mm, with a 135° anchorage) requirements. All the specimens had a corner radius of 25 mm. Among the 31 specimens, four (two for each stirrups typology) have been tested as reference unwrapped specimens, while the others can be classified based on wrapping typology (sheets or strips) and material (carbon and glass), and also on the preliminary application (before the composite wrapping) of an axial load in order to simulate an initial damage condition. Here, only the non-damaged specimens are considered so that the results of 17 (2 unwrapped) specimens will be analysed and all of them refers to the former (not modern) requirements. Among the 15 wrapped specimens, 6 were characterized by glass sheets wrapping (2 and 4 plies, 3 specimens for each typology), 6 were characterized by carbon sheets (2 and 4 plies, 3 for each typology), the remaining 3 were wrapped with carbon strips (2 plies). The adopted concrete had 15 MPa 28-day cylinder strength that evolved to 21.2 MPa at the time of the tests.
In Wang and Wu (2007) compression tests were performed on 108 concrete specimens (300 mm tall). The section of all the specimens can be considered inscribed in a square (150x150 mm) section with six values of the corner radius: 0, 15, 30, 45, 60 and 75 mm (so that circular sections have been included in the tests). Two different types of concrete (C30 and C50) and two jacket thicknesses (0.165 and 0.33 mm) have been considered, so that 36 classes of specimens have been tested (including the unwrapped specimens). The composite mechanical properties regards those obtained by means of coupon tests, as reported by the authors.
In (de Diego et. al, 2007) compression tests were performed on thirty specimens of square (150×150 mm) concrete columns (600 mm tall). All the specimens were characterized by rounded corners with curvature radius of 25 mm. The top and bottom part of each specimens consists of capitels (400×400×140 mm) that simulate the beam-column connection. The concrete specimens have been reinforced by means of longitudinal bars (4ø6) and transversal stirrups (ø 6/100) steel bars. The tested specimens can be grouped based on the confinement devices that are: 1) wrapping, 2) prefabricated shell, and 3) prefabricated shell and wrapping at the column top and bottom. For each group, two different composite materials (glass and carbon) were adopted, and five concrete cylinder unconfined strengths ranging between 8.8 and 17.5 MPa were used.
The tests on small specimens could be considered exhaustive and general conclusions can be: 1) the ultimate strength increase is evident if the radius corner is appropriate, 2) the ultimate strain

increase is evident even if statistically it is difficult to find a strong dependence of that increase on both mechanical and geometrical properties of the confining device.
Even if the test database can be considered as exhaustive, the lack of systematic tests on large scale specimens (columns) is felt: contributions have been given in (Toutanji *et al*, 2007) and (Monti *et al*., 2007).
In (Toutanji *et al*, 2007), the authors performed tests on square (355x355 mm) and rectangular (250x500 mm) concrete columns (2000 mm tall). The concrete characterized by un unconfined strength of 38.5 MPa (in average), have been reinforced by means of longitudinal bars (8ø14) and transversal stirrups (ø 8/140 in the central part and ø 8/50 at the column top and button). The adopted wrapping consists of two-layer GFRP straps, placed using the wet lay-up technique. For the square sections, two corner radii have been considered (15 and 30 mm); the corner of the rectangular was characterized by a radius of 30 mm. For each typical section two different configurations were considered: 1) unwrapped, and 2) fully wrapped.
In (Monti *et al*., 2007), the authors performed tests on nine columns of square (200x200 mm) and rectangular (200x300 and 200x400 mm) concrete columns (1400 mm tall). All the specimens were characterized by rounded corners with curvature radius of 20 mm. For each typical section three different configurations were considered: 1) unwrapped, 2) fully wrapped, and 3) fully wrapped with steel L-shaped angles placed along the corners. The wrapping consists of HM Carbon FRP straps, placed using the wet lay-up technique: 1) the 200×200 and 200×300 mm sections were characterized by one FRP layer along the height and two layers at the top and bottom of the column, 2) the 200×400 mm sections were characterized by two layers along the whole height. The steel L-shaped angles (4 mm thick and 86 mm long) have been preformed so to have the same curvature radius of the corner they are placed on. The test results highlight that: 1) the axial strain cannot be considered as uniformly distributed along the column, 2) the ultimate global strain is generally significantly lower than the maximum strain, 3) the damage is generally localized at the column top and in general is not smeared but tends to be concentrated along an inclined crack, and 4) a concentration of damage along the section sides is not observed, which implies a weak arching effect.

3 ULTIMATE STRAIN PREDICTION

The problem of the prediction of the ultimate axial strain, as well as the ultimate stress, is clearly dependent on both the specimen geometry and the mechanical properties of concrete and confinement device. Regarding the mechanical properties of concrete, clearly the past literature have said a lot in terms of measurability and statistical distribution even if more has to be done. Regarding the composite material combined with concrete, the crucial points are related to the effective ultimate strain (here called $\varepsilon_{j,rupt}$) that can be lower than the ultimate strain (here called ε_j) measured by means of either flat coupon or split disk tests. In general, the composite behaviour is assumed as linear, by neglecting material hardening, so that the ultimate composite force can be expressed according to the following expression:

$$F_{lu} = E_j \cdot (n \cdot t) \cdot (\alpha \cdot \varepsilon_j) \quad (1)$$

where E_j = fiber Young modulus, n = number of layers, t = conventional width of each layer and α reduction factor of ε_j .
It is well known that, for circular sections, if one knows the composite ultimate resisting force as expressed through Equation 1, the ultimate confinement stress is simply evaluable (see Equation 2), by neglecting the material non-homogeneity as well as the absence of axial symmetry due to the composite overlapping zone:

$$f_{lu} = 2\frac{F_{lu}}{D} = E_l \cdot (\alpha \cdot \varepsilon_j) \quad (2)$$

where D is the section diameter and E_l is the so-called confinement modulus.

Studies on ultimate prediction of ultimate strain (De Lorenzis and Tepfers, 2003) showed that the ultimate strain predictive models are less performing if compared to the ultimate strength predictive ones. For circular section the authors proposed to predict the ultimate strain through Equation 3, whose Average Error (AE) is ~20%, adopting a) c_1 = 26.2 2; b) c_2 = 0.80 for FRP wraps, and c_2 = 0.68 for FRP tubes; c) c_3 = -0.148 for FRP wraps and c_3 = -0.127 for FRP tubes.

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1 + c_1 \cdot \left(\frac{f_{lu}}{f_{co}} \right)^{c_2} \cdot \left(E_l \right)^{c3} \tag{3}$$

The previous expression can be rearranged as follows:

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1 + 26.2 \cdot \left(\frac{\varepsilon_{ju}}{f_{co}} \right)^{|c_3|} \cdot \left(\frac{f_{lu}}{f_{co}} \right)^{(c_2 - |c_3|)} \tag{4}$$

in order to highlight the ultimate strain dependence on: 1) unconfined strength, 2) confinement device ultimate strain, and 3) maximum confinement stress.
The previous dependence is also evident by looking at other models. In (Lam and Teng, 2003) the following expression have been proposed:

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1.75 + 12 \cdot \left(\frac{f_{lu}}{f_{co}} \right) \cdot \left(\frac{\varepsilon_{j,rup}}{\varepsilon_{co}} \right)^{0.45} \tag{5}$$

In (Xiao and Wu, 2000) the authors proposed an expression to capture the dependence of the transverse (radial) strain (ε_r) on axial strain. The proposed expression, approaching the material the ultimate condition, can be expressed as follows:

$$\varepsilon_r = -0.0005 - 7.0 \cdot \varepsilon_{cc} \cdot \left(\frac{f_{co}}{E_l} \right)^{0.8} \Rightarrow \varepsilon_{cc} = -\frac{1}{7} \left(\varepsilon_r + 0.0005 \right) \cdot \left(\frac{E_l}{f_{co}} \right)^{0.8} \tag{6}$$

Considering that, at ultimate ($\varepsilon_r = \varepsilon_{rup}$), the transversal strain attains at least (depending on the adopted composite) a value of 0.005 (one order greater than 0.0005) and that E_l can be expressed in terms of f_{lu} and ε_{rup}, the previous expression can be rearranged as follows:

$$\varepsilon_{cc} = -\frac{1}{7} \left(\varepsilon_r \right)^{0.2} \cdot \left(\frac{f_{lu}}{f_{co}} \right)^{0.8} \tag{7}$$

Based on the previously discussed literature expressions, it is evident that the prediction of the ultimate axial strain can be based on the following expression, which can be regarded as an attempt of generalization of the literature proposals:

$$\varepsilon_{cc} = B_1 + B_2 \cdot \left(\alpha \cdot \varepsilon_{j,coup} \right)^{B_3} \cdot \left(\frac{f_{lu}}{f_{co}} \right)^{B_4} \tag{8}$$

Furthermore, in order to obtain a generalized expression applicable for both circular and square/rectangular sections, it is possible: 1) to express the confinement stress f_l in terms of predicted ultimate stress f_{cu}, 2) to introduce a shape factor (r^*) in terms of the ratio between the corner radius (r_c) and the minimum half length side (section radius in case of circular section). After different attempts, based on a trial-and-error approach, the following expression has been developed:

$$\varepsilon_{cc} = \beta_1 + \beta_2 \cdot \frac{f_{cu}}{\left(f_{co} \right)^{\alpha_1}} \cdot \left[\left(\frac{f_{cu}}{f_{co}} \right)^{\alpha_2} + \left(r^* \right)^{\alpha_3} \right] \cdot \left[\beta_3 \cdot \varepsilon_{j,coup} \left(2 \cdot \frac{r_c}{L_{\min}} \right)^{\alpha_4} \right]^{\alpha_5} \cdot \left(\frac{f_{lu}}{f_{co}} \right)^{\alpha_6} \tag{9}$$

4 RESULTS AND DISCUSSIONS

Equation 9 defines the ultimate strain evaluation for both circular and square/rectangular sections as function of: 1) nine parameters, and 2) the ultimate stress whose value can be predicted according to the expressions reported in a companion paper (Monti and Nisticò, 2008). After a preliminary calibration that allowed the definition of the eight parameters (see Equation 10, in MPa), the proposed expression has been validated against a selected set extracted from the experiments discussed in section 2 (see Figure 1):

$$\varepsilon_{cc} = \alpha \times \left\{ 0.0052 + 0.2877 \cdot \frac{f_{cu}}{\left(f_{co}\right)^2} \cdot F \cdot \left[\frac{f_{lu}}{f_{co}} \cdot \varepsilon_{j,coup} \left(2 \cdot \frac{r_c}{L_{\min}} \right)^{0.29} \right]^{0.1} \right\} \tag{10a}$$

where α is a scale factor equal to 1 in case of specimens and 0.4 in case of tall columns and:

$$F = \left[\left(\frac{f_{cu}}{f_{co}} \right)^{-0.33} + \left(r^*\right)^{3.73} \right] \tag{10b}$$

In case of small specimens, the evaluated errors are reported in Table 1 in terms of: 1) Average absolute percentage Error (AE), and 2) Average Ratio (AR) between predicted and experimental values (the errors have been specified distinguishing the sets of square, rectangular and circular sections here intended as sections with $r^* \geq 0.5$). Regarding tall columns the expression has been matched against some of the results reported in (Toutanji *et al*, 2007) and (Monti *et al*, 2007) obtaining AE ~ 20.0 and AR ~ 1,1: regarding the former tests, column with steel angle have not been considered, while regarding the latter, the rectangular section column has been excluded due to an absence of axial strain recording at the collapse zone (the recorded ultimate axial strain regards the column central part, while the composite collapse occurred at the top).

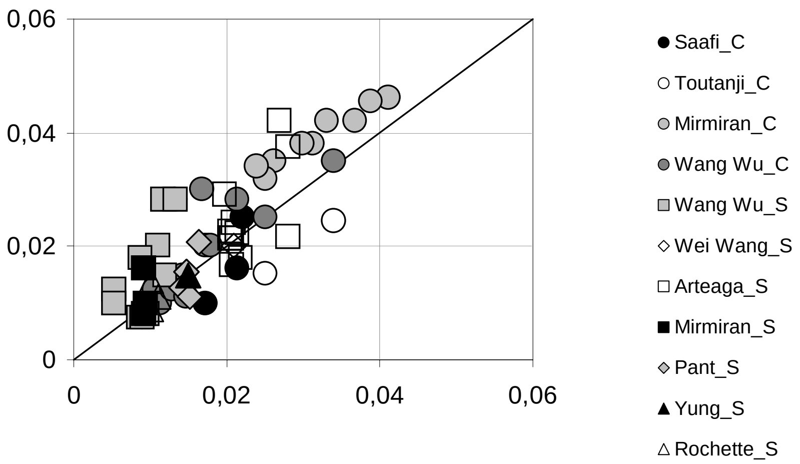

Figure 1. Experimental axial strain *vs* predicted values.

Table 1. Predictive equations: evaluated errors

	Square ($r^* \geq 0.5$)	Square ($r^* < 0.5$)	All
N_{tests}	27	38	65
AE	~24.20	~24.00	~24.00
AR	~1.13	1.25	~1.20

5 CONCLUSIONS

This paper presented an experiment-based model conceived and calibrated to predict the ultimate axial strain of FRP-confined square sections with different corner rounding radii. The model is based on a preliminary prediction of the confined section ultimate strength as well as the mechanical properties of the FRP adopted as confinement device. The model has been validated against a set of 70 tests.

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