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Behavior of square and circular columns strengthened with aramidic or carbon fibers

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ABSTRACT

The confinement of reinforced concrete (RC) columns with transverse reinforcement has been extensively studied and it is known that the response of concrete cylinders subjected to equivalent levels of pressure depends on how that lateral pressure is transmitted, and not on its magnitude alone. When confinement is, additionally to that given by steel stirrups, provided by external jackets of fiber reinforced polymers (FRP) the complexity and the scarcity of experimental data increase and tests to gain insight into the structural behavior and consequent design procedures are still required. The present study reports tests performed on axially loaded RC columns, with and without jackets. The FRP tested were made either of carbon fibers reinforced polymers (CFRP) or aramidic (AFRP) wraps and the geometry of the specimens included square and circular cross-sections. Comparison of gains of axial strength and ductility are presented and aspects of the variation of the lateral pressure and rupture of FRP jackets are examined.

1. Introduction

Reinforced concrete (RC) columns with outer confinement provided by fiber reinforced polymers (FRP) have their properties enhanced, especially increased ductility and maximum load carrying capacity. Those beneficial effects are achieved as a result of the lateral pressure, applied by the external jackets. The confinement prevents lateral expansion under axial load, adding to the stiffness of the concrete column. Indeed, well dimensioned lateral confinement can also increase lateral deflection capability of the columns and FRP composites have been used for instance for seismic upgrades.

The effectiveness of confinement is known to be greater for specimens of circular cross-section than for those of rectangular section, due to the singularity and stress concentration introduced at the edges and the reduced confinement on the flat sides. The mitigation of this shape effect may be achieved by rounding the corners of rectangular sections with the effectiveness of the procedure increasing with rounding radius, until a certain threshold is reached.

This paper examines comparatively the behavior of square and circular RC columns strengthened with outer reinforcement of carbon fiber reinforced polymers (CFRP) or aramidic fibers composites (AFRP). A brief survey of literature results on these topics is presented next.

A review of predictive equations to calculate the ultimate compressive strength and strain is presented in Lam and Teng [1] who carried out an extensive literature survey of tests made on FRP-confined circular concrete columns and found from the corresponding database that the relationship between strength of confined concrete lateral confining pressure to be linear. The entire stress–strain diagrams can be obtained from different proposed models as summarized in Manfredi and Realfonzo [2].Rochette and Labossière report the results on the behavior of square and rectangular columns confined with carbon and aramid fiber sheets that confirmed that confinement increased the strength and ductility of the concrete columns axially loaded [3]. However, the different dimensions of the specimens tested and the relatively high stiffness of the jackets pose some difficulties comparison and extrapolation of the results to actual practice.

Earlier work on modeling concrete confined with FRP can be found on [4] where an incremental-iterative approach was used to consider the interaction jacket-concrete and detect failure. The study allowed also the calculation of the ultimate strength and strain of concrete confined with FRP and was certified by contrasting predictions with available data at the time (1999).

Paula and Silva developed an experimental program to study the properties of square and circular columns confined with CFRP and defined an effective lateral confining pressure determined by introducing a confinement effectiveness coefficient k_e related to the ratio of the area of the confined concrete core and the area of concrete (gross cross-sectional area minus area of longitudinal steel reinforcement) [5].

Lam and Teng reported on experimental studies of CFRP-wrapped and axially loaded columns of circular and elliptical cross-sections and used previously proposed models to obtain

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numerical estimates [6]. Concrete in elliptical specimens is not uniformly confined, and the effects of confinement are reduced. Based on the tests, a compressive strength model is proposed, in which the effect of the section shape is taken into account by a shape factor that relates the capacity of elliptical columns to that of reference circular columns. The compressive strength of FRP-confined concrete f'_{cc} is then evaluated from

$$\frac{f'_{cc}}{f'_{c0}} = 1 + k_1 \frac{f'_l}{f'_{co}} \quad (1)$$

where k_1 is a constant due to the linearity of the relationship between the strength of confined concrete and f_l; f'_{cc}/f'_{c0} and f_l/f'_{c0} are, respectively, the strengthening and the confinement ratios; f'_{cc} and f'_{c0} the compressive strengths of confined and unconfined concrete and f'_l is the effective confining pressure, obtained by multiplying the lateral pressure f_l on an "equivalent" cylinder, with the same volumetric FRP as the elliptical specimen, by a shape factor k_2.

The lateral pressure on that circular column is obtained from the well-known formula

$$f_l = \frac{2 f_{frp} t}{d} = \frac{\rho_{frp} f_{frp}}{2} \quad (2)$$

where f_{frp} is the tensile strength of FRP in the hoop direction; t total thickness of the composite; d the diameter of the confined cylinder; and ρ_{frp} is the FRP volumetric ratio.

A total of 52 half-scale, short columns with an aspect ratio of 3.65 were tested to failure under axial load to the strength of the columns and an analytical procedure is proposed to evaluate the load capacity of the strengthened columns in [7]. CFRP and glass fiber reinforced polymers (GFRP) were utilized. Delamination was found to be more likely to occur with GFRP than with CFRP. Anchoring the transverse fiber sheets along the wider faces of the column led to better confinement of the concrete and longitudinal fiber sheets,

Carneiro et al. [8] made a thorough study of the problem, typified by tests on 54 short column specimens to investigate the increases on strength and ductility of concrete confined by CFRP jackets, considering as variables the column cross-section (circular, square and rectangular) and the number of CFRP sheet layers confining the models (one or two layers). Among the rectangular columns the strength increased with the increase of the radius of rounding corners, and the strength added to the circular columns was found as substantially higher than for columns with rectangular cross-section and almost three times that of square columns.

Other authors generated results from numerical models and experimental work [9–11], in general, confirming the strength enhancement for various levels of confinement and the inefficiency of low lateral pressure, as well as the superior behavior of circular as compared to rectangular columns.

More recently, rectangular columns were studied by Karam and Tabbara [12] who numerically confirmed the importance of (i) the cross-section shape ratio, a/b, a and b being the length of the sides, (ii) the parameter measuring corner sharpness (a/R), R being the radius of the rounded corner and (iii)the stiffness ratio $(t/a)(E_f/E_c)$, t being the thickness of the composite wrap and E_f and E_c the longitudinal moduli of the composite and concrete, respectively.

The benefit of using a prefabricated stay-in-place formwork circular or elliptical FRP composite shell to cast additional concrete around square or rectangular sections is shown in [13,14]. Expansive cement concrete has its expansion restrained by the FRP shell, tensioning the FRP composite and increasing confinement, while imposing radial pre-compression stresses on the concrete core. An incremental numerical model based on plasticity theory is also presented and verified in [14].

A procedure for seismic design of FRP confinement of square concrete columns, obeying ductility requirements is described in [15] and checked against experimental results.

Recently a general approach that can specialize into the special cases of sharp corners, or circular sections, has been presented based on a parameter that measures the degree of roundness of square section columns with external confinement [16]. The authors present also a database of experimental results published for similar cases.

Results of an experimental study on the effects of the cross-sectional shape on the structural performance of reinforced concrete members confined with CFRP and subjected to various loading conditions are presented in [17]. Test parameters included the cross-sectional shape and both axial and eccentric loading condition. The gains in load capacity and ductility of the axially loaded members ranged from 23% to 44% increase in load capacity and 250% to 350% increase in axial deformation for the rectangular and circular cross-sections, respectively.

In terms of design models and estimates, some have been published and are referred in the literature, e.g. in [18], but the present priority rests on experimenting actual size columns like in [19] to better evaluate the accuracy of available models.

A few other publications will be mentioned on the sequel as deemed convenient to interpret results.

This work allows comparison of the response of axially loaded square columns when wrapped with CFRP or AFRP jackets and, in the process, to further examine how the detrimental effects of sharp edges on the confinement of columns with FRP may be mitigated by rounding the corners of the cross-section.

No effort is made to submit any new approximate model that would fit well the results and suggested to be used in comparable conditions. There are numerous models, and it appeared as more important, at present, to increase the data base of experimental results for specimens that can represent prototype behavior. This option is expected to contribute for additional testing and certification of available numerical models.

2. Experimental program

The experimental program was directed to study the behavior of columns of reinforced concrete, rather than plain concrete, because they are more representative of actual cases of outer confinement with FRP. Tests were performed on reinforced concrete cylinders and square prisms of 0.75 m height, with an aspect ratio (height/diameter or width) equal to five, with external jackets either of CFRP or AFRP, Fig. 1. The reasons to adopt the 1:5 scaling are discussed in [20] and generalize conclusions taken from studies with GFRP. The prismatic columns of square cross-section were divided into three groups according to corner sharpness: R1 – sharp-edged corner; R2 – corner radius equal to 20 mm; R3 – corner radius equal to 38 mm, which corresponds to 1/4 of the width of the square section. Columns with small chamfer, $R \approx 0$, were also tested.

All square prisms have the same gross cross-sectional area, i.e. for larger R there was a corresponding increase of the side of the square so as to keep the area 225 cm^2. Table 1 identifies the different CFRP columns that were tested.

The longitudinal and transverse reinforcing steel is the same in all specimens, 8 rods φ6 in the longitudinal direction, steel A500NR, and φ3 stirrups, steel A500L, every 10 cm, as shown in Fig. 2. Concrete limestone aggregates had d_{max} < 15 mm, and regular Portland cement was used. The ultimate compressive strength obtained on cubes at 28 days of age was 33.1 MPa, whereas 26.5 MPa were found on cylindrical standard tests.