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Experimental tests on RC hollow columns strengthened with FRPs

R. Modarelli & P. Corvaglia
CETMA, Brindisi, Italy

G. P. Lignola, A. Prota & G. Manfredi
University of Naples Federico II, Naples, Italy

G. De Canio & N. Ranieri
ENEA, Casaccia R. C., Rome, Italy

ABSTRACT: The paper presents a study conducted on five specimens designed and realized with rectangular hollow cross section and subjected to compression-bending action. The design of the specimens aimed at reproducing dimensions and characteristics of real members scaled with a reduction factor of 5. Three samples matched the guidelines of old Italian design codes, while the others were characterized by insufficient lap-splices of the longitudinal steel bars. One column for each group was not retrofitted and used as a control specimen. The remaining specimens were externally wrapped with CFRP and tested in order to study the influence of two parameters on the structural behavior of the column: the FRP number of plies and the lap-splice degree. The obtained results confirm that significant improvement in ductility and energy absorption capacity can be achieved as a result of the investigated retrofitting technique.

1 INTRODUCTION

Past studies demonstrated the structural efficiency of FRP-confinement for reinforced concrete (RC) columns to increase their strength and ductility. Research related to FRP-confinement of hollow RC columns is very limited at the moment (see Lignola et al. 2007a for a brief review of the available experimental tests on hollow piers). This clashes with the thousands of applications all over the world in which bridge piers are designed as hollow columns to maximize structural efficiency in terms of strength/mass and stiffness/mass ratios.

The authors have already carried out large experimental programs on hollow concrete members reinforced with FRPs. Modarelli et al. 2005 tested a great number of hollow cylinders and prisms subjected to uniaxial compression. Tests results revealed the effectiveness of FRP-confinement for hollow-core concrete sections, even if the increase of strength and ductility decreased passing from circular to square and rectangular sections, as same as for full-core columns. Lignola et al. 2007a-b tested a total of 7 hollow square concrete columns (reproducing in 1:5 scale typical hollow square cross section bridge piers with section dimensions of 360x360 mm^2 and walls thickness of 60 mm) under combined axial and bending load (load eccentricities kept constant during each test). Therefore slender specimens, whose behavior is dominated by flexure, were investigated. The strengthening scheme consisted of unidirectional Carbon FRP laminates applied in the transverse direction. Strength improvement was more relevant in the case of specimens loaded with smaller eccentricity, while ductility improvement was more relevant in the case of bigger eccentricity. At lower levels of axial load also the brittle effect of reinforcement buckling was less noticeable.

In this work five piers, with the same cross section as in Lignola et al. (2007b), were subjected to compression-bending action by means of horizontal shear force applied on a cantilever scheme. The objective of the research was to investigate the influence of two experimental parameters on the structural behavior of hollow-section concrete member: the FRP number of plies used for the reinforcement and the lap-splice degree.

2 EXPERIMENTAL PROGRAM

2.1 *Materials and specimens*

The hollow-section concrete piers reproduce dimensions and characteristics of real members scaled with a reduction factor of 5. Despite a size effect could be expected, the same geometry dimensions were used as in Lignola et al. 2007a-b for comparison purpose. Concrete had an average 28-day compressive strength equal to 28 MPa, while the steel had a stress-strain relationship with the same yield and ultimate average strength of 670 MPa, relatively high. These materials reproduce the ordinary properties employed in the past. The spacing of the confining reinforcement does not satisfy the requirements to prevent buckling of longitudinal bars suggested by Priestley et al. 1996, in which it was recommended to adopt spacing less than six times the diameter of longitudinal bars. Three specimens matched the guidelines of old Italian design codes, while the others were characterized by insufficient lap-splices of the longitudinal steel bars as shown in Figure 1. An insufficient overlapping of 200 mm, allowed by several old codes of practice, equal to 20 longitudinal bars diameters was adopted instead of 400 mm.

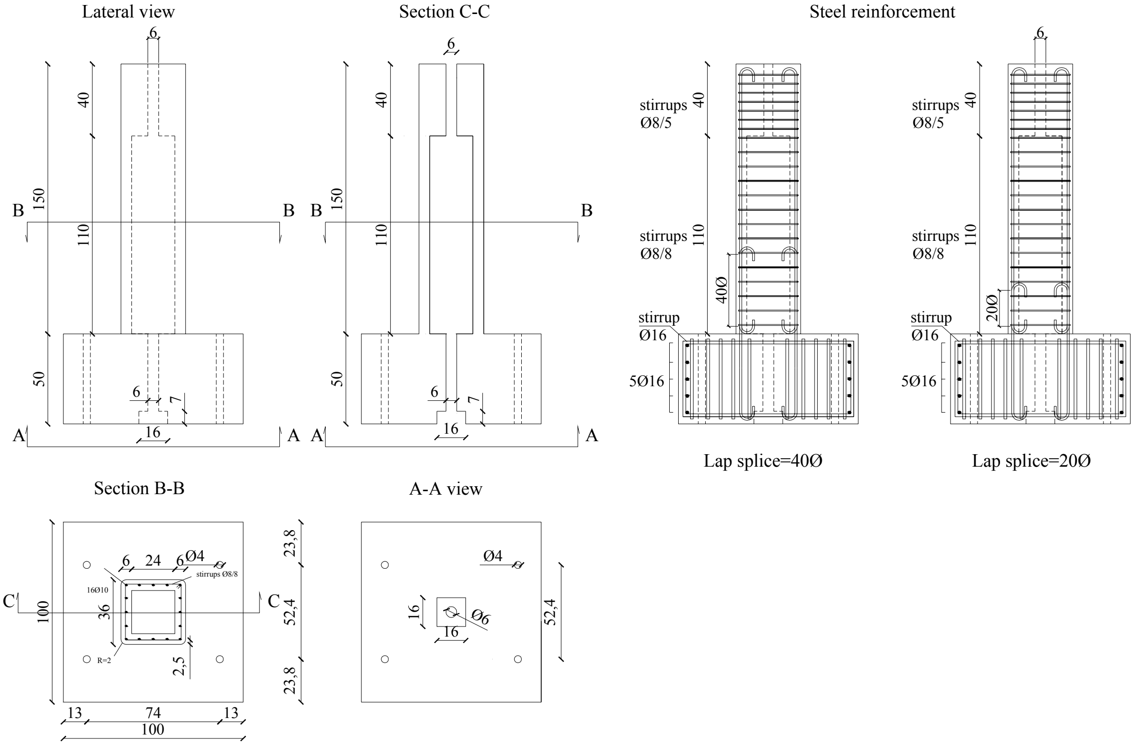

Figure 1. Specimens geometry and steel reinforcement.

One column for each group was not retrofitted and used as a control specimen. The remaining specimens were externally wrapped with uniaxial CFRP sheets (chosen for the high stiffness) in the plastic hinge zone (Fig. 2). A parametric study has been conducted using 1 or 2 plies of carbon fibers. This number of plies is considered a realistic technical application (considering the scale factor) as repair strategy to increase the energy dissipation and the deformation capacity, and preventing bond slippage in poorly detailed columns. The mechanical properties of the FRP fabrics are reported Table 1, while Table 2 summarizes the test matrix.

Table 1. Mechanical properties of the FRP fabric

	Weight (g/m^2)	Thickness (mm)	Young modulus (GPa)	Tensile strength (MPa)	Ultimate strain (%)
CFRP	600	0.333	230	4830	2

Table 2. Experimental program

Specimen designation	Number of CFRP plies	Lap splice
R40	0	40 ϕ
R20	0	20 ϕ
A40	1	40 ϕ
A20	1	20 ϕ
B40	2	40 ϕ

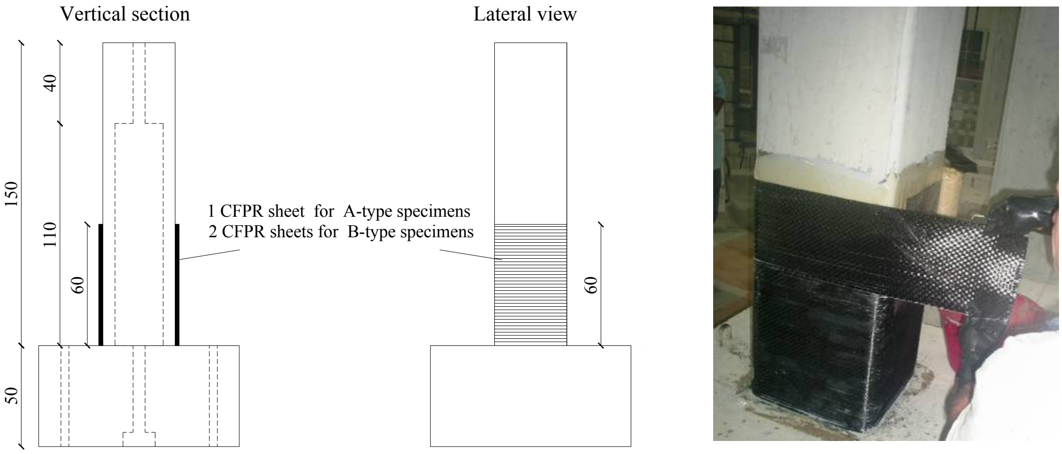

Figure 2. CFRP reinforcement

2.2 *Test setup*

The vertical load, equal to 81kN, namely the 5% of the column ultimate compressive load (according to typical values for bridge piers: see Fib TG 7.4 on Seismic Design and Assessment Procedures for Bridges), was applied coaxially to the column by two inclined hydraulic jacks (by means of two hinges to reduce the P-Δ effects), while the horizontal load was produced by an actuator and measured by a load cell (see Figure 3). Tests were carried out in displacement control with a rate of 0.05 mm/s. Displacements were measured by several LVDTs applied on concrete, while strains were measured by strain gauges set on steel bars and FRP,(Fig. 4a). These data were collected continuously by a data acquisition system.

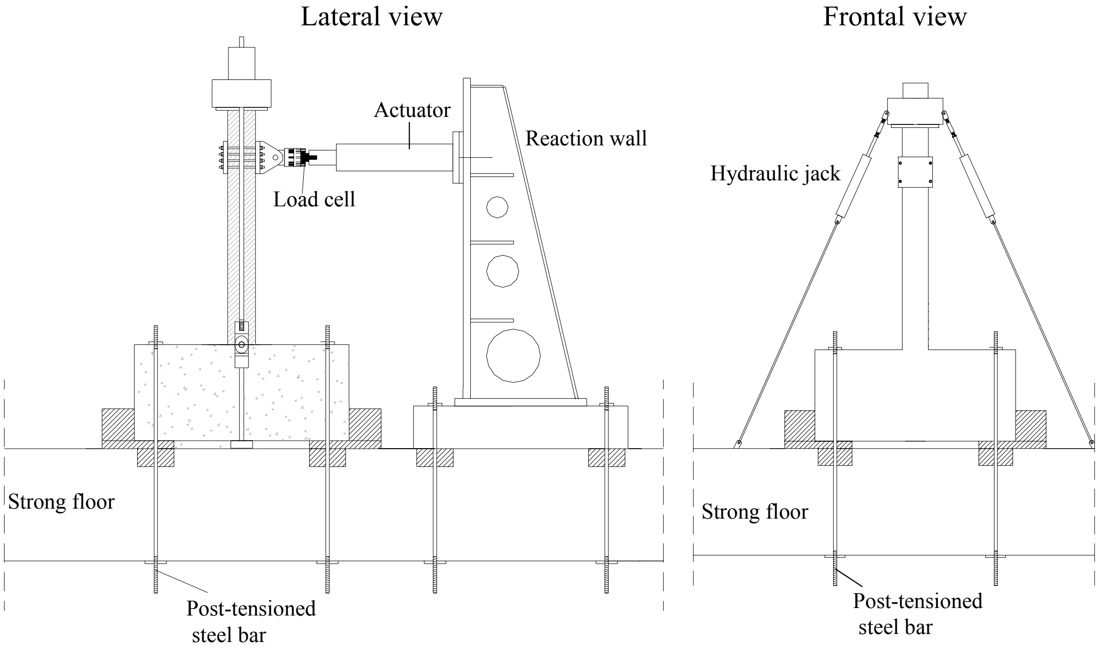

Figure 3. Lay-out of the test setup

3 EXPERIMENTAL OUTCOMES

The failure of the hollow unconfined member R40 was strongly affected by the occurrence of premature compressed bars buckling and unrestrained concrete cover spalling.

For the specimens with FRP sheets, no inclined cracks were observed in the plastic hinge region. Plastic hinges fully formed at the bottom of the columns, which contributed to the development of higher ductility. FRP was able to delay bars buckling and to allow obtaining higher values of compressive concrete strains, so that the ultimate performance was mainly dominated by flexure because of crushing of concrete at the bottom of the column. The CFRP jacket did not fail in any case.

The unconfined specimen R20, of the ‘20Φ’ series with insufficient lap splice, was characterized also by limited flexural capacity due to the slippage of the longitudinal reinforcement at the base. The failure mode was characterized by a wide crack crossing the base of the pier, in the region of insufficient bars overlapping. Flexural cracks perpendicular to the column’s axis developed first close to the bottom end of the columns; then they tilted and extended, after the yielding point, into the hollow portion of the column, due to the influence of shear, so showing a mixed shear-flexural collapse mechanism (Fig. 4b). In the pre-yielding phase a marked deviation from the pure flexural behavior is evidenced by the inclined cracks (Fig. 5). This failure mode took place when the pier was still in the elastic phase, giving a strength reduction of about 15% compared to the corresponding unreinforced specimen R40. In the wrapped specimen A20 the application of the FRP plies resulted in an upward shift of the critical section, where the steel bars could yield without slippage, thanks to their effective anchorage (Fig. 4c). Hence, as, in this case, the function of the retrofitting intervention was also to overcome the problem of reinforcement slippage at the base, it can be considered successful as the response was similar to the case of ‘40Φ’ with sufficient lap splice.

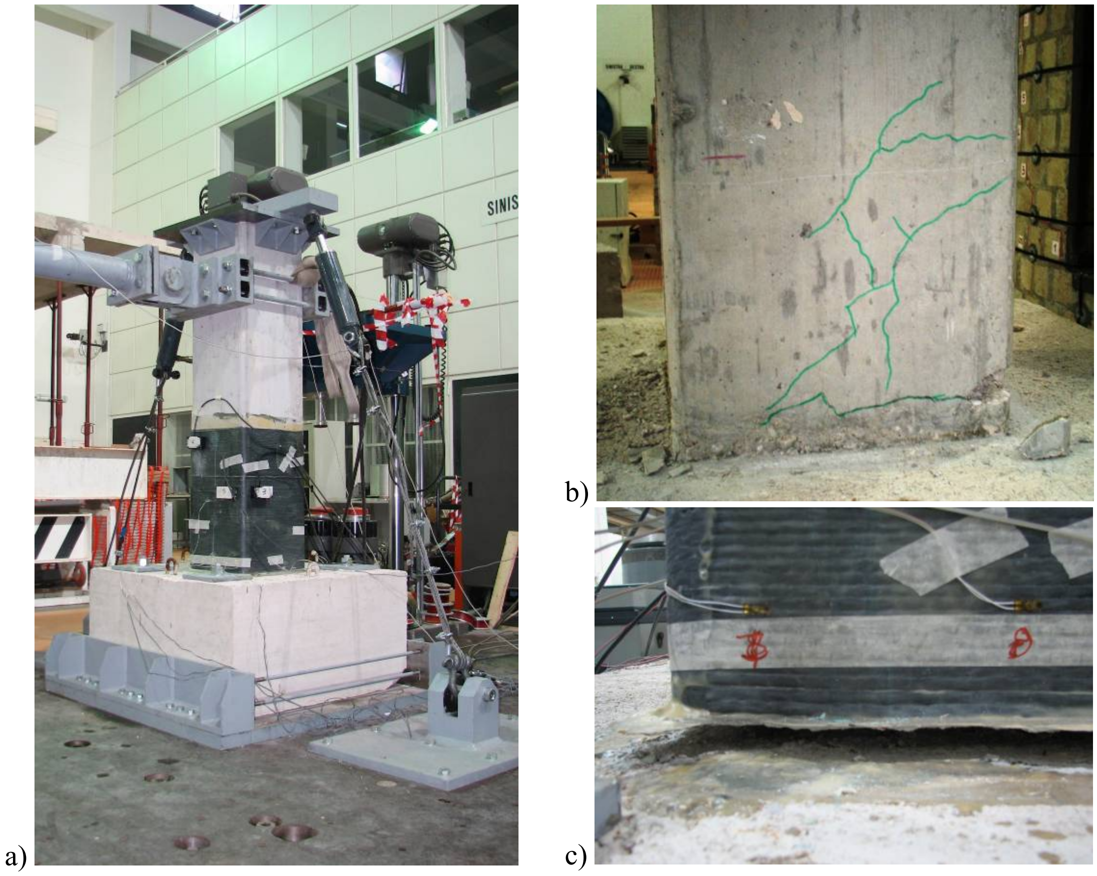

Figure 4. a) A40 test setup; b) A20 crack pattern at base; c) A20 crack opening at base;

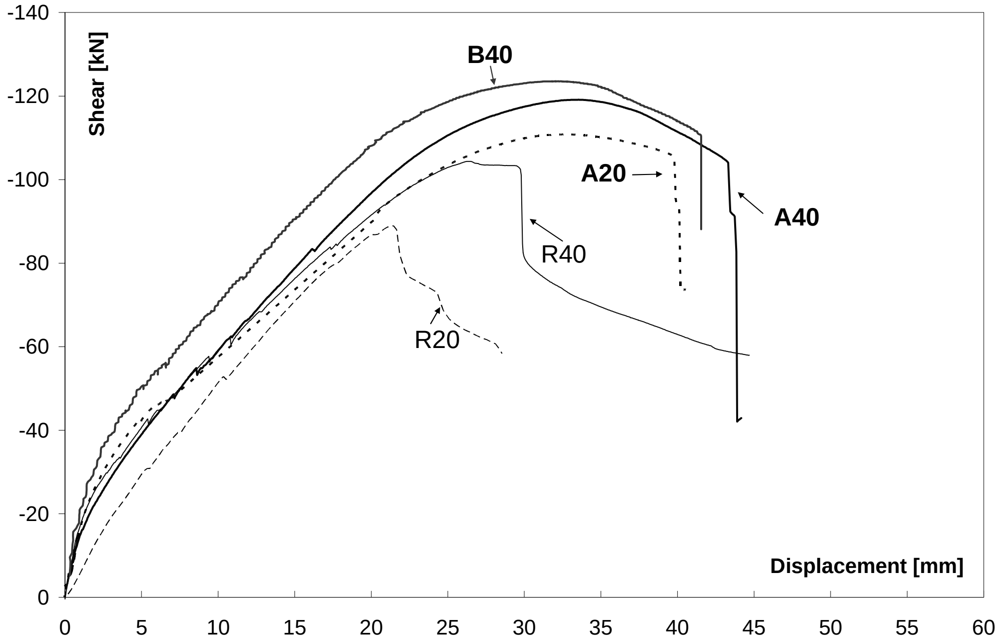

Figure 5. Shear-displacement curves

The wrapped specimen, A20, showed an improved behavior due not only to the change of the failure mode, but also to the significant enhancement of both strength and ductility as evidenced in the following. In Figure 5 the experimental shear force versus top measured displacement curves are plotted for the five tested specimens. A sudden loss of stiffness in the elastic phase without any apparent external damage and a progressive loss of strength along the softening branch can be seen in the R20 specimen due to the bars slippage in the lap splice.

The FRP wrapping was in every case very efficient: in Table 3, the peak shear force, T_{max}, the peak displacement, δ_{max}, and displacement ductility, μ_δ (defined as the ratio of the displacement on the softening branch at 80% of peak force and the yielding displacement corresponding to the yielding flexural moment) are reported for each tested specimen. The strength increment was about 14% and 18% in the case of one CFRP ply and two CFRP plies, respectively, for columns with sufficient lap splice (‘40Φ’ series). Higher increments can be found in the case of insufficient lap splice, ‘20Φ’ series (in this case the increment is about 25% with one CFRP ply).

Displacement ductility extended from 1 to 2.51. Furthermore, it has to be noted that the failure mode in presence of FRP wrapping changed from brittle to flexural failure and it can be considered very satisfying both in terms of deformation capacity and energy dissipation (proportional to the area under the shear-displacement curves).

Table 3. Experimental results

Specimen	T_{max} [kN]	δ_{max} [mm]	μ_δ [-]
R40	104.36	26.23	1.37
R20	88.96	21.42	1
A40	119.14	33.54	2.18
A20	110.84	32.53	1.83
B40	123.56	30.93	2.51

It is focused that, due to data acquisition problems, it was not possible to define the yielding point for specimen R20 (because it was evaluated at the time of steel yielding measured by strain gauges) and consequently it was not possible to evaluate the displacement ductility. In any case it is clear that this index is about one because the capacity loss occurred in an almost elastic phase.

4 CONCLUSIONS

The performance of as built and retrofitted hollow bridge piers under horizontal loads was investigated. Comparison between experimental tests performed both on retrofitted and as built specimens allowed to estimate the effectiveness of CFRP wrapping on the behavior of deficient hollow piers, designed according to obsolete design philosophy assumptions and with insufficient lap-splices of the longitudinal steel bars.

On the basis of the results presented in this paper, the following conclusions can be drawn.

The failure sequence of poorly detailed as built hollow piers is: concrete cracking, slippage of the longitudinal bars (in the case of insufficient overlapping), yielding of longitudinal reinforcement, concrete cover spalling and buckling of longitudinal compressed bars in the plastic hinge region.

FRP confinement is able to delay bars buckling and to let compressive concrete strains attain higher values, thus resulting in higher load carrying capacity of the column (maximum strength improvement is about 25%) and significantly in ductility enhancement (maximum ductility improvement is about 83%). The increase in the FRP plies number (studied in the case of columns with sufficient lap splice) produces not proportional effects; in fact the strength increment was about 14% and 18% in the case of one CFRP ply and two CFRP plies, respectively. Similar considerations can be drawn for ductility results.

Moreover the test results indicate that the use of CFRP wraps transforms the failure mode from a brittle to a more ductile flexural behavior. For example, while the reference specimen R20 had a poorly dissipative and brittle failure mode, governed by the slippage of the longitudinal bars, in the corresponding reinforced specimen A20 specimen, the behavior was improved by the retrofit intervention, overcoming the problem of reinforcement slippage at the base.

As a main conclusion, it can be stated that FRP confinement of hollow bridge columns is a very promising application not only to obtain a more ductile behavior, but also to avoid slippage in the case of insufficient overlapping.

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