Cyclic behaviour of concrete columns confined with FRP systems

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ABSTRACT: The subject of this paper concerns the problem of repairing and seismic retrofitting the existing reinforced concrete (RC) gravity load designed (GLD) buildings by using fiber reinforced polymers (FRPs).
The paper presents several results from a wide experimental program in progress at the Laboratory of Structures of the University of Salerno (Italy).
Full scale square (300x300 mm) RC columns were tested under a constant axial load and monotonic or cyclically reversed horizontal loads; in particular, two levels of the axial load were considered, while the horizontal action was applied under displacement control.
Studied columns were designed to represent structural components of existing buildings, i.e. characterised by a concrete having low compression strength; for the same reason, tested columns were reinforced using both smooth and deformed steel rebars, while the reinforcement details (i.e. lap splice lengths, anchorages, hoop spaces, etc.) were arranged following design rules used in the past – nowadays not admitted in seismic zone – and without keeping into account any seismic details.
Tests were conducted on FRP confined and unconfined RC columns: the confinement system was obtained by partially wrapping unidirectional carbon (CFRP) or glass (GFRP) layers around the RC member. Furthermore, a retrofitting system provided by both the external CFRP wrapping and steel angles has been considered, but tests performed on columns strengthened with this system are not discussed herein.
Tests results have allowed to evaluate the benefits in terms of strength, ductility and energy dissipation capacity provided by FRP confining system.

1 INTRODUCTION

The subject of this paper is very topical: the problem of repairing and seismic retrofitting existing infrastructural patrimony is considered.

The objectives of this study are to deepen the current knowledge on the behavior of RC columns subjected to axial load and bending moment and to evaluate under the same load conditions the benefits induced by externally wrapping columns with fiber reinforced polymer (known with the acronym FRP) layers.

For these purposes a wide experimental program is carrying out at the Laboratory of Structures of the Department of Civil Engineering of the University of Salerno. In particular, such program consists of several tests on full scale RC columns - having square and rectangular cross sections - to be performed under a constant axial load and a cyclic transversal force.

The experimental results allowed to:
1. highlight the differences between the response - under monotonic and cyclic horizontal load - of members reinforced with smooth rebars and of members reinforced with deformed rebars;
2. evaluate the benefits achievable with the FRP confinement technique.

Some preliminary results of the experimental program have been widely described in (Faella et al. 2006a, b; Faella et al. 2007).

2 EXPERIMENTAL PROGRAM AND TEST SETUP

2.1 *The concrete specimens*

The experimental program, still in progress at the University of Salerno, includes more than 30 tests on full scale RC columns. The samples consisted of square columns, 300 mm on each side and 2200 mm long, and of rectangular columns, 300 mm by 700 mm and 2500 mm long; the two types of concrete specimens had a stub with 1400 mm x 600 mm x 600 mm and with 1400 mm x 600 mm x 800 mm dimensions, respectively.

Studied columns were designed to be representative of existing building structural components; for this reason, they were realized with two types of concrete - the first one having a cylindrical compression strength (f_{cm}) of about 25-30 MPa, while the second mixture having a f_{cm} equal to about 12-17 MPa - and were reinforced by using both smooth and deformed steel rebars. In particular, 14 mm diameter rebars were used as a longitudinal reinforcement, while the transversal reinforcement was constituted by 8 mm diameter steel stirrups, 200 mm spaced. The longitudinal rebars were characterized by a lap splice length equal to 600 mm at the column base-foundation joint. The reinforcement details (i.e. lap splice lengths, anchorages, hoop spaces, etc.) were arranged following design rules used in the past.

Tests conducted up to now are 19 and all were performed on 300x300 mm RC columns having a shear span to depth ratio equal to 5.7.

2.2 *Steel rebars and FRP layers mechanical properties*

The mean values of the mechanical properties of smooth and deformed steel rebars are shown in Table 1, where: f_y and ε_y indicate the strength and strain at yielding, respectively; ε_h is the strain at the beginning of the strain hardening; f_u is the ultimate steel strength and ε_{su} is the corresponding strain. The type of steel of smooth rebars can be considered more or less equivalent to the “AQ50” one, which represents the steel class currently used in the Italian practice during the years ’50-’70 (Fabbrocino et al. 2002). The used deformed steel rebars, instead, can be classified as “FeB44k” type and are used in Italy nowadays.

Table 1. Mechanical properties of steel rebars

Type of rebars	f_y (MPa)	ε_y (%)	ε_h (%)	f_u (MPa)	ε_{su} (%)
smooth	346	0.165	3.68	498	23.80
deformed	556	0.265	3.97	655	16.73

Some of the concrete members were strengthened by means of a passive confinement system obtained by partially wrapping unidirectional carbon or glass FRP layers around the element; the value of the corner radius was approximately equal to 30 mm.

Other members were unconfined and used as terms of comparison to evaluate the benefits introduced by the FRP systems.

In order to significantly enhance the flexural strength, further specimens were retrofitted by using both an external CFRP confinement system and four steel angles placed in correspondence of the corners of the column and glued to the concrete substrate by means of an epoxy adhesive layer. This retrofitting technique (FRP + steel angles) was also considered to strengthen some previously tested and damaged columns in order to perform the comparison between the behaviour of the undamaged columns and of the repaired ones.

Nevertheless, for sake of brevity, only results from tests on unretrofitted and on FRP confined columns are presented and discussed in this paper.

The main properties of the used glass and carbon fibers - i.e. the thickness of the single layer (t_f), the elastic modulus (E_{FRP}), the tensile strength ($f_{u,FRP}$) and the corresponding ultimate strain ($\varepsilon_{u,FRP}$) - are reported in Table 2.

Table 2. Mechanical properties of FRP layers

Fiber	t_f (mm)	E_{FRP} (GPa)	$f_{u,FRP}$ (MPa)	$\varepsilon_{u,FRP}$ (%)
Carbon	0.22	390	3000	0.80
Glass	0.48	80.7	2560	3-4

2.3 *Loading procedure and instrumentation*

Columns were tested in displacement control under combined axial and (monotonic or cyclic) lateral loads: in the case of cyclic tests, an increment of the displacement every three cycles was considered in order to evaluate the strength and stiffness degradation at repeated lateral load reversals.
Each test was conducted up to a “conventional collapse” which corresponds to 10% strength degradation.

During tests performed up to now (all on 300x300 mm RC columns) the axial load “N” was applied by using a 2000 kN (MOOG) hydraulic actuator and its magnitude was mantained constant throughout the test; two values of the normalized compression load “ν”- respectively equal to 14% and 40% - were considered, being “ν”given by:

$$\nu = \frac{N}{B \cdot H \cdot f_{cm}} = \frac{N}{A_c \cdot f_{cm}} \tag{1}$$

where: f_{cm} is the average value of the actual cylindrical compressive strength of the concrete (evaluated by performing compression tests on concrete specimens cast with each column and subsequently cured under the same environmental conditions); B and H are the dimensions of the column cross section.

The horizontal force, instead, was applied by using a 240 kN (MTS) hydraulic actuator placed at the height “H_{col}” of 1700 mm from the base of the column.

The test set up and the cyclic displacement loading history are shown in Figure 1.

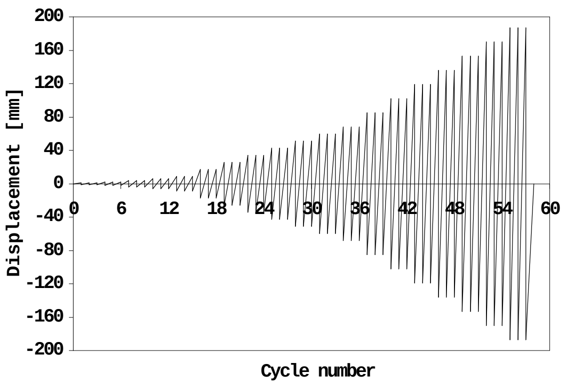

Figure 1. Test setup and loading displacement history.

Test measurements included: slip response of the steel rebars; average curvatures or rotations in the “critical region”; loads applied by the actuator; vertical and horizontal strains (in particular those close to the column-stub interface section); deflections along the length of the column.
Curvatures and slip of rebars were measured using LVDTs, strains using electric resistance strain gauges, drifts by means of potentiometers placed at the top of the column and in correspondence of the horizontal actuator axis.

3 EXPERIMENTAL RESULTS

3.1 *Strength and ductility*

Table 3 summarizes the main results of the 15 tests considered in this paper.
In the Table each test is identified with a label that indicates: the type of test (“M” means monotonic, “C” cyclic); the column number; the type of longitudinal steel reinforcement (“S” and “D” stands for smooth and deformed rebars); the type of fiber wrapped around the column (“G” and “C” indicates glass and carbon, respectively): for example, the label “C4-S-G” denotes the cyclic test performed on column number 4, which is reinforced by using smooth steel rebars and retrofitted by wrapping glass fibers around its perimeter.

Table 3. Test results

TEST	Rebars	$Type_{FRP}$	N_L	ν	f_{cm} (MPa)	N (kN)	F^{+}_{max} (kN)	F^{-}_{max} (kN)	d_{max} (mm)	δ_{max} (%)
M5-S		-	-	0.14	26.4	333	51.15	-	149.60	8.80
C3-S		-	-		25.7	325	52.73	50.91	65.62	3.86
C4-S-G		GFRP	2		24.8	312	55.07	50.31	123.76	7.28
C1-S-G	Smooth	GFRP	4		28.8	363	62.45	56.51	125.12	7.36
C10-S-C		CFRP	2		26.0	330	49.71	51.02	87.21	5.13
C13-S-C		CFRP	2		28.9	360	49.08	48.14	99.62	5.86
C16-S		-	-		27.5	990	81.51	69.82	52.02	3.06
C17-S-C		CFRP	2	0.40	17.0	609	61.95	56.26	79.90	4.70
C18-S		-	-		13.5	485	42.33	41.21	41.99	2.47
C9-D		-	-	0.14	31.8	365	71.08	66.32	61.03	3.59
C7-D-C		CFRP	2		26.1	328	65.33	69.10	122.23	7.19
C8-D-C	Deformed	CFRP	2		26.5	334	69.74	63.51	110.84	6.52
C21-D		-	-		11.7	420	52.83	47.05	47.43	2.79
C22-D-C		CFRP	2	0.40	11.7	420	55.74	59.54	95.03	5.59
C23-D-C		CFRP	4		12.5	450	72.94	69.03	140.00	8.24

Table 3 also reports:
1. the type and the number of FRP layers "N_L" used to confine the column;
2. the normalized axial load "ν";
3. the mean value of the cylindrical concrete strength under compression;
4. the value of the axial load ($\approx \nu \bullet A_c \bullet f_{cm}$);
5. the peak horizontal force measured in positive and negative direction (F^{+}_{max} and F^{-}_{max});
6. the maximum horizontal displacement (d_{max}) at the conventional collapse, measured in correspondence of the horizontal actuator;
7. the "chord rotation" at the conventional collapse that, for the tested members, coincides with the lateral drift ($\delta_{max}=d_{max}/H_{col}$).

Observing the results reported in Table 3 the following conclusions can be drawn:

a) columns tested under low values of ν (=14%)
  - a1. regardless of steel rebars used as a longitudinal reinforcement (smooth or deformed), the FRP confinement produces significant increases in terms of ductility;
  - a2. on the other hand, the flexural strength of the FRP confined columns attains values very similar to ones of the unconfined elements;
  - a3. the ductility mostly enhances when a confinement system with GFRP layers is used;

b) columns tested under higher values of ν (=40%)
  - b1. lower ductilities and higher strengths have been observed by comparing test results with those obtained in case of ν=14% (for example, compare tests C16 and C3);
  - b2. tests performed on FRP confined columns showed that not only the ductility but also the flexural strength can be improved with the considered confinement technique in case of higher axial load values (see tests C17 and C18);
  - b3. the benefits obtained with the FRP confinement technique are more evident by increasing the number of layers used in wrapping the columns (compare tests C21, C22 and C23).

Figures 2 and 3 show the monotonic envelopes of the horizontal load-top displacement cyclic curves obtained for several tests. In particular Figure 2 regards tests conducted on columns reinforced by using smooth rebars, while Figure 3 shows results from tests on columns having deformed rebars as longitudinal reinforcement. The comparisons reported in these diagrams allow to visually verify the observations relative to the experimental results indicated in Table 3.

Nevertheless, it has to be remembered that tests performed up to now have regarded specimens realized by using two different concrete mixtures; as a result, comparisons between the experimental data can be more effective only normalizing the flexural strengths.

For this reason, Figures 4 and 5 depict the experimental curves in the μ-δ plane, being μ the "normalized bending moment" given by:

$$\mu = \frac{F \cdot H_{col}}{B \cdot H^2 \cdot f_{cm}} = \frac{M}{B \cdot H^2 \cdot f_{cm}} \tag{2}$$

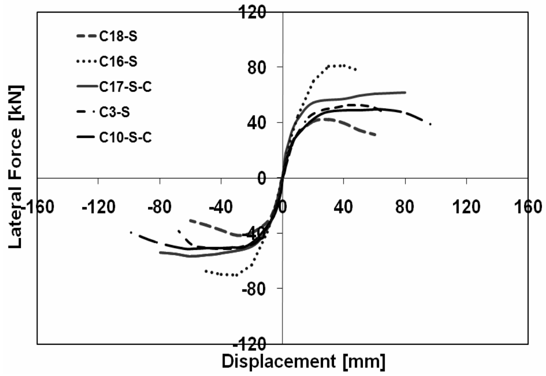

Figure 2. F-d envelopes: columns reinforced with smooth steel rebars.

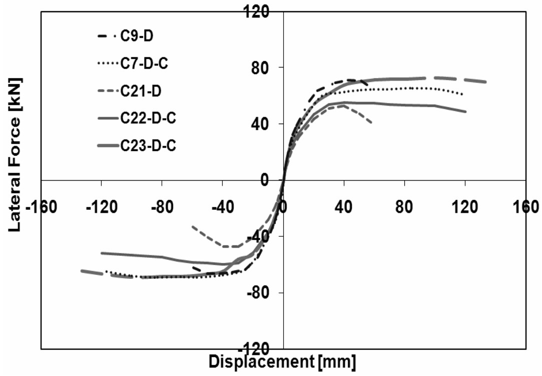

Figure 3. F-d envelopes: columns reinforced with deformed steel rebars

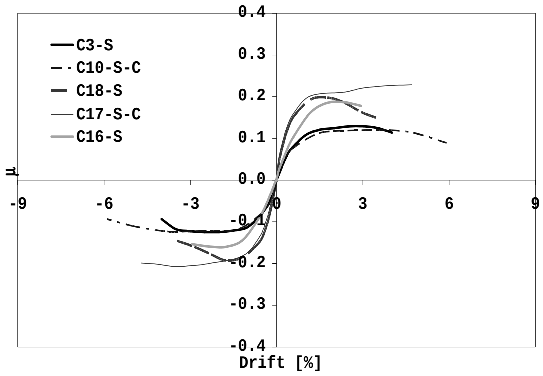

Figure 4. μ-δ envelopes: columns reinforced with smooth steel rebars.

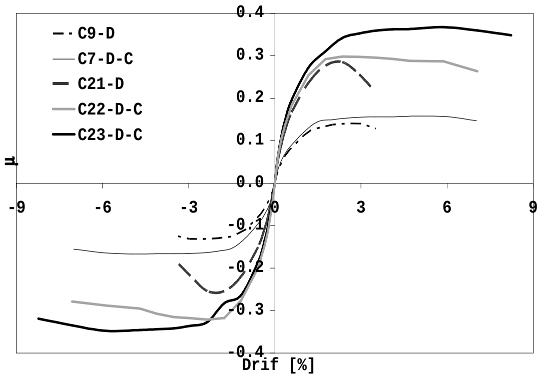

Figure 5. μ-δ envelopes: columns reinforced with deformed steel rebars

The meaning of the symbols reported in Eq. (2) has been previously explained.

The observation of the Figures 4 and 5 allows to confirm the conclusions previously reported.

3.2 *Observation of damages and crack patterns*

Figure 6 shows some concrete damages evidenced during tests.

In case of tests performed on columns reinforced with smooth rebars (Fig. 6a) a wide flexural crack at the column-stub interface was observed, whose width significantly increased during the test due to the low bond between smooth rebars and concrete; the collapse was characterized by the concrete failure in compression; the presence of the FRP system prevented the spread of further cracks and produced an improvement of the column behavior, reducing the damage and avoiding the spalling of the concrete cover.

Cracks situated in correspondence of the steel hoops (i.e. spaced of about 200 mm) were observed in case of concrete members having longitudinal deformed rebars (Fig. 6b); a collapse characterized by the tensile failure of longitudinal rebars was noted for FRP confined columns.

Increasing the value of the axial load (i.e. from ν=14% to ν=40%), smaller crack widths have been observed; in particular, a significant reduction of the crack width at the column-stub interface was evidenced during tests performed on columns reinforced with smooth rebars; furthermore, in case of ν equal to 40%, the collapse of the columns was always characterized by the concrete failure in compression and by the buckling of the longitudinal rebars (Fig. 6c).

4 CONCLUSIONS

In this paper, several results from a wide experimental program in progress at the University of Salerno have been presented. Full scale square RC columns were tested under combined axial compression-flexural loading: in particular, two levels of the axial load were considered.

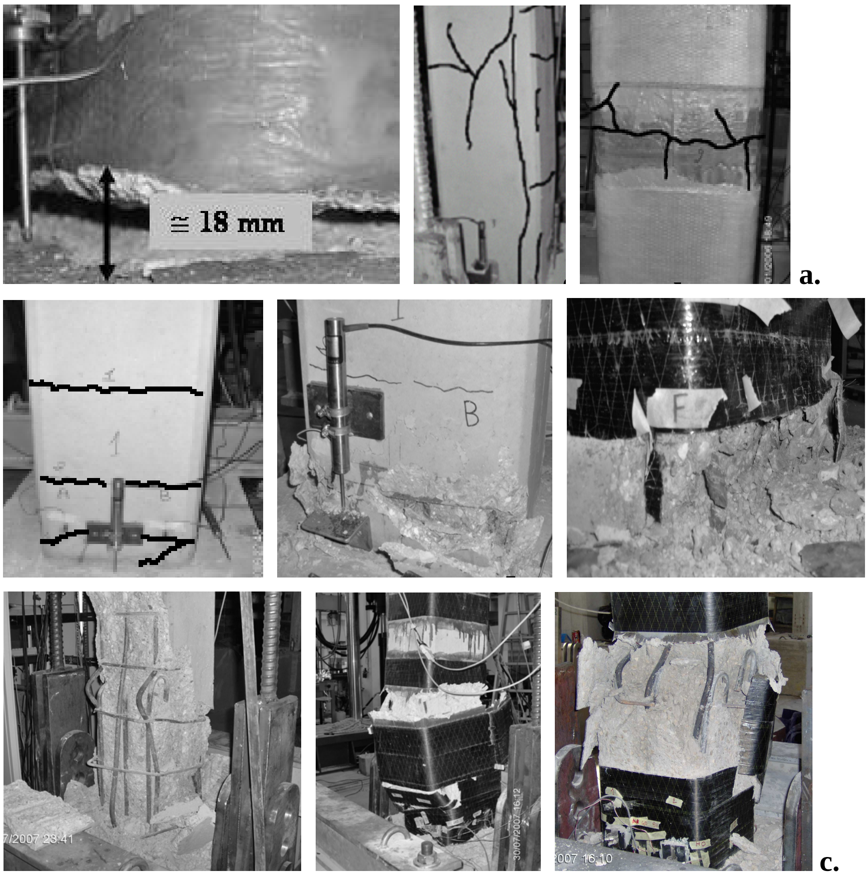

Figure 6. Crack patterns and damages at collapse

The samples were reinforced by using both smooth and deformed longitudinal steel rebars. Some columns were externally confined by using GFRP or CFRP layers; others were unstrengthened and used as terms of comparison.

The analysis of the test results allowed to draw the following conclusions: for low values of the applied axial load, the FRP confining system produces only increases in terms of ductility; for higher axial load levels, the FRP jacket provides an improvement both in terms of ductility (still more evident by enhancing the number of FRP layers) and in terms of flexural strength.

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