EXPERIMENTAL EVALUATION OF EFFECTIVENESS OF LOCAL STRENGTHENING ON COLUMNS OF R/C EXISTING STRUCTURES

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1 INTRODUCTION

All over the world, most of the R/C framed buildings in seismic zones were designed only for gravity loads or with inadequate criteria, and their collapse is often the major cause of casualties during strong earthquakes. Complete replacement of such structures with properly designed R/C buildings is impractical and therefore the interest for simple, effective and economic design methods to strengthen existing structures is growing up.

A design method shall include all the phases needed by the actual design procedures, i.e. the assessment of the actual characteristics of the building at hand, the definition of the targets of the rehabilitation in terms of design seismic actions and structural performances, the design of an effective and economic rehabilitation intervention.

The problem of the assessment of the seismic behaviour of existing buildings is more and more attracting the interest of several researchers. However, further studies and experimental tests are still needed to get a satisfactory evaluation of the seismic behaviour and a more accurate modelling of existing R/C structures.

As regards retrofitting, besides the traditional techniques, based on widespread member jacketing and/or addition of new stiff and resistant elements, like R/C walls or steel braces, passive control techniques appear very effective, especially those based on energy dissipation through special devices. In any case, local repairing or strengthening of some structural elements is often required. This can be necessitated by many reasons, among others: (i) presence of damage caused by previous events; (ii) inadequacy of shear strength, as a consequence of insufficient or poorly detailed transverse reinforcement; (iii) poor confinement, particularly within potential plastic hinge regions; (iv) insufficient lap-splice length at lower end of columns.

When confinement increase in columns with a possible improvement of inadequate lap-splices are of particular concern, then strengthening can be implemented using several intervention techniques, including steel or R/C jacketing, FRP encasement as well a more recently proposed technique named CAM jacketing [1]. Each system shows peculiar characteristics as regards their effectiveness, cost savings and execution difficulties.

The steel jacketing (SJ) system is made up of thick steel plates welded to four corner angles. This technique is presently not very used as repair or strengthening intervention, being considered above all as a temporary support in post-earthquake emergency measures [2]. Due to its simplicity, low cost and speed of application, it was extensively used in the past years, often adding to the steel cage a thick layer of new concrete (R/C jacketing). In any case, only passive confinement effects can be obtained using this technique, as it becomes effective only when concrete suffers significant cracking. Actually, some degree of pre-compression can be accomplished by pre-heating the plates just prior to welding, however this beneficial result can not be calibrated and is strongly conditioned upon an accurate execution of the intervention.

The Fiber Reinforced Polymers (FRP) are non-metallic reinforcement made up of high performance carbon, glass or aramid fibers encapsulated into a resin matrix. They have been widely employed throughout the world, primarily as an alternative to steel reinforcement in avoiding their typical corrosion problems and more recently in repairing/strengthening of reinforced concrete and masonry structures [3]. In fact, even though its relatively high cost, FRP strengthening system has several advantages, among others [4]: (i) high strength-to-weight ratio; (ii) immunity to corrosion; (iii) easy handling and installation. The system is implemented by glueing one or more FRP sheets on the column surface using epoxy resin. As in the case of SJ system, only passive confinement is usually obtained.

The CAM system, patented by Dolce and Marnetto, was initially conceived and set up for strengthening of masonry buildings [1]. Later, also the application to R/C structures has been considered, exploiting the CAM system in confining concrete columns [5]. In this case it is implemented by using steel angles with smoothed edge and high strength stainless steel ribbons 0.8-1.0 mm thick, 18-20 mm wide. The ribbons are arranged around the 4 profiles using a strapping machine able to provide a measurable pre-tension to the ribbons, thus producing a low pre-compression state in the column. This technique has many advantages: (i) little encumbrance, provided that, having the confining device a total thickness of the order of 6-8 mm, it can be easily contained within the normal plaster thickness; (ii) total reversibility; (iii) ease and speed of application; (iv) active confinement, being the pre-compression state in concrete immediately effective when increasing axial loads.

In order to evaluate the effectiveness of the above different local intervention techniques aimed at repairing and/or strengthening R/C members, a wide experimental investigation has been initiated at the Laboratory of testing materials and structures of the University of Basilicata.

Main objective of the study was the evaluation of the role of confinement on ductility and strength. The achievement of such objective was carried out through an extensive experimental investigation on real scale structural elements (columns). 24 full scale models of column were designed and constructed according to old codes, taking into account only gravity loads. Cyclic loading-unloading compression tests were carried out on both strengthened and not strengthened columns.

2 EXPERIMENTAL INVESTIGATION

2.1 Characteristics of specimens

In the experimental program a total of 24 columns with rectangular cross section 250×300 mm and 800 mm high were cast vertically using wood forms. Several cubic specimens (about two for each column) were also prepared in order to estimate the concrete strength before the tests on columns. A purposely studied mixture was used to obtain poor quality concrete ($f_{cm} \leq 15$ N/mm²), representative of typical conditions of Italian existing buildings constructed in the '50s-'60s.

Two types of columns were made (12 specimens for each type):

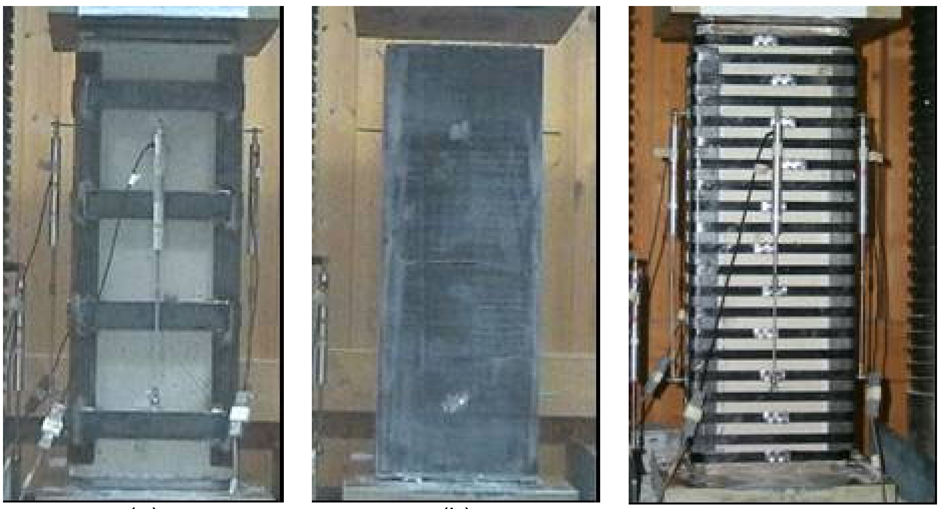
- Type UR → UnReinforced → A_{sl} / A_c = 0%
- Type R → Reinforced → A_{sl} / A_c = 0.75% (4 rebars with ϕ = 12 mm)

where A_{sl} = area of longitudinal reinforcement and A_c = gross concrete area.

In the type R specimens the reinforcement was designed according to the old Italian code for RC structures [6] using mild steel type FeB32K having a yield strength equal to 320 N/mm^2. Also a transverse reinforcement is present in the columns (ϕ6/120 mm). The concrete used for reinforced columns had a mean value of the cylinder strength f_{cm} equal to 14.90 N/mm^2 with coefficient of variation (CoV) equal to 7.4%. In the unreinforced columns the concrete had f_{cm} = 12.71 N/mm^2 with CoV = 7.3%.

Beyond the case of not strengthened columns, three types of strengthening were examined (Fig. 1):

- Steel jacketing;
- FRP encasement;
- CAM jacketing.



(a) (b) (c)

Fig. 1: Strengthening techniques: (a) Steel Jacketing, (b) FRP encasement, (c) CAM jacketing.

In Tab. 1 the characteristics and number of the specimens are reported.

Table 1 Characteristics of specimens

		Strengthening Technology	Specimen number	Type Label
24 Specimens	Specimens n. 1-12 Type R (Reinforced)	Not Strengthened	3	R-NS
		Steel Jacketing	3	R-SJ
		CAM jacketing	3	R-CAM
		FRP encasement	3	R-FRP
	Specimens n. 13-24 Type UR (UnReinforced)	Not Strengthened	3	UR-NS
		Steel Jacketing	3	UR-SJ
		CAM jacketing	3	UR-CAM
		FRP encasement	3	UR-FRP

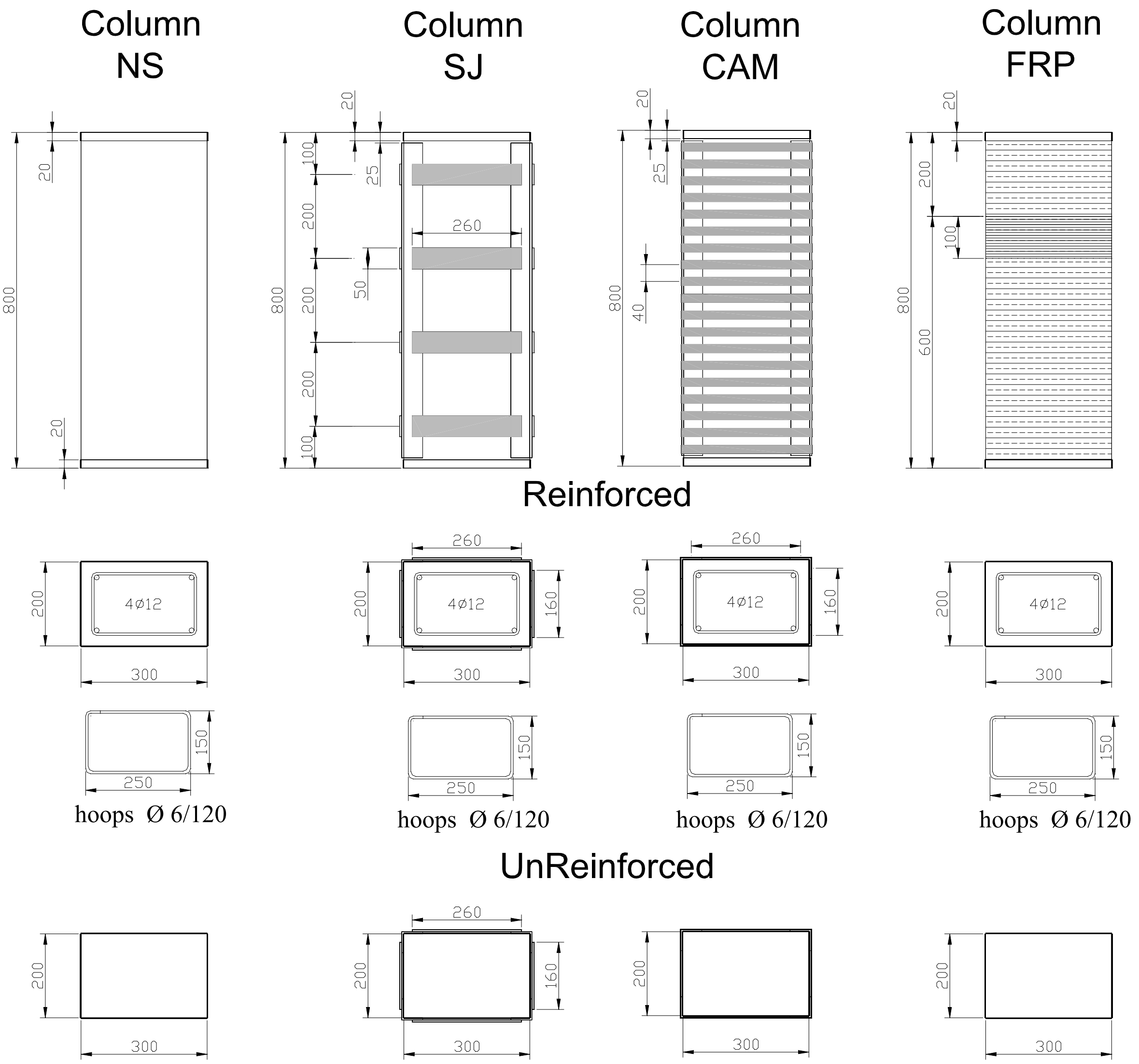


Fig. 2: Characteristics of columns under examination.

In this study the steel jacketing (Fig. 1a) was implemented using four L-shape 50x50x5 mm angles 750 mm long, and 260x50x5 mm and 160x50x5 mm plates (respectively along the 300 mm side and the 200 mm side of the column), 200 mm spaced out (Fig. 2). A mild steel typically employed in Italy

(Fe360) was used, having yield strength equal to 330 N/mm^2, 450 N/mm^2 tensile strength and high values of elongation at failure (tab. 2). According to typical construction practice, the plates were not pre-heated prior to welding.

The FRP strengthening (Fig. 1b) was realised using 1 sheet of carbon fiber reinforced polymer (CFRP) realising an overlapping length equal to 100 mm both along the height and along the perimeter of the column (Fig. 2). Before the glueing of sheets the edges of columns was suitably rounded.

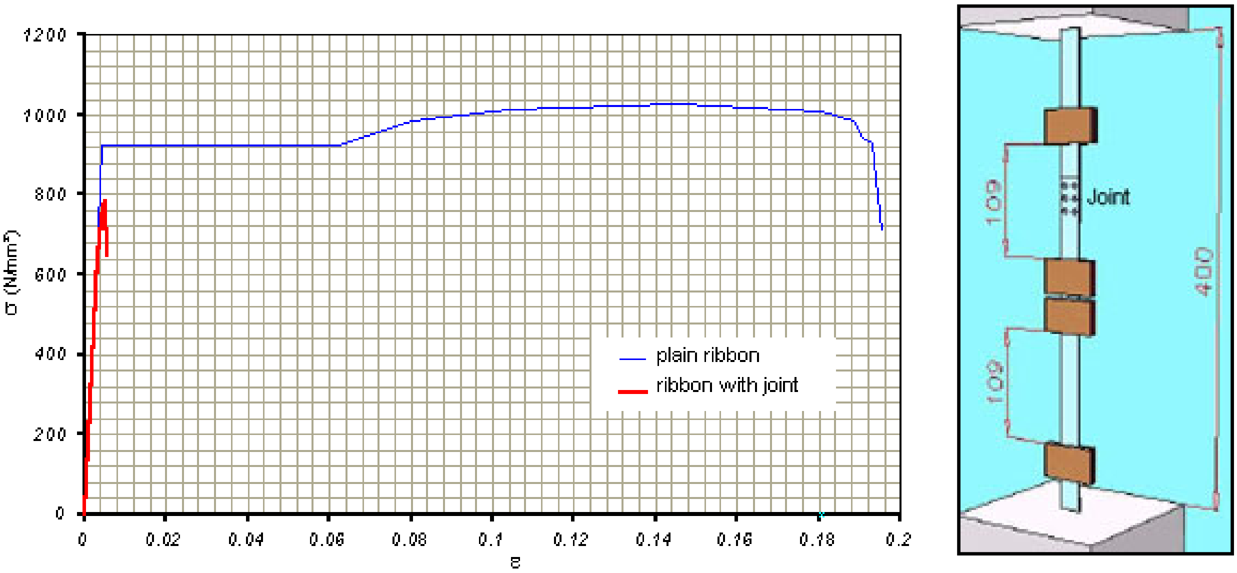
The CAM system (Fig. 1c) was implemented using ribbons 0.8 mm thick, 19 mm wide, 40 mm spaced out (Fig. 2). Also four steel angles were used, having the same dimensions and characteristics as the ones used in the SJ system. They have the role of spreading the stresses applied by the ribbons as well of reducing the friction effects during the pre-tensioning.

The mechanical characteristics and dimensions of materials used in the strengthening interventions are reported in table 2. It is worth noting that the tensile strength adopted for CAM ribbons is relevant to the jointed ribbons. The dimensions and number of the confining elements in the different systems have been determined with reference to design solutions typically adopted in practice. In the last column of tab. 2 the strengthening unit resistance is reported, which has been computed as follows:

(Tensile strength x Thickness x Total height) / Column height

Table 2 Characteristics of strengthening materials

Material	Tensile Strength (N/mm^2)	Elongation at failure (%)	Thickness (mm)	Total width (mm)	Strengthening unit resistance (kN/mm)
FRP sheet	3500	1.5	0.13	800	0.46
CAM ribbon (with joint)	780	19	0.80	19 x 19	0.28
Steel jacketing plate	450	38	5.00	4 x 50	0.56



(a) (b)

Fig. 3: (a) Stress-strain curve for CAM ribbons without and with joint. (b) Test setup

As can be seen different strengthening unit resistance are availabe for the different strengthening techniques, mainly due to geometrical and technological reasons. Therefore also the results relevant to them should be compared taking that into account.

2.2 Test results

The compression tests were carried out using a force-controlled press machine with 3000 kN capacity. The displacements were measured by 5 inductive linear transducers arranged to evaluate global and local displacements and also possible rotations of the column (Fig. 4):

- 1 total vertical transducer ('TVC-Le1' in Fig. 4), to measure the total displacement between the press plates;
- 4 local vertical transducers ('TVP-Le-2', 'TVP-Le-3', 'TVP-Le-4' and 'TVP-Le-5' in Fig. 5), placed in the middle of the column sides (both in height and in width) to measure local deformations in the columns.

Each specimen was tested with loading-unloading cycles. Unloading at each cycle was started at 95% of the maximum load reached at that cycle. The tests were stopped when the columns showed very heavy damage or when the maximum load reached at a cycle was less than 30% of the maximum force at the first cycle. Fig. 5 shows a typical load-displacement diagram, where the curves relevant to the cyclic loading-unloading test on the specimen and the envelope curve of the cyclic test can be seen.

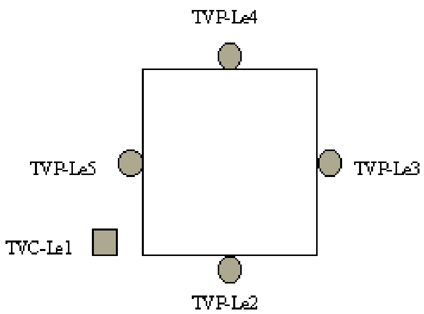


Fig. 4: Testing arrangement

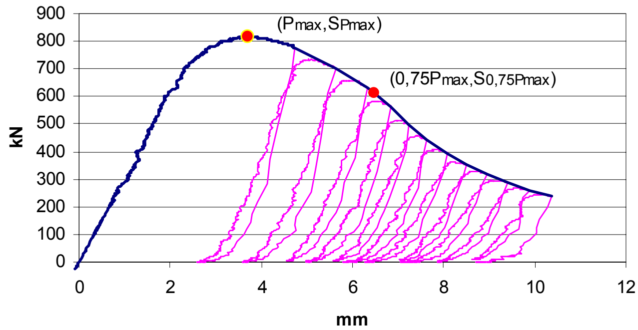


Fig. 5: Typical load-displacement diagram

Table 3 Summary of test results

Specimen	Strengthening technique	P_{max} (kN)	S_{Pmax} (mm)	$S_{0,75Pmax}$ (mm)	E_{Pmax} (kNmm)	$E_{0,75Pmax}$ (kNmm)
1	R_FRP	1072.4	7.43	8.48	5744	6763
2	R_FRP	1128.7	6.70	10.33	5601	9309
3	R_FRP	1020.5	7.64	9.34	5387	7052
4	R_NS	812.0	3.94	6.20	2086	3768
5	R_NS	815.2	3.72	6.48	1906	3944
6	R_NS	780.6	3.91	6.47	1645	3170
7	R_CAM	1359.6	8.19	17.87	7955	19444
8	R_CAM	1358.1	6.78	15.39	5844	16227
9	R_CAM	1265.0	8.60	21.94	7342	22161
10	R_SJ	1301.7	9.07	-	-	-
11	R_SJ	1306.0	8.64	30.49	7655	32413
12	R_SJ	1334.4	9.43	24.23	8178	25416
13	UR_FRP	869.0	6.39	8.30	4230	5761
14	UR_FRP	846.1	6.29	8.91	3686	6002
15	UR_FRP	765.6	4.55	8.94	2124	4859
16	UR_NS	618.9	1.28	1.63	454	1596
17	UR_NS	705.4	2.15	4.14	862	2101
18	UR_NS	600.4	1.91	2.42	652	960
19	UR_CAM	1133.9	5.2	-	-	-
20	UR_CAM	1190.6	6.61	19.71	6162	11688
21	UR_CAM	1106.5	6.68	15.66	5012	13443
22	UR_SJ	1124.8	10.14	20.38	7998	17266
23	UR_SJ	1058.9	9.02	22.67	6762	18904
24	UR_SJ	1038.6	8.15	19.59	6406	16285

Table 3 summarizes the test results relevant to the various types of reinforced, unreinforced, strengthened and not strengthened specimens (totally 8 different types). P_{max} is the peak load (strength) reached during the test and S_{Pmax} is the relevant displacement, $S_{0.75Pmax}$ is the displacement corresponding to the load value equal to 75% of the peak load at the first cycle, E_{Pmax} and $E_{0.75Pmax}$ are some measures of the energy dissipation capacity evaluated as the areas under the envelope curve, respectively, for $P = P_{max}$ and $P = 0.75\ P_{max}$ (see Fig. 5).

Figs. 6 and 7 show typical failure mechanisms, respectively, in the reinforced and unreinforced columns.

In Fig. 8 some load-displacement diagrams are reported, showing the typical cyclic behaviour observed in the eight different types of specimens under examination.

In the reinforced columns buckling of longitudinal bars was frequently observed after spalling of concrete, due to the hoop spacing, that was 10 times the diameter of the longitudinal bars. In the case of strengthened columns using either steel or CAM jacketing, the presence of steel angles partly prevented premature buckling of bars, which were forced to alternative and longer buckling paths.

The columns strengthened with FRP, though showing some strength and ductility increase in the first branch, were subjected to brittle, almost explosive, failures leading to a drastic reduction in the strength capacity of the columns (Fig. 8). On the contrary, a more ductile behaviour was shown even in the subsequent cycles by the columns strengthened with the CAM and, particularly, with the SJ system (Fig. 8). In these cases columns lost just a limited amount of their resistance capacity, also under large displacements (up to 40-50 mm).

Fig. 6: Typical failures observed in the reinforced columns

Fig. 7: Typical failures observed in the unreinforced columns

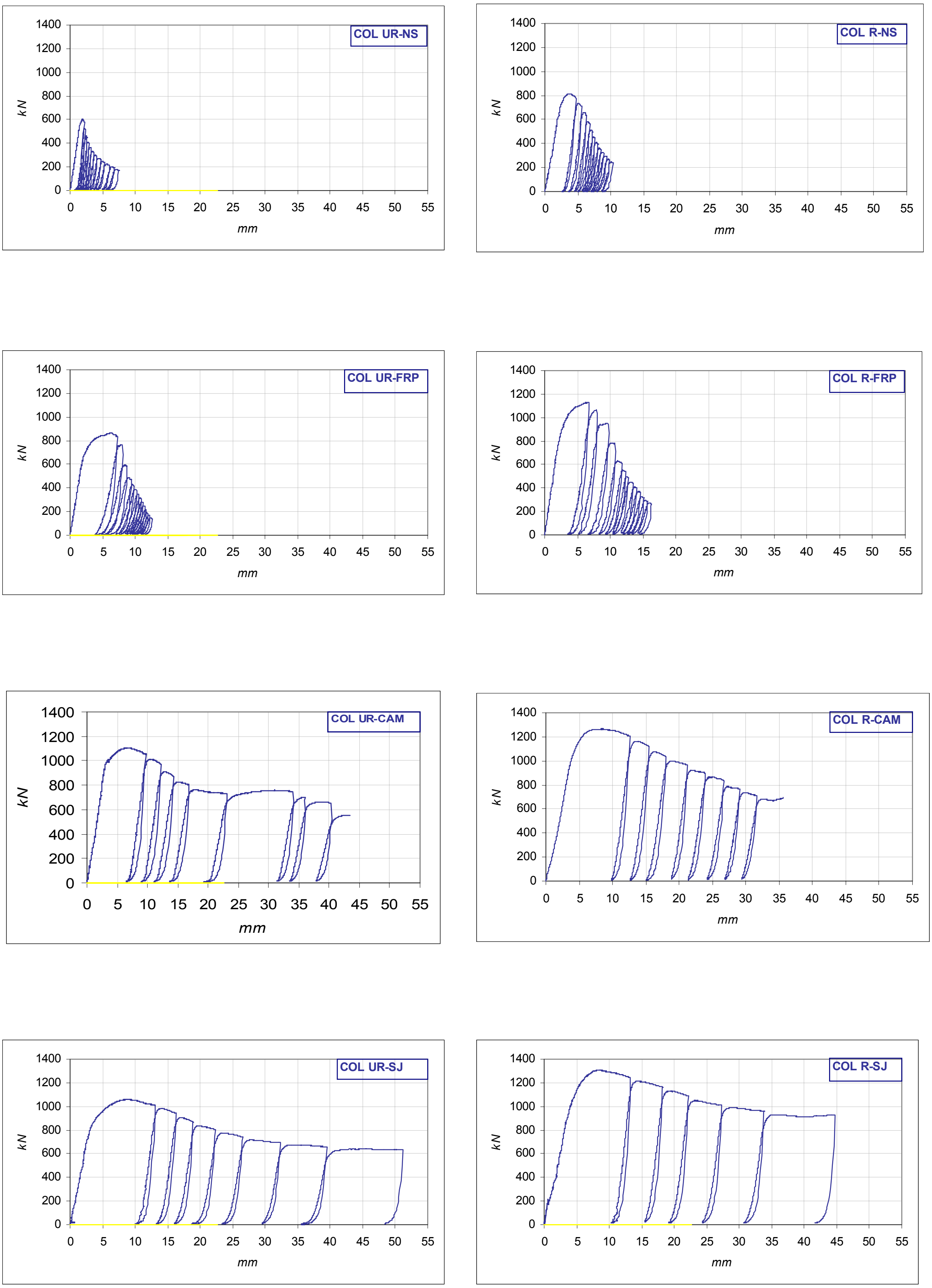


Fig. 8: Typical load-displacement curves for the various types of specimens

3 ANALYSIS OF TEST RESULTS

The experimental results relevant to the unreinforced columns are summarized in Table 4 and in Fig. 9, where four stress-strain envelope curves of the strengthened specimens are shown.

Table 4 Mean values and coefficients of variations of test results on unreinforced specimens

		P_{max} (kN)	$P_{max}/P_{max,NS}$	S_{Pmax} (mm)	$S_{Pmax}/S_{Pmax,NS}$
UR_NS	MEAN	641.6	1	1.78	1
	CoV (%)	8.7		25.2	
UR_FRP	MEAN	826.9	1.29	5.74	3.22
	CoV (%)	6.6		18.0	
UR_CAM	MEAN	1143.7	1.78	6.27	3.52
	CoV (%)	3.8		10.4	
UR_SJ	MEAN	1074.1	1.67	9.10	5.11
	CoV (%)	4.2		11.0	

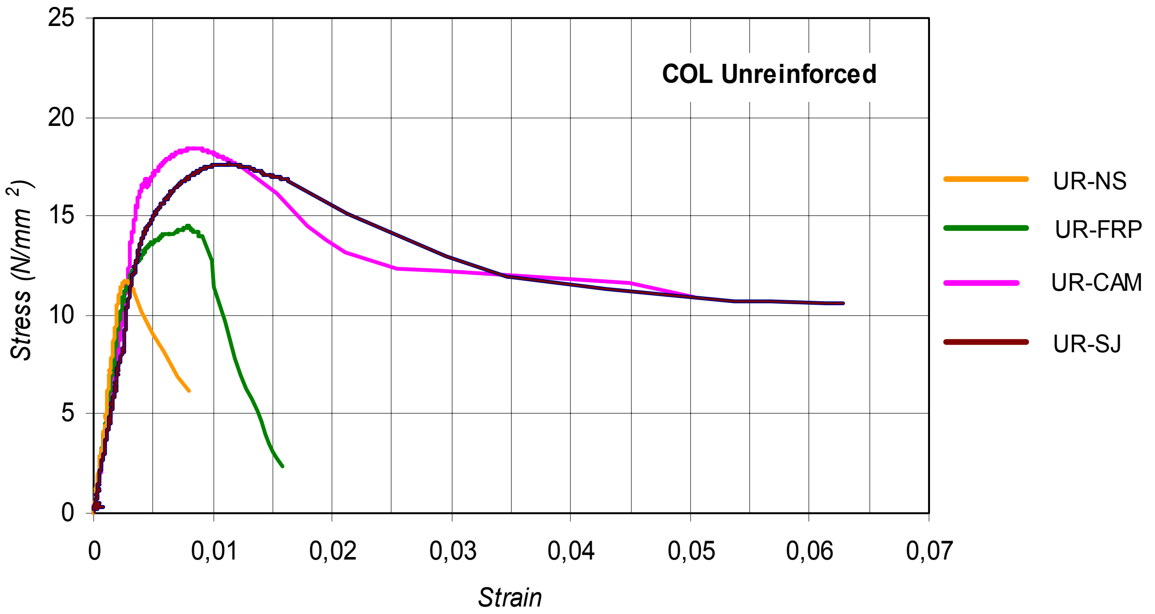


Fig. 9 Typical stress-strain envelope curves of unreinforced columns

The UR_NS columms have a mean value of the peak load P_{max} = 641.6 kN, i.e. about 80% of the strength computed from the mean concrete cylindrical strength drawn from the cubic specimens (f_{cm} = 12.71 N/mm^2). This reduction can be explained by scale effects and, mainly, by casting effects: the columns were cast in vertical forms, thus their resistance decreases along the height. In fact, Figs. 6 and 7 show that the failure is always placed in the upper part of the column.

P_{max} increases by about 30%, when using FRP, and about 70%, when using SJ and CAM. Also the mean value of S_{Pmax} remarkably increases in the strengthened columns, by 3-4 times in the UR_FRP and UR_CAM strengthened columns and about 5 times in the UR_SJ columns. Further, Fig. 9 shows that UR_SJ and UR_CAM strengthened columns are able to sustain loads equal to about 65% of P_{max} under deformation values up to 5-6%. These results show a two-fold aspect of SJ strengthened columns: on one hand they highlight the good ductile performances obtainable with steel jacketing, on the other hand they emphasise that such a system requires high deformations to provide significant confinement actions.

The experimental results relevant to the reinforced columns are summarized in Table 5. In Fig. 10, four stress-strain envelope curves of the strengthened specimens are shown.

The R_NS columns have a mean value of the peak load P_{max} = 802.6 kN. Similarly to the unreinforced columns, the FRP strengthening increases P_{max} by about 30%, whereas more remarkable increases (equal to about 60%) are provided by the SJ and CAM systems. S_{Pmax} is larger in the strengthened columns, but increasing by about 2 times also in the R_SJ columns, highlighting the positive role of reinforcement in preventing damage evolution with respect to the unreinforced columns.

Both groups of specimens (unreinforced and reinforced columns) show a remarkable improvement of the ductile capacities when strengthened either with SJ or with CAM system, whereas the columns strengthened with the FRP system show lower improvements.

Table 5 Mean values and coefficients of variations of test results on reinforced specimens

		P_{max} (kN)	$P_{max}/P_{max,NS}$	S_{Pmax} (mm)	$S_{Pmax}/S_{Pmax,NS}$
R_NS	MEAN	802.6	1	3.86	1
	CoV (%)	2.4		3.1	
R_FRP	MEAN	1073.9	1.34	7.26	1.88
	CoV (%)	5.0		6.8	
R_CAM	MEAN	1327.6	1.65	7.86	2.04
	CoV (%)	4.1		3.7	
R_SJ	MEAN	1314.0	1.64	9.05	2.34
	CoV (%)	1.4		4.4	

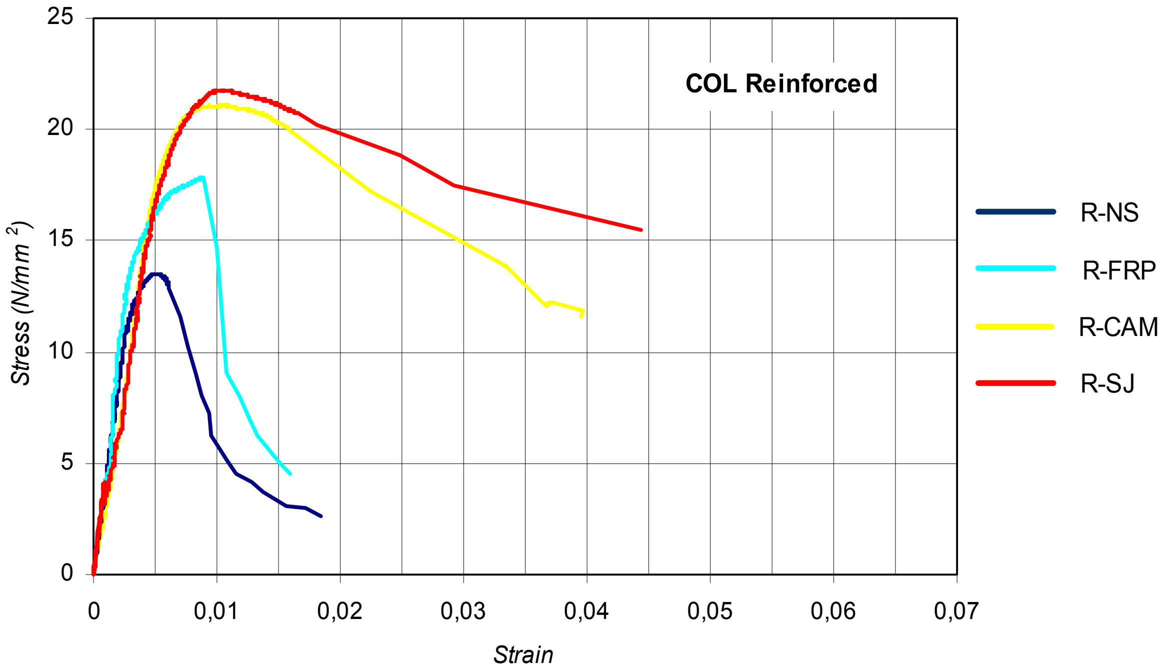


Fig. 10 Typical stress-strain envelope curves of reinforced columns

4 COMPARISON WITH ANALYTICAL PREDICTIONS

The experimental results relevant to the strengthening techniques under examination are compared to the corresponding values drawn from the analytical expressions provided as a design tool in the Annex A of the draft of Eurocode 8 – Part 3: Design and Strengthening of Structures [7].

The strength of concrete confined by steel jacketing f_{cc} is evaluated from:

$$f_{cc} = f_{c0}\left[1 + 3.7\left(\frac{0.5\alpha\rho_s f_{yw}}{f_{c0}}\right)^{0,87}\right] \quad (1)$$

where:

f_{c0} is the unconfined concrete strength;
f_{yw} is the yield strength of the jacketing steel;
α is the efficiency factor given by the ratio of the confined concrete area (shaded area in Fig. 11) to the total area of the cross-section;
$\rho_s = \frac{4A_s}{ds}$ is the geometric steel ratio of the jacketing steel;
A_s is the cross-sectional area of the lateral reinforcement;
s is the centre spacing between the lateral reinforcement;
d is the larger section width.

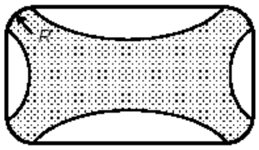


Fig. 11 Effectively confined area in rectangular cross-sections.

The confinement action provided by the CAM system is similar to that one provided by the steel jacketing, thus the increase of concrete strength can be evaluated using again eq. (1).

As regards the FRP system, the strength of confined concrete for the case of circular cross-sections wrapped with continuous sheets, can be evaluated as:

$$f_{cc} = f_{c0}\,(1 + k_1\,(f_l / f_{c0})) \qquad (2)$$

where:
$f_l = 2\,E_j\,\varepsilon_{ju}\,t_j / d_j$ is the confinement pressure provided by the FRP jackets in case of circular cross-sections;
E_j, ε_{ju} *and* t_j are, respectively, the elastic modulus, the ultimate deformation and the thickness of the FRP jackets;
d_j is the diameter of the circular cross-section;
k_1 is a coefficient which can be evaluated using some expressions proposed by several authors ([8] - [11]).

Actually, in the case of rectangular cross-sections, the confinement pressure f_l' provided by the FRP jackets is far lower. f_l' can be evaluated as a fraction of f_l using the following expression [7]:

$$f_l' = k_S\,f_l \qquad (3)$$

For rectangular cross-sections in which the corners have been rounded with corner radius R to allow wrapping the FRP around them, can be assumed

$$k_S = (2\,R / d) \qquad (4)$$

where d is the larger section width.

Finally, the strength of concrete confined by FRP jackets f_{cc} can be evaluated from the eq. (2) where f_l' is considered and k_1 is computed according to the expression proposed by Samaan [8] that provides the best estimate of f_{cc} among the above cited expressions:

$$k_1 = 6 \cdot f_l^{-0.3} \qquad (5)$$

In Table 6 the strength of confined concrete drawn from the tests are compared to the corresponding values obtained from eqs. (1) and (2).

As can be seen the analytical predictions are in good agreement with the test results, particularly in the case of columns strengthened with the CAM and FRP systems. It is worth noting that, in these cases, tests provide higher values both for reinforced and unreinforced columns. The contrary happens for the columns strengthened with steel jacketing, where the EC8 expressions appear overestimating the confinement effect on concrete strength.

Table 6 Comparison among experimental results and analitycal predictions according to EC8

	Reinforced columns f_{cc} (N/mm^2)		Unreinforced columns f_{cc} (N/mm^2)	
Strengthening technique	Test results	EC8 values	Test results	EC8 values
CAM	20.72	19.83	19.06	17.85
Steel Jacketing	20.51	22.15	17.90	20.12
FRP	16.80	15.25	13.80	13.41

5 CONCLUSIONS

The effectiveness of some strengthening techniques aimed at repairing and/or strengthening R/C columns of existing structures has been examined in the present paper. To this purpose, a wide experimental investigation was carried out at the Laboratory of testing materials and structures of the University of Basilicata. Main result to be attained within the experimental program was the experimental validation and the comparison of performances of some local strengthening techniques, including steel jacketing, FRP encasement and the recently proposed CAM system. Such result was obtained through the analysis of the test results on strengthened and non-strengthened column specimens, as well as by comparing these results among them and with expressions available in the technical literature and in recent seismic codes.

24 full scale models of columns were designed and constructed according to old codes and taking into account only gravity loads. Cyclic loading-unloading tests on the models under axial loads were carried out.

The test results allows the following considerations to be made:

- all the strengthening techniques lead to a remarkable increase of the failure strength, compared to that of the unstrengthened columns, particularly when using the CAM and the SJ sistems (strength increases of the order of 60% in the reinforced columns and 70% in the unreinforced ones vs. about 30% obtained with FRP);
- the columns strengthened with CAM and SJ show a much more ductile behaviour than columns strengthened with FRP, these latter suffering a drastic strength reduction after FRP breaking;
- the columns strengthened with both CAM and SJ were able to keep a significant amount of their strength capacity (about 65% of the peak load), also under large axial deformations (up to 40-50 mm, corresponding to about 5-6% strain);
- the analytical predictions, mainly drawn from expressions suggested by EC8, are in good agreement with the test results, providing conservative estimates for the columns strengthened with the CAM and FRP systems and lightly overestimating the confinement effect for steel jacketing.

In conclusion the results have shown the superior performances of steel jacketing and CAM system with respect to FRP, in terms of both strength and ductility increase. As far as CAM is concerned, it should also be observed that its overall confining strength was lower than the other two techniques and that even better performance can be achieved if mechanically equivalent systems are considered.

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