Experimental Investigation of Nonconventional Confinement for Concrete Using FRP

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Abstract: The present study investigates experimentally the behavior of concrete confined with fiber reinforced polymers (FRP) in the form of jackets which are applied according to a number of nonconventional techniques. First, the effectiveness of various jacketing configurations combined with anchors as a measure of increasing the strength and deformability of L-shaped columns is investigated. It is concluded that easy to install and low-cost anchors made of resin impregnated fibers properly placed at the reentrant corner of L-shaped columns enable excellent mobilization of confining stresses supplied by the FRP jackets. Next, a number of alternative confinement methods are investigated on concrete cylinders, aimed at quantifying the effectiveness of (1) unbonded jacketing, (2) spirally applied strips attached only at their ends, and (3) jacketing directly on concrete with mortar plastering. Although the study may be regarded as preliminary, it provides useful experimental support to a number of techniques which have the potential to open new horizons in the field of externally applied FRP for enhancing concrete confinement.

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Introduction and Background

In the last 2 decades, fiber reinforced polymers (FRPs) have gained increased popularity as externally applied confining reinforcement of concrete, due to their ease of application, excellent durability characteristics, high strength, and high deformability. Confinement of concrete with FRP jacketing has become a common technique today for increasing the axial load capacity of columns in nonseismic areas as well as for increasing the ductility, preventing lap-splice failures, and delaying rebar buckling of columns subjected to seismic actions. External confinement with FRP materials is typically applied on circular or rectangular columns, wrapped with epoxy-bonded sheets made of unidirectional fibers in the circumferential direction. Application of the fibers is normally done directly on properly prepared concrete surfaces.

The literature on the mechanical behavior of FRP-confined circular or rectangular concrete elements is vast. Numerous investigations have provided substantial test data on the load–deformation response of concrete specimens (typically small) confined with externally bonded FRP. These data have been quite helpful not only in understanding the confining action of FRP jackets, but also in calibrating models for the strength, ultimate strain and constitutive response of concrete wrapped with FRP (e.g. Fardis and Khalili 1981; Saadatmanesh et al. 1994; Nanni and Bradford 1995; Priestley and Seible 1995; Karbhari and Gao 1997; Samaan et al. 1998; Matthys et al. 1999; Spoelstra and Monti 1999; Toutanji 1999; Xiao and Wu 2000; FIB 2001; Shehata et al. 2002; Becque et al. 2003; De Lorenzis and Tepfers 2003; Teng and Lam 2004).

Despite the extensive treatment of the subject, structural engineers are sometimes faced with problems and issues relevant to FRP confinement which have not received proper attention by the research community yet. One issue of great practical interest in some countries is concerned with confinement of columns with L-shaped cross sections, sometimes found at the corners of reinforced concrete frames. Could FRP jacketing offer a solution in such a case? If yes, how? Limited test data presented by Vintzeleou and Sigalas (2003) indicated that FRP jackets used to confine L-shaped columns fail prematurely due to debonding at the reentrant corner. This occurs at low lateral strains, well below the jacket's strength, resulting in rather poor confinement, due to the inability of the jacket to transfer significant confining stresses in the vicinity of the reentrant corner. The writers have made an attempt to solve this problem by providing anchorage of the FRP (at the reentrant corner), through the use of FRP-based anchors.

Another issue of concern is the potential reduction of epoxy resin in the FRP system, aimed at lowering the cost of the FRP strengthening technique. Is it absolutely necessary to impregnate the whole surface of the fiber sheets with resin? Could the resin be limited only to those areas where it is absolutely necessary to transfer stresses, that is only at the fiber sheet overlap lengths? Or, perhaps, would it be possible to limit the resin only at the termination points (start and end) of spirally wound unbonded strips?

A third important issue is that of concrete surface preparation.

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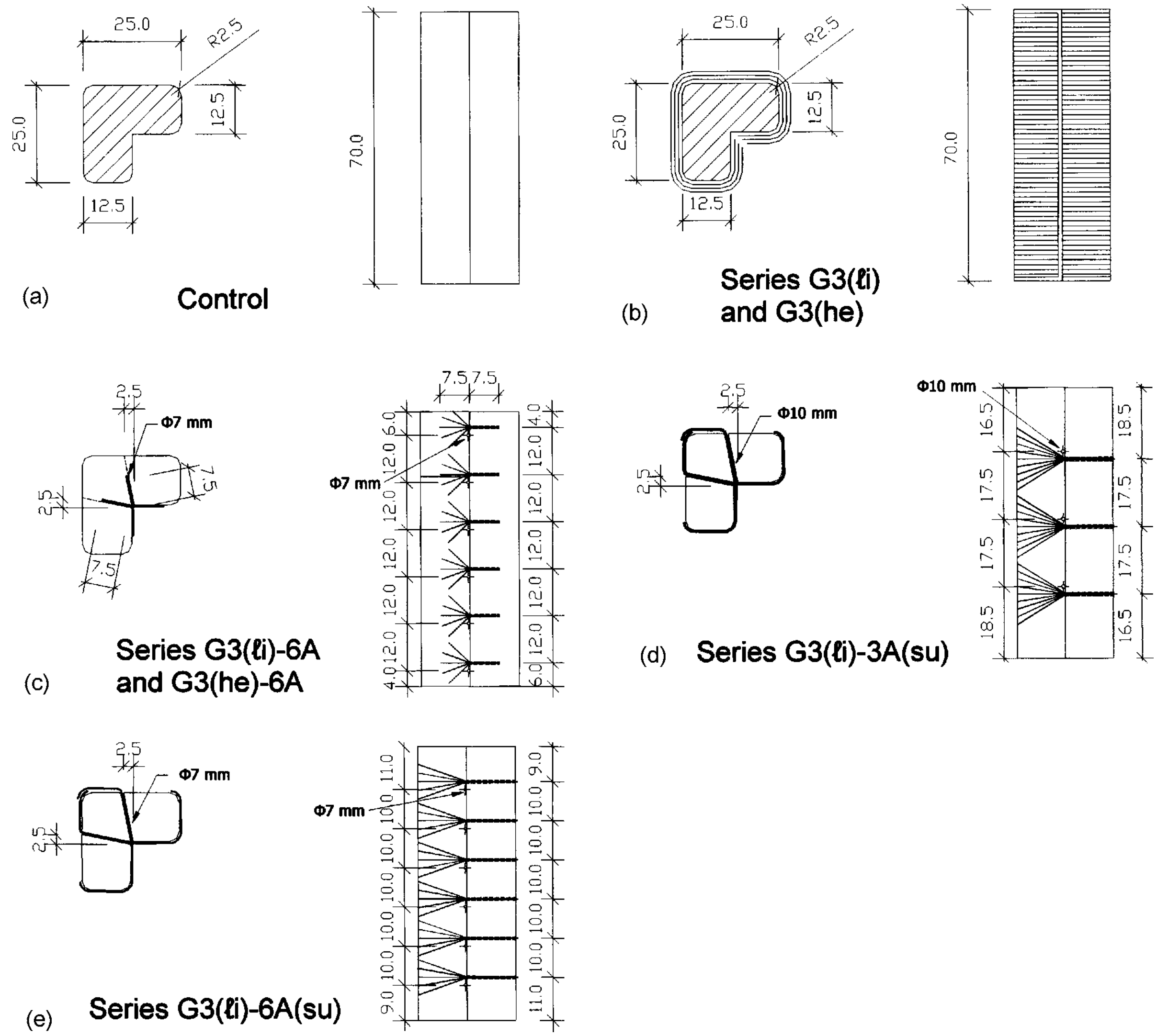


Fig. 1. Schematic layout of L-shaped columns: (a) control; (b) without anchors; (c) with six partial depth anchors; (d) with three "super anchors;" and (e) with six "super anchors"

In many strengthening and/or seismic retrofitting projects, the application of FRP materials needs to be done on concrete columns covered with mortar plastering, which is removed prior to jacketing; this process is both time consuming and labor intensive. Would it be possible to wrap columns using the FRPs on top of existing mortar plastering? If yes, what is the role of mortar strength in such applications?

The writers have conducted a series of tests on concrete specimens trying to provide some answers to the questions stated above. Although the study may be regarded as preliminary in nature, it provides useful experimental support to a number of "nonconventional" FRP confinement methods, which have the potential to open new horizons in the field of externally applied FRP for enhancing concrete confinement.

Confinement of L-Shaped Sections

Objective and Experimental Method

The objective of this experimental program was to provide a better understanding on the effectiveness of various FRP jacketing schemes, with or without anchorages, for the confinement of concrete columns with L-shaped cross sections. The investigation was carried out on seven series of specimens with cross section dimensions $250\times250\times125$ mm and height 700 mm [Fig. 1(a)]. The five corners of all specimens were rounded at a radius equal to 25 mm. Each series comprised two identical specimens, so that a total of 14 L-shaped columns were tested in uniaxial compression. The parameters considered in the investigation were as follows: thickness of FRP jacket, anchored versus nonanchored jackets, number of anchors and type of anchors. A summary of all column configurations tested is given in Fig. 1; details are provided below.

Casting of the specimens was made with one batch of ready-mix concrete in stiff steel molds. The water:cement:sand:gravel proportions in the concrete mix were roughly 0.6:1:2:3 by weight. All specimens were capped at the top with a special self-leveling high strength mortar. For the specimens receiving jacketing, two different types of unidirectional E-glass FRP sheets were applied in three layers: one was relatively light, with a weight of 505 g/m^2 and a nominal thickness of 0.19 mm, and another one was heavier, with a weight of 915 g/m^2 and a nominal thickness

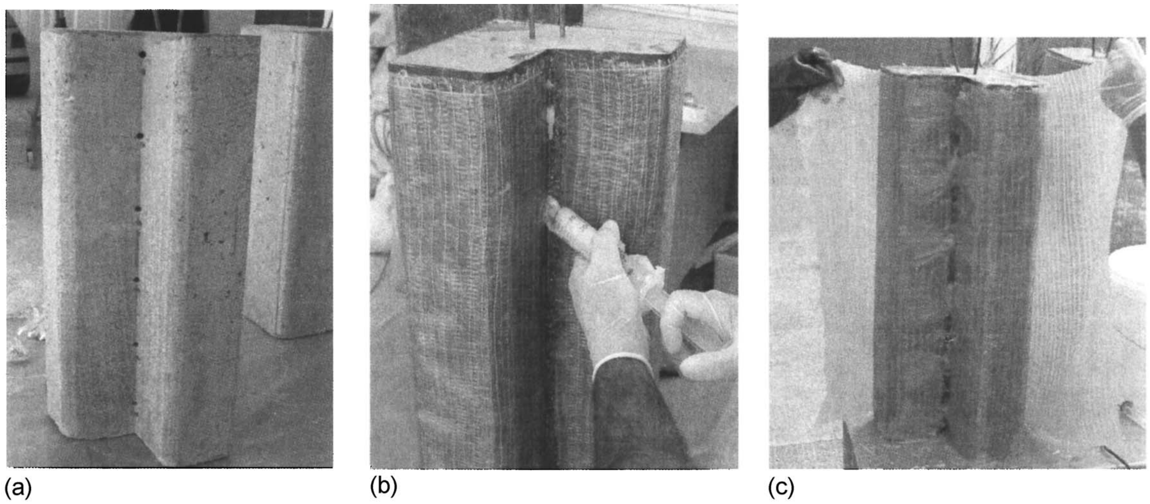


Fig. 2. Photographs of L-shaped specimens tested: (a) six pairs of holes at anchorage locations; (b) filling of holes with resin; and (c) anchors in position and wrapping of last glass fiber reinforced polymer layer

of 0.36 mm. The specimen series with the three layers of lightweight or heavyweight glass FRP are marked as G3(li) or G3(he), respectively. Application of the FRP took place approximately 2 months after concrete casting, by prewetting each sheet manually (using a roller brush) with a two-part epoxy adhesive. Each of the three consecutive layers was bonded on each specimen so that both the starting and the finishing edges of the wraps were located at the reentrant corner [Fig. 1(b)]. Note that the number of layers (three) was chosen such that a substantial increase in strength and deformation capacity would result.

Specimens in Series G3(li)-6A and G3(he)-6A received the glass fiber reinforced polymer (GFRP) jackets in combination with six pairs of 150 mm long spike anchors [Fig. 1(c)]. Each anchor comprised a tow of unidirectional E-glass fibers, which were used to attach the resin-impregnated sheets into 7 mm diameter holes drilled in the concrete; the weight of each tow was approximately equal to 8.5 g. The holes were drilled at a depth of 75 mm near the reentrant corner of the columns at six equally spaced locations (120 mm apart) along the height [Fig. 2(a)]; dust was blown out and then the holes were filled with a two-part high viscosity epoxy adhesive [Fig. 2(b)]. Next, each tow was impregnated with epoxy resin (the same as that used to impregnate the fabrics) and one half of it was forced inside a hole. The other (protruding) half was spread uniformly outwards, with the fiber ends forming a semicircle. The protruding bundle was placed between the second and third layer of FRP in each column, as shown in Fig. 2(c). This method of anchoring was selected on the basis of transferring the tension forces from the FRP sheets terminating at the reentrant corner of the column into the concrete, thus enabling the jacket to act as a system confining both of the two rectangular elements of the cross section simultaneously [Fig. 3(a)].

Specimens in Series G3(li)-3A(su) and G3(li)-6A(su) received the GFRP jackets in combination with three and six pairs of anchors, respectively, which were 500 mm long, which is much longer than those in the previous series [Figs. 1(d and e)]. These "super anchors" were made exactly as those described above, except that the holes which accommodated their middle part were made all the way through the thickness of concrete; hence, both ends of the super anchors were spread outwards, enabling the formation of a closed jacket system on each one of the cross section rectangular elements [Fig. 3(b)]. Another interesting feature of the anchoring systems in Series G3(li)-3A(su) and G3(li)-6A(su) was that their total axial capacity was identical, in the sense that the total fiber volume of the three pairs of anchors in Specimens G3(li)-3A(su) was equal to that of the six pairs of anchors in Specimens G3(li)-6A(su). This was made possible by using anchors twice as heavy for Specimens G3(li)-3A(su); those had a weight of 70 g each, whereas the ones for Specimens G3(li)-6A(su) had a weight of 35 g each. Notably, the super anchors were much heavier than the simpler ones used in Specimens G3(li)-6A and G3(he)-6A.

Testing was performed approximately 1 month after application of the FRP jackets. All specimens were tested in uniaxial compression through the application of monotonic loading at a rate of 0.01 mm/s in displacement control, using a 4,000 kN compression testing machine. Loads were measured from a load cell and displacements were obtained using external linear variable differential transducers (LVDTs) mounted on the two long sides, at a gage length of 180 mm, in the middle part of each specimen. From the applied load and average displacement measurements, the stress–strain curves were obtained for each test.

Results and Discussion

All the uniaxial compression stress–strain curves are plotted in Fig. 4. Average values for peak stresses, ultimate strains (defined at the point where the slope of the σ-ε curve drops suddenly, see

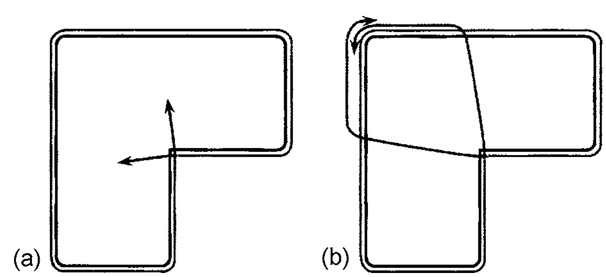


Fig. 3. Schematic of (a) simple anchors and (b) super anchors

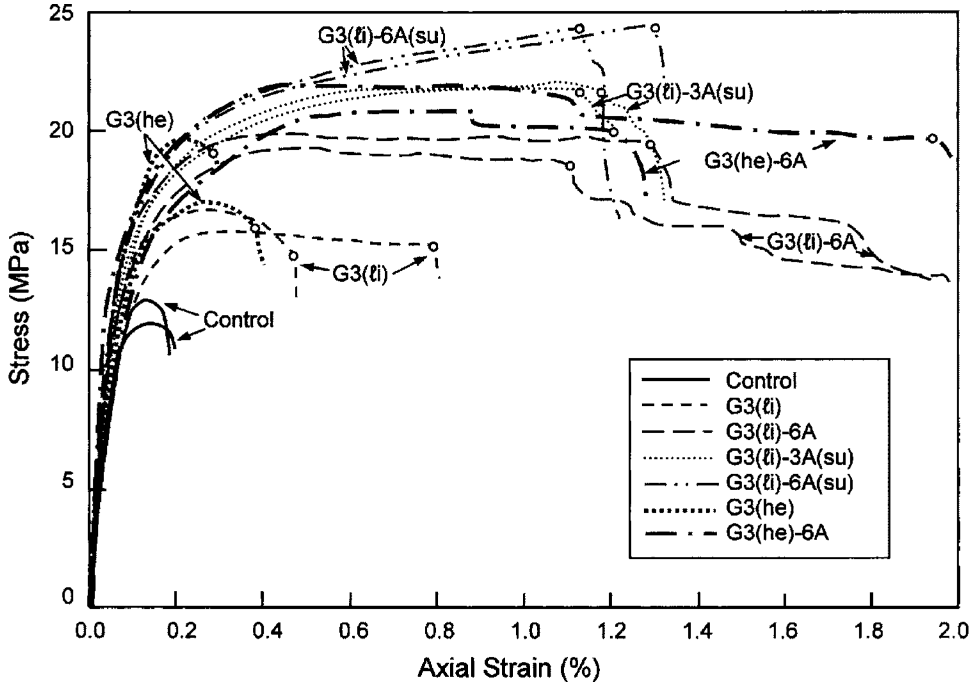


Fig. 4. Axial stress–strain diagrams of L-shaped specimens in uniaxial compression

empty circles in Fig. 4) and effectiveness ratios (that is ratios of confined to unconfined properties) for each jacketing system are given in Table 1.

Failure of the control specimens was typical of unconfined concrete, through the formation of vertical cracks. The specimens that received FRP jackets without anchors demonstrated a 32 or 48% strength increase, and an utimate strain increase by a factor of 4.5 or 2.43, when the jacket was made of lightweight or heavyweight sheets, respectively [G3(li) versus G3(he)]. Failure in these cases was the result of debonding, which initiated at the column reentrant corners, where the FRP terminated [Fig. 5(a)]. Note that this failure mode is in agreement with the results obtained by Vintzeleou and Sigalas (2003) on L-shaped columns (with dimensions similar to those in the present study) without any special anchorage provisions. It is concluded that: (1) jacketing without anchors does not allow full utilization of the fiber strength and (2) thick jackets result in slightly increased strength but also in reduced deformability.

The specimens with partial depth anchors (at six locations along the height) exhibited a much better behaviour compared to the ones without anchors. The strength increased by 59 or 72%, and the ultimate strain increased by a factor of 8.57 or 11.21, when the jacket was made of lightweight or heavyweight sheets [G3(li)-6A versus G3(he)-6A], respectively. In specimens with the light jacketing system failure occurred at the outer corner due to fracture of the fibers in the lateral direction [Fig. 5(b)], whereas in specimens with the heavy jacketing system failure was the result of tensile rupture in the anchors [Fig. 5(c)]. Here it is concluded that the partial depth anchoring system is extremely effective in mobilizing high confining stresses.

All specimens with super anchors performed well. In those where anchors were attached at six locations along the height, G3(li)-6A(su), the strength increased by 97% and the ultimate strain by a factor of 8.64. The corresponding values for the specimens with anchors at three locations, G3(li)-3A(su), were 77% and 8.28, confirming the reduction in effectiveness of confinement as the spacing of anchors increases. Failure, in all cases, was due to anchor fracture at the reentrant corner, which propagated into the jacket [Fig. 5(d)]. It appears that full mobilization of the jacket strength was not achieved, due to the limited capacity provided by the anchors.

Comparing the behavior of columns with super anchors, G3(li)-6A(su), with that of columns with the partial depth ones, G3(li)-6A, it is concluded that the effectiveness of the former is

Table 1. Specimen Notation and Summary of Test Results on L-Shaped Columns

Specimen notation	Compressive strength, f_{cc} (MPa)	Normalized strength, f_{cc}/f_{co} (−)	Ultimate strain, ε_{ccu} (%)	$\varepsilon_{ccu}/\varepsilon_{co}$ (−)	Failure mode of fiber reinforced polymer
Control	12.42	1.00	0.14[a]	1.00	—
G3(li)	16.35	1.32	0.63	4.50	Debonding
G3(li)-6A	19.75	1.59	1.20	8.57	Fracture
G3(li)-3A(su)	22.02	1.77	1.16	8.28	Anchor fracture
G3(li)-6A(su)	24.47	1.97	1.21	8.64	Anchor fracture
G3(he)	18.44	1.48	0.34	2.43	Debonding
G3(he)-6A	21.40	1.72	1.57	11.21	Anchor fracture

[a]Ultimate strain of control specimens is taken at peak stress.

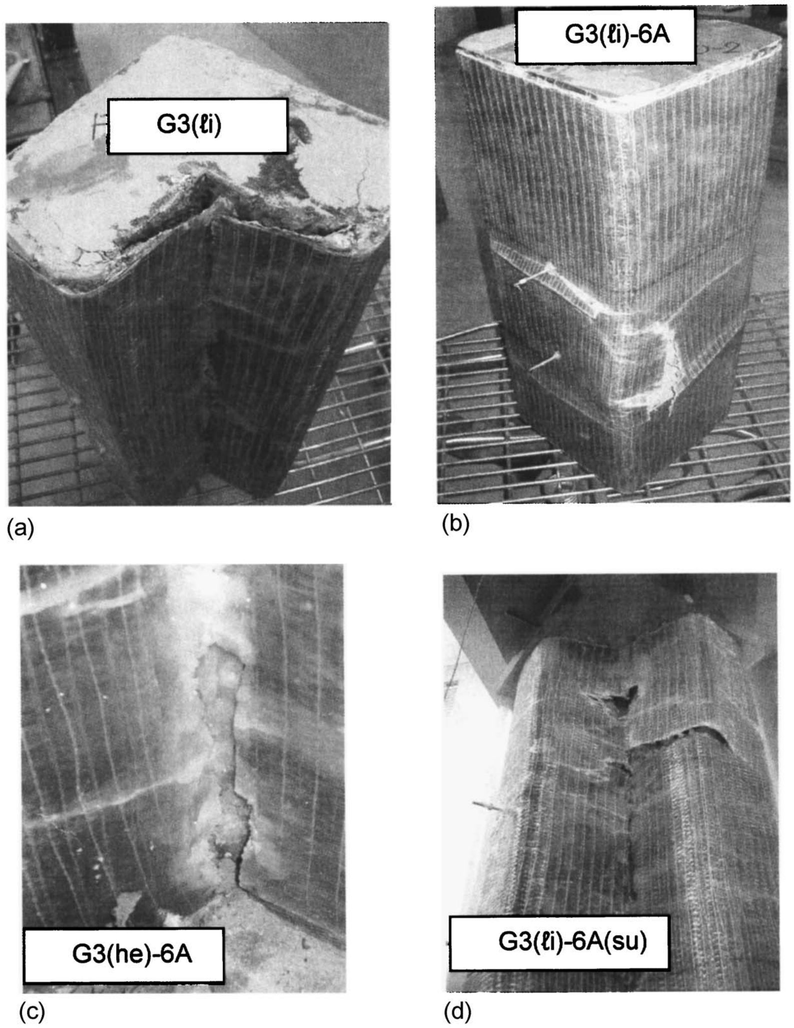


Fig. 5. Failure of L-shaped specimens: (a) no anchors, debonding at the reentrant corner; (b) tensile fracture of fiber reinforced polymer at outer corner; (c) tensile fracture of anchor at bottom; and (d) anchor fracture at reentrant corner, propagating into jacket

higher in terms of strength (97 versus 59% increase) but only marginally improved in terms of deformability (8.64 versus 8.57). Hence, in view of the much higher difficulty associated with the application of super anchors, the writers believe that their use is not justified.

Alternative Confinement Systems

Objective and Experimental Method

The second part of the present study aims at investigating experimentally the effectiveness of various alternative confining systems which involve the application of FRP according to a number of different methods, as explained next. First, the conventional confinement with fully bonded FRP jackets is compared with two alternative systems: one with unbonded jackets and a second one which comprises the formation of each jacket layer using a single strip, spirally applied and bonded only at the ends; the amount of epoxy resin used in both cases is minimal. Next, the conventional method of confinement where FRP jackets are bonded on concrete surfaces is compared with jacketing on surfaces with mortar plastering; the investigation in this case addresses the role of mortar strength between concrete and FRP.

The experimental study was carried out on six series of cylindrical specimens with diameter 200 mm and height 350 mm. Each series comprised three identical specimens, so that a total of 18 cylindrical columns were tested in uniaxial compression. Casting of the specimens was made with one batch of ready-mix concrete in stiff plastic molds. After curing, all specimens were capped at the top with a special self-leveling high strength mortar. Jacketing was provided with unidirectional carbon fiber sheets, which had a weight of 230 g/m^2, a nominal thickness of 0.12 mm, and an elastic modulus of 230 GPa. Bonding of the sheets was made using a two part epoxy resin (mixing ratio 4:1). The adhesive was pasty, with a viscosity such that complete wetting of the fibers was possible by using a plastic roller.

The first series involved the control specimens, which were plain concrete cylinders without any type of jacketing. Series B included specimens confined with two layers of carbon fiber reinforced polymer (CFRP) applied "as usual," that is with a single sheet wrapped around each cylinder until the desired number of layers (two in this study) was achieved, with an overlap length equal to 150 mm [Fig. 6(a)]. The carbon sheets were impregnated with resin, forming a full bond with the concrete. Specimens in Series U were identical to those in Series B except that impregnation of the sheets with resin was applied only at the overlap

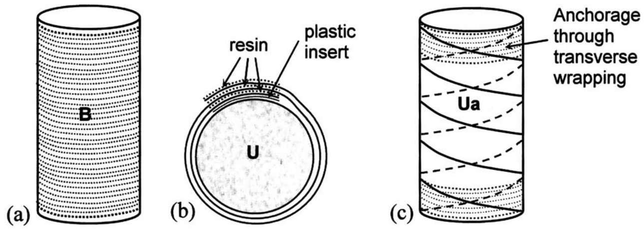


Fig. 6. Alternative fiber reinforced polymer jacketing: (a) conventional wrapping with full bond; (b) unbonded jacketing with resin impregnation only at overlap length; and (c) spirally applied strips bonded at top and bottom

length. Contact between the resin and the concrete surface was prevented by using a 150 × 350 mm plastic film, which was attached on the concrete surface at the location of the ovelap [Fig. 6(b)]. Jacketing of specimens in Series Ua was provided using a new concept, according to which each jacket layer was formed through the use of a single strip. The strip was 70 mm wide and was wrapped around the specimen in a spiral configuration, starting from one end (column top) and stopping at the other (column bottom), at an angle of about 6° with respect to the horizontal. The next strip was wrapped in the direction opposite to that of the previous one. Finally, the strips were attached onto the concrete at the ends only using a simple method, which involved wrapping and epoxy bonding of a 70 mm wide strip, applied circumferentially in two layers at each end (top and bottom) of the specimen [Fig. 6(c)].

The next two series of specimens (M-h and M-l) were wrapped with CFRP as those specimens in Series B (conventional method, full bond), but the concrete surface was plastered with mortar. The strength of mortar was different in each series, so that specimens in Series M-h received a mortar plastering with a higher strength than those in Series M-l. The two different mortars were produced using a water:cement:lime:sand proportion equal to 0.7:1.2:1.3:4 and 0.85:1:1.3:4 by weight, for mortars M-h and M-l, respectively. Application of the mortar was made with a metal trowel, in an approximately 10 mm thick layer.

The strength of the two different mortars was obtained through flexural and compression testing, according to *EN 1015-11* (CEN 1993), using a servohydraulic MTS testing machine. Flexural testing was carried out on 40 × 40 × 160 mm hardened mortar prisms, at an age of 28 days. Compression testing was carried out on each of the fractured parts using two 40 × 40 mm bearing steel platens on top and bottom of each specimen, which was carefully aligned so that the load was applied to the whole width of the faces in contact with the platens. The average flexural and compressive 28 day strength values for the mortar used in Cylinders M-h were 2.02 and 7.74 MPa, respectively. The corresponding values for Specimens M-l were 1.29 and 4.84 MPa.

Testing of all cylindrical specimens was performed approximately 2 weeks after application of the FRP jackets (in those specimens which were plastered, the mortar was at an age of approximately 5 weeks). All specimens were tested in uniaxial compression through the application of monotonic loading at a rate of 0.02 mm/s in displacement control, using a 2,600 kN compression testing machine. Loads were measured from a load cell and displacements were obtained using external LVDTs mounted on two opposite sides, at a gage length of 190 mm, in the middle part of each specimen. From the applied load and average displacement measurements the stress–strain curves were obtained for each test.

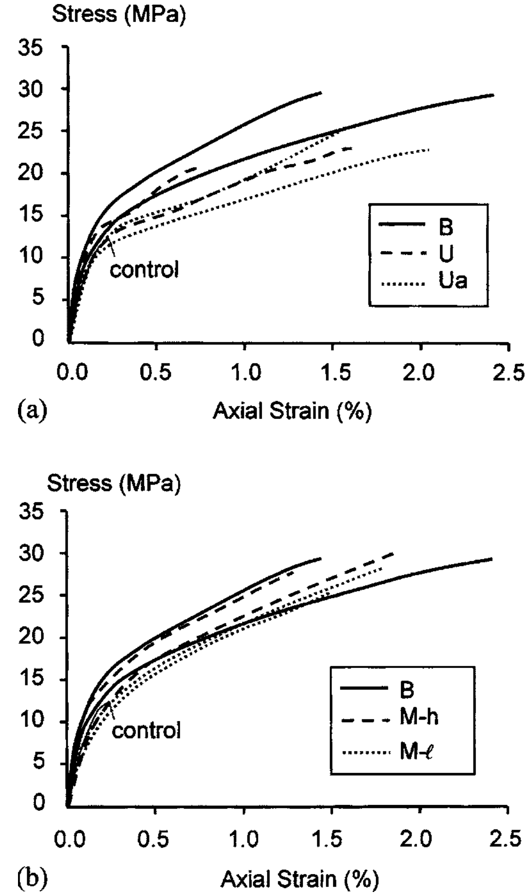


Fig. 7. Axial stress–strain diagrams for: (a) unbonded or spirally applied jackets versus fully bonded jackets and (b) jackets applied on mortar plastering (two different strengths) versus jackets applied on concrete

Results and Discussion

Typical uniaxial compression stress–rain curves are plotted in Fig. 7. Average values of peak stresses, ultimate strains and effectiveness ratios for each jacketing system are given in Table 2. Failure of the control specimens was typical of unconfined cylinders, through the formation of vertical cracks. All confined specimens failed due to tensile fracture of the fibers in the circumferential direction (Fig. 8). An interesting feature of the specimens with mortar plastering was that those FRP pieces that fractured caused complete debonding of the mortar from the concrete [Fig. 8(c)], thus revealing the relative weakness of the mortar–concrete interface.

In terms of jacketing effectiveness, quantified by the ratio of confined to unconfined specimen property, it was concluded that fully bonded conventional jackets on concrete surfaces demonstrated the best performance: the strength increased by 142% and the ultimate strain by a factor of 9.6. Unbonded jacketing with resin only at the overlap length demonstrated the worse performance: the strength increased by 78% and the ultimate strain by a factor of 5.8. The effectiveness of spirally wrapped fiber strips bonded at the ends only was remarkable, as the strength increased by 97% and the ultimate strain by a factor of 9. Finally, FRP jackets on concrete cylinders with mortar plastering behaved quite well too: for the higher strength mortar the strength increased by 136% and the ultimate strain by a factor of 7.75,

Table 2. Specimen Notation and Summary of Test Results on Cylinders

Specimen notation	Compressive strength, f_{cc} (MPa)	Normalized strength, f_{cc}/f_{co} $(-)$	Ultimate strain, ε_{ccu} (%)	$\varepsilon_{ccu}/\varepsilon_{co}$ $(-)$
Control	12.10	1.00	0.20[a]	1.00
B	29.25	2.42	1.92	9.60
U	21.54	1.78	1.16	5.80
Ua	23.85	1.97	1.80	9.00
M-h	28.60	2.36	1.55	7.75
M-l	26.31	2.17	1.63	8.15

[a]Ultimate strain of control specimens is assumed equal to $\varepsilon_{co}=0.2\%$, which agrees well with the mean value (0.22%) recorded at peak stress.

whereas for the lower strength mortar the strength increased by 117% and the ultimate strain by a factor of 8.15.

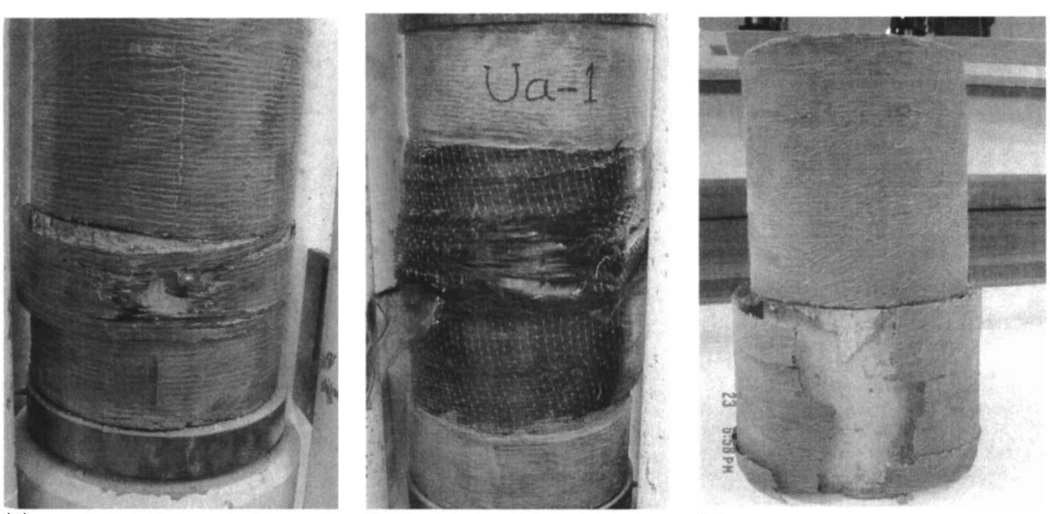
Overall, all jacketing techniques investigated in this study resulted in substantial confining stresses. It appears that the conventional technique of fully bonded FRP maximizes the jacket effectiveness, even when the jackets are bonded directly on mortar plastering, provided that the mortar strength is not too low. A mortar with flexural strength in the order of 2 MPa results only in marginally reduced effectiveness. A point of concern with unbonded jacketing is the higher risk associated with mechanical damage and environmental degradation of the fibers.

Conclusions

Testing of L-shaped concrete specimens confined with FRP jackets leads to the following conclusions: (1) Use of jackets without anchors results in limited increase in strength and deformability, regardless of the FRP thickness (lightweight versus heavyweight sheets), due to rather poor utilization of the FRP as a result of premature debonding at the reentrant corner. (2) Partial depth spike anchors provide a cost effective and easy to install method of confinement, by allowing the jacket to deform substantially and even exhaust (as in the case of the lightweight sheets used in this study) its tensile capacity. (3) Compared with their partial depth counterparts, full depth anchors (the super anchors in this study) result in increased effectiveness in terms of strength but marginal benefits in terms of deformability; in view of the high difficulty associated with their installation, the use of such anchors is not justified. (4) The effectiveness of confining jackets increases as the spacing of anchors decreases.

Based on preliminary test results on cylinders confined with FRP in various configurations it is concluded that: (1) Unbonded jacketing with resin only at the overlap length is considerably less effective (by approximately 45%) than fully bonded jacketing. (2) Compared with fully bonded jackets, the effectiveness of spirally wrapped strips bonded at their ends only is slightly inferior (by approximately 30%) in terms of strength, but practically unreduced in terms of deformability. (3) The strength of mortar plastering on concrete surfaces plays an important role on the effectiveness of FRP jacketing; the results obtained in this investigation indicate a reduction in confined concrete strength and deformability (in comparison with unplastered concrete), but despite the relatively low strength of mortars, the overall effectiveness of jacketing remains high.

The present investigation may be regarded as preliminary in nature and should be followed by detailed studies on each one of the issues covered. However, the writers' view is that it provides useful experimental support to a number of "nonconventional" FRP confinement methods, which have the potential to open new horizons in the field of externally applied FRP for enhancing concrete confinement.



(a) (b) (c)

Fig. 8. Failure of confined cylinders: (a) fully bonded fiber reinforced polymer on concrete; (b) spirally applied strips bonded at ends; and (c) fully bonded fiber reinforced polymer on mortar

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Notation

The following symbols are used in this paper:

f_{cc} = strength of confined concrete;
f_{co} = strength of unconfined concrete;
ε_{ccu} = ultimate strain of confined concrete; and
ε_{co} = strain of unconfined concrete at peak stress.

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