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STRENGTH OF SHORT SQUARE COLUMNS CONFINED WITH GFRP WRAPS

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Abstract

This research reports the results of an experimental investigation carried out on short noncircular columns strengthened with GFRP wraps. A total number of 45 specimens (100x100x500mm) were tested under concentric loads. The major parameters of the study were the strengthening configuration including the number of GFRP layers and extension of the composite along the column height, volume fraction of the transverse reinforcement and degree of column surface roughness. Using the hand lay-up technique, continuous layers of a woven fiberglass fabric were bonded along the column height to introduce a confining pressure, which increases the apparent concrete compressive strength and consequently the column capacity. The results indicated that significant increase in the ultimate load and ductility improvement could be achieved by proper application of GFRP wraps.

يقدم هذا البحث نتائج الاختبارات المعملية على أعمدة قصيرة ذات قطاع مربع تم تقويتها باستخدام مواد مركبة من البولي استر المسلح بالألياف الزجاجية؛ حيث تم اختبار الأعمدة تحت تأثير حمل مركزي يتزايد حتى الانهيار. تضمن البحث دراسة تأثير عدد من المتغيرات ومنها تأثير سمك وامتداد القميص من المادة المركبة، نسبة الحديد العرضي بالأعمدة وتأثير خشونة السطح الخرساني وذلك على السلوك الإنشائي للأعمدة بدلالة الحمل الأقصى والانفعال عند هذا الحمل. وقد أظهرت النتائج كفاءة ملحوظة للنظام الإنشائي المقترح ومدي ملائمة معادلات معهد الخرسانة الأمريكي المقترحة لاستنباط قيمة الزيادة بالحمل الأقصى نتيجة أعمال التقوية.

Keywords: strengthening, short columns, GFRP, polyester, fiberglass, wrapping

INTRODUCTION

The need for column strengthening arises in regions of seismic activity to increase the column shear capacity against inclined cracking or when the transverse reinforcement is insufficient or poorly distributed at potential flexural plastic hinge regions. Several studies have shown the role of transverse reinforcement in increasing the load capacity of existing columns by generating a triaxial stress state in the confined concrete core [1,2]. Recently, the use of fiber reinforced polymers (FRP) as external reinforcement to provide the confinement action has been thought within an increasing interest in using advanced composites in strengthening applications. Tests have shown that the use of FRP jacket wrapped directly onto the existing column offered an increase in both column strength and ductility [3-9].

Strength improvement is attributed to an apparent increase in the concrete compressive strength due to the confining pressure provided by the jacket, while ductility improvement refers to the ability of developing higher ultimate compressive strain in the concrete, delay of longitudinal steel buckling and claming the lap splices of longitudinal steel [10]. The improvement in the behavior of a strengthened column is influenced by the shape of the transverse cross section, mechanical properties of concrete and FRP mechanical properties and thickness.

Tests have shown that the strength gain due to FRP jacketing was higher in circular columns compared to rectangular columns that showed almost no strength gain in some cases [9]. This result is due to stress concentration near the corners of the rectangular section and consequently the lower confining pressure and also to the smaller effectively confined concrete core in rectangular cross sections compared to circular ones. The influence of these two factors can be reduced by rounding the corners of noncircular columns as suggested by experimental observation [11]. Carbon, aramid and glass fibers are used as matrix reinforcement. Because of their higher stiffness and strength, carbon fibers provide a superior confining action in terms of higher ultimate concrete strain and limited lateral dilation associated with delayed buckling of the longitudinal bars. However, the relatively low cost of fiberglass products in the form of sheets and fabrics makes them an attractive choice for this application. The very few tests reported in the literature on FRP strengthened columns did not provide specified conclusions about the influence of the combined action of the longitudinal transverse weaves in bi-directional fabrics [4,12]. Actually, unidirectional composites are almost always used in practical applications of this type. The required FRP jacket thickness and extension along the column height are to be determined through proper design. Priestley et al. [13] described the FRP jacket length when confinement is intended primly to enhance flexural ductility. Short columns strengthened in shear need to be wrapped along their full height, while there is no need to extend the jacket beyond the extent of the lap-splice to enhance the splice performance [10].

DESIGN CONSIDERATIONS

Different criteria may be considered as the basis for the design of compression members confined with FRP jackets. For instance, flexural ductility enhancement, improving the performance of lap-splices regions and shear strengthening are possible targets in seismic retrofitting of existing columns. Design equations were presented by Ghoneim [10] to compute the jacket thickness along with the theoretical basis of the theoretical analysis for the previous applications. In all cases, the column capacity and ductility are generally improved due to the confining action that may be provided along the whole column height or only along the plastic hinge regions. The axial load capacity of confined reinforced concrete columns with ties as transverse reinforcement can be calculated according to the following equation:

$$\phi P_o = \phi [\, 0.85 f'_{cc} \,(A_g - A_{st}) + f_y A_{st} \,] \qquad (1)$$

which is the same as the ACI 318-95 Code [14] equation for conventional columns with the apparent confined concrete strength f'_{cc} replacing f'_c. Obviously, the determination of f'_{cc} is the key parameter in calculating the axial capacity. The analytical methods described in the literature considered only the case in which failure occurs due to composite rupture assuming that the ultimate stress f'_{cc} and ultimate strain ε_{cu} are reached simultaneously with the ultimate jacket strain ε_{ju}. It can be concluded that the main challenges in the design of reinforced concrete columns confined with FRP jackets are: (1) Adopting a constitutive law to describe the behavior of confined concrete, (2) determination of the apparent confined concrete strength, (3) determination of the ultimate concrete strain and (4) setting upper limits for the confined concrete and FRP jacket strains.

At this stage, the results of extensive testing are needed to verify the proposed analytical models and to set the appropriate design criteria. In the following, a brief description is presented for the current knowledge obtained from testing and the attempts to fulfill the above challenges.

The experimental results show that the behavior of confined compression members strongly depends on the shape of the cross section. Generally, the stress-strain relationship for FRP confined concrete shows a continuously increasing branch upon reaching the ultimate load because the composite remains elastic up to failure, while this branch decays in a softening manner in steel confined columns because the steel jacket exerts a constant confining pressure upon yielding. This trend particularly describes the behavior of circular columns rather noncircular columns in which the confining pressure is less effective due to stress concentration near the corners. Concerning the pre-peak behavior, the tests conducted by Seliem and Ghoneim [15] and many others showed that the stiffness improvement was limited due to FRP jackets. Because of their lower elastic modulus, GFRP jackets are expected to provide the least stiffness improvement among other composite types.

Recently, Campione and Miraglia [11] proposed an analytical model to evaluate the confining pressure for different shapes of the cross section taking into account the effective confined cross section. The well known model proposed by Mander et al. [1], based on the energy balance approach and originally proposed for steel jackets, was revised and modified to account for FRP jackets to determine f'_{cc} and ε_{cu}. Most of the available test data needed to validate the proposed model were related to circular columns and showed that the analytical ultimate strain values were highly conservative.

The design guidelines reported in [16] recommended an allowable FRP jacket strain ε_{ja} as the smaller of 0.004 or $0.75\varepsilon_{ju}$. Limiting the jacket strain is intended to provide an adequate protection against jacket failure under unexpected overload and to avoid large dilation strains associated with possible buckling of the longitudinal bars and degradation of the aggregate interlock action which is a basic component of the concrete shear strength.

Once the above design requirements are satisfied, a regular design can be performed according to the steps demonstrated in Fig. (1) to determine the ultimate load corresponding to a given jacket thickness t_j. The design of reinforced concrete columns confined along the full column height is based on the following basic hypotheses [11]: (1) all transverse cross sections of the member are in the same condition along the height of the member due to the presence of continuous FRP reinforcement. (2) FRP behaves elastically up to failure and sudden failure occurs once the tensile strength is reached and (3) perfect adhesion between concrete and FRP is ensured up to failure.

The ACI 440-F guide [17], concerned with the design of externally bonded FRP systems for seismic strengthening of reinforced concrete structures, gives the following simple equations to compute f'_{cc} for noncircular columns with and without rounded corners:

$$\rho_f = 2\, n\, t_j\, (b+d) / bd \quad (2)$$

$$K = 1 - [(b-2r)^2 + (d-2r)^2] / 3bd\, (1-\rho_f) \quad (3)$$

$$\varepsilon_{ja} = 0.004 \leq 0.75\, \varepsilon_{ju} \quad (4)$$

$$f_l = 0.5\, K\, \rho_f\, \varepsilon_{ja}\, E_j \quad (5)$$

$$f'_{cc} = f'_c\, [2.25 \sqrt{1 + 7.9 f_l / f'_c} - 2f_l/f'_c - 1.25] \quad (6)$$

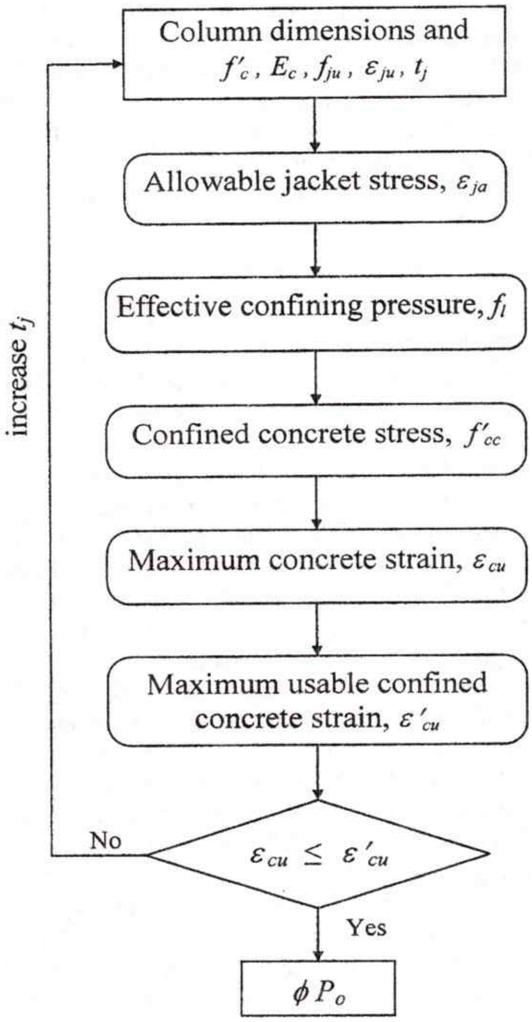

Fig. (1): Design procedure for FRP confined columns

RESEARCH SIGNIFICANCE

The current experimental work was planned to obtain more information about the response of short RC columns concerning different variables that affect the confinement phenomenon in terms of column strength and ductility. Despite the fact that externally bonded FRP composites have been employed in numerous rehabilitation works of RC structures, their potential application for strengthening noncircular columns still comprises certain difficulties and restrictions. In this regard, the ACI 440-F guidelines stated that "Testing has shown that confining square and rectangular members with FRP jackets can provide marginal increase in axial compression capacity of the member. Given the many unknowns with this type of application, there are no recommendations provided at this time on the use of FRP. Applications of this nature should be closely scrutinized and evaluated. In no case FRP jackets with fibers running longitudinally is relied upon to resist compression". This statement shows the significant need to conduct extensive testing to provide experimental data considering the rehabilitation of columns as structural members that are most frequently designed with noncircular cross sections. These research efforts are directed towards an urgent need to obtain more reliable design equations to accurately predict the structural behavior. Thus, the rehabilitation works can be accomplished at the lowest possible cost, which is a basic requirement with regard to the relatively high cost of FRP materials.

EXPERIMENTAL PROGRAM

Specimen details

A total number of 45 short columns (100x100x500mm) were tested. In all specimens the longitudinal reinforcement consisted of four 6 mm in diameter mild plain steel bars, so that the reinforcement ratio A_{st}/A_g was 1.17 percent. The same reinforcing bars with a yield stress of 325 MPa were used for ties. All ties were effectively anchored by means of end bends sufficiently embedded in the confined core of the column. The specimens were divided into five groups C, F1, F2, F2R and P2. The abbreviation describes the repair configuration. Specimens in group C were control RC columns without strengthening, while those in groups F1 and F2 were wrapped with one and two layers of FRP along the full height of the column. Specimen in group F2R were similar to those in group F2 with column side surfaces intentionally roughened to enhance the bond, while in P2 the columns were partially wrapped along one third of the column height at the two ends. Each group was divided into three subgroups with different volumetric ratios of the transverse reinforcement. Each subgroup was characterized by a number (3, 5 and 9) indicating the number of the ties that were evenly distributed along the column height with a spacing of 22, 11 and 5.5 mm, respectively. Each subgroup consisted of three identical specimens yielding a total number of 45 specimens for testing.

Materials

Concrete: a batch of one third cubic meter of ready mix concrete proportioned for a specified 28-day compressive strength f'_c of 25 MPa and a slump of 75 mm was used. Natural gravel of a maximum size of 19 mm and Type I portland cement were used in the concrete mix. Six cylinders 150x300 mm and three prisms 100x100x500 mm were cast and cured under the same conditions as the RC columns and tested at 28-days age to determine the average compressive strength, modulus of elasticity and modulus of rupture. The results are given in Table (1).

Steel: one size of 6 mm mild steel plain bars was used for longitudinal and transverse reinforcement. Tension tests were conducted on full-size bar samples to determine yield and ultimate strengths as given in Table (1).

FRP: a commercially available fiberglass reinforced polymer matrix was used for column strengthening as external reinforcement. The composite consisted of a number of layers of woven roving fiberglass embedded in a polyester resin. The fabric is made by weaving untwisted rovings in a plane weave (half of the strands are laid at right angles to the other half) with a nominal thickness of 0.5 mm and a density of 450 g/m2. Tests were conducted to explore the mechanical properties of different locally available polymers including polyester, vinyl ester and epoxy adhesives. Based on these results, polyester was a convenient choice because of its excellent mechanical properties and relatively low price. The liquid polyester resin is cured with benzoyl peroxide as an initiator that was supplied in the form of an emulsion as it may cause fire when used in a pure state due to rapid decomposition. An initiator dose of 8 ml/kg of polyester allowed for a curing time of 90 minutes before setting into a solid state in the mixing mold. The mixed amount was limited so that it can be applied with a brush without going into the gel state.

Table (1): Mechanical properties of different materials

Mechanical Properties, MPa	Material			
	1	2	3	4
Comp. strength	25.5		102	
Mod. of elasticity	27E3		1970	14E3
Mod. of rupture	2.6		61.7	
Yield strength		325		
Ultimate strength		425		350
Bond strength			1.5	
Shear strength			1.73	

(1) concrete, (2) steel, (3) polyester and (4) GFRP

Separate plates were manufactured to prepare the FRP specimens tested in tension. The plates were manufactured to simulate the actual behavior of the FRP wrap by extracting the test specimens from a wrapped column that was covered with a polyethylene sheet to prevent bonding of the composite to the column faces. 24 hours later, three specimens were cut out and tested in uniaxial tension. Because of the column dimensions, it was necessary to cut the specimen with its length parallel to the column height assuming that the tensile properties of the bidirectional composite are the same in the longitudinal and transverse directions. The material exhibited a linear elastic behavior up to failure. Average fiber content was 63% by weight (71% by volume) of the composite. Table (1) gives the results of the mechanical testes performed in accordance with ASTM specifications on both the FRP material and the polyester matrix.

Fabrication of test specimens

Five wooden forms each with nine cells 100x100x500 mm were prepared to cast all test specimens at the same time. The concrete mix was placed in the forms and vibrated to ensure consolidation of the concrete. The specimens were stripped after 2 days of casting and covered with wet burlap that was kept moist for the first 3 days and stripped after 2 days of casting. The specimens were left to cure at room temperature and tested after 28 days of casting. The columns were strengthened by FRP wraps one week before testing. Prior to the application of the composite overlays, the four column edges were rounded to a radius of 10 mm using a light hammer. Early experience with wrapping rectangular column showed it was extremely difficult to avoid the creation of gaps near the edges when the FRP wraps is bent at right angles. Columns in group F2R were further prepared by using a sand blasting machine to roughen the concrete surface to enhance the bond with the FRP composite. The surfaces were then thoroughly cleaned of debris and dust using an air blower. For a convenient application of the FRP wraps, the reinforcing fabric was cut to the proper dimensions using scissors and infused with polyester to saturate the fabric laid flat over a polyethylene sheet. The wet fabric was then used to wrap the column that was hold in a vertical position. In all specimens the FRP wrap covered a column side providing an anchorage length of 100 mm to avoid debonding of the composite during testing. The use of wooden forms did not provide end loading surfaces that were in full contact with the loading plates that were mounted to the heads of the testing machine. To overcome this problem that may cause local failure at the loaded ends, the tested column was placed in testing position one day after wrapping and a quantity of Paris mortar was applied to the end surfaces. A little amount of load was applied to force the mortar to squeeze leaving a cap of not more than 2 mm to avoid stress concentration. The mortar acquired some strength after about 10 minutes, after which the specimen was removed and stored until testing.

Instrumentation and test procedure

The overall shortening along the full height of the test column was measured by means of two dial gauges providing an accuracy of 0.001 mm. The gages were fixed to measure the upward movement of the testing machine head with respect to the fixed head. The two gauges were aligned with the center of the column cross section on two opposite sides with respect to the column axis. The tests were carried out in a 500 kN capacity Shimadzu testing machine. After adjusting the test specimen for concentric loading, the zero-load readings of the dial gages were recorded. The load was applied in regular increments of 50 kN until the specimen cracked, then the load increment was reduced to 25 kN up to failure. The column shortening was recorded after each load increment and the strain was computed using the average of the two readings.

RESULTS AND DISCUSSION

The load-strain curves of the test columns are presented in Figures (2-4). Each curve represents the average of three identical specimens. The curves show that the strengthened columns exhibited different response depending on the amount of transverse reinforcement and jacket thickness and its extension. In all test specimens, the ultimate load was reached once the FRP jacket fractured in tension. It was possible to trace the post-peak behavior in many tests, while that was not possible in other tests as the load dropped suddenly. Fig. (2) shows the load-strain curves for columns with three ties. This number of ties was intended to serve only the purpose of holding the longitudinal bars in place and thus, no confining action was expected due to transverse reinforcement. Fig. (2) shows that all curves consist of two distinct branches: an ascending portion shared by all test specimens up to ultimate load and a descending branch. The slope of the softening branch was steeper in group F1/3 compared to P2/3. The descending branch in groups F2/3 and F2R/3 was identical and almost flat with respect to other groups. The curves show a limited increase in the ultimate strain that varied between 0.003 and 0.004 due to strengthening.

By increasing the number of ties, the curves in Figures 3 and 4 show that the behavior of columns in groups P2 and F1 was very much similar to that of control specimens with higher ultimate load and slightly increasing ultimate strain. This behavior can be explained by the fact that failure in group P2 columns occurred in the unconfined middle third, while the small jacket thickness in group F1 columns caused an early failure and thus the behavior was similar to that of conventional columns. By increasing the jacket thickness in groups F2 and F2R, the stress-strain curves continuously increased up to the ultimate load at which the load dropped suddenly. This behavior indicates that the delayed failure of the jacket allowed the strength of other components, i.e. steel and concrete, to be more efficiently used. The ultimate strain was considerably increased and was about three times higher than the ultimate strain in control columns.

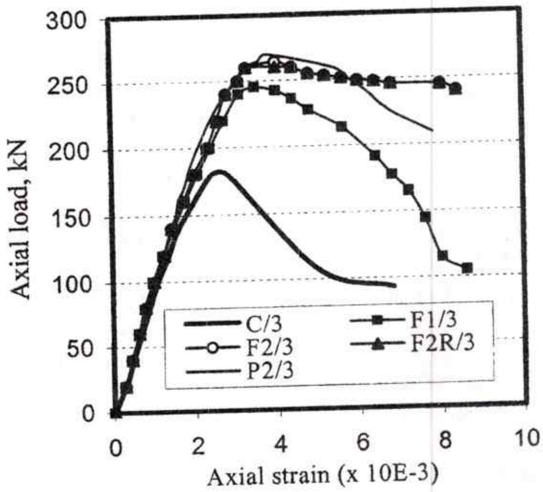

Fig. (2): Load-strain curve for columns with three ties

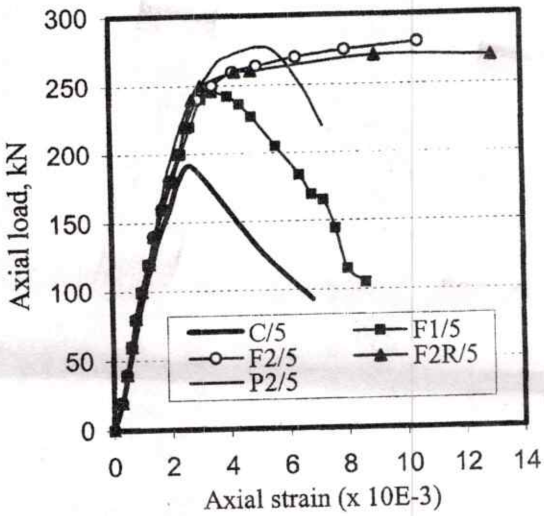

Fig. (3): Load-strain curve for columns with five ties

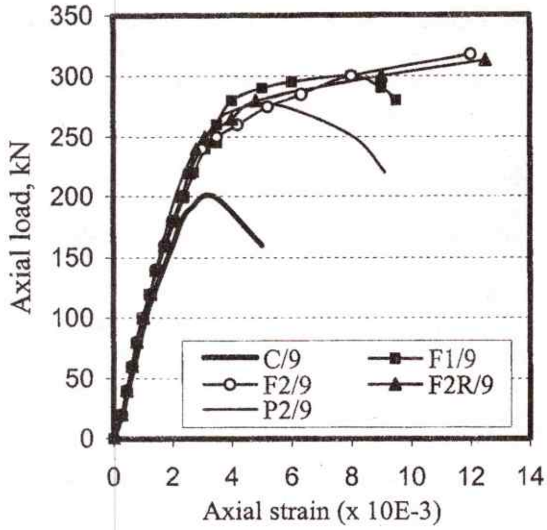

Fig. (4): Load-strain curve for columns with nine ties

While the ultimate load was not significantly influenced by the repair scheme in those columns with five ties, a pronounced increase was achieved as the number of ties increased to nine. This can be attributed to the continuous confinement provided by the jacket allowing the ties along the column height to act effectively. The curves also show that roughening the column surfaces in group F2R was an extra effort that did not further enhance the performance.

In all control specimens, failure occurred due to concrete crushing initiated at one end and the damage was limited along about one third of the column height. Failure of control columns was accompanied with remarkable lateral strain and concrete cover spalling as seen in Fig. (5.a). Concrete crushing near the column end is attributed to the inadequate end confinement that is usually avoided in column testing by enlarging the dimensions of end cross sections or using a steel jacket at the column ends. Failure in the strengthened columns was characterized by composite rupture and concrete crushing localized within a limited portion along the column height. Depending on the failure location, the following cases were observed: (1) concrete crushing initiated at the column end and FRP composite rupture at the corner as shown in Fig. (5.b), (2) concrete crushing in the middle third of the column and FRP composite rupture at the corner, (3) concrete crushing in the middle third of the column and FRP composite rupture within column side as shown in Fig. (5.c) and (4) concrete crushing in the middle third. Table (2) gives the average ultimate load for each group along with the case number indicating the failure location and the analytical ultimate load computed according to Equations (1-6) neglecting the strength reduction factor.

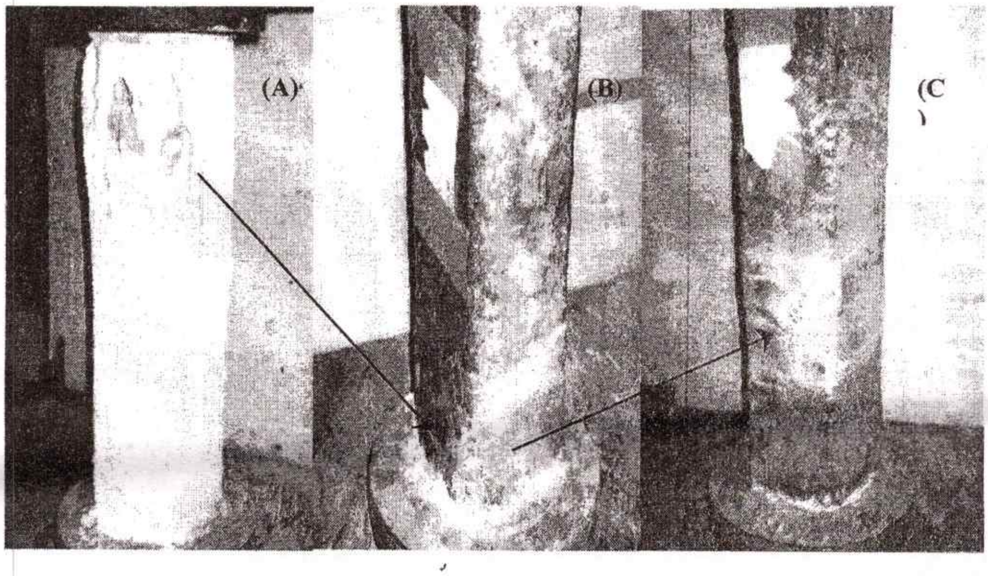

Fig. (5): Location and extension of concrete crushing and FRP rupture at ultimate load

The results in Table (2) show that the experimental ultimate load was only 80 percent of the analytical load in group C/9. This can be attributed to the local damage and thus, the contribution of reinforcement was not fully utilized. Strengthening the column ends in group P2 successfully shifted concrete crushing to the middle third of the column yielding an average ten percent increase in the ultimate load with respect to the analytical control load. Compared to control columns, experimental ultimate load increased by 52, 46 and 39 percent in groups P2/3, P2/5 and P2/9, respectively. In groups F2/3, F2/5 and F2/9 the ultimate load increased by 48, 47 and 59 percent compared to control columns, respectively.

Table (2): Experimental and analytical ultimate loads, kN

Group	Number of ties			Analytical
	3	5	9	P_u
C	178	190	200	251
F1	245 (1)	250 (1)	302 (1)	268
F2	264 (1)	280 (3)	318 (1)	285
F2R	260 (2)	270 (1)	313 (1)	285
P2	270 (4)	277 (4)	278 (4)	--

However, it should be mentioned that the above percentages are considerably high and may be deceiving taking into account the influence of failure localization near the ends. The results in Table (2) describing the failure location show that higher ultimate loads may have been achieved by carefully rounding the corners to avoid stress concentration which caused the jacket to rupture early at the corner.

CONCLUSIONS

The research presents an experimental work to evaluate the efficiency of using GFRP composites to improve the behavior of axially loaded columns in terms of strength and ductility. Continuous confinement was provided by external reinforcement in the form of wet fiberglass fabric wrapping the square test columns. Within the scope of the investigation reported in this research, the following conclusions could be drawn:

1. Through proper design, FRP jackets can be effectively used to improve the behavior of square columns in terms of strength and ductility. The best strengthening results showed that the ultimate strain was three times higher compared to control columns associated with limited dilation and concrete cover spalling.
2. The wet lay-up system is flexible enough to conform with the geometry of noncircular columns provided that the corners are carefully rounded .
3. Sufficient rounding of the corners is important to avoid stress concentration causing an earlier rupture of the jacket at the corner and consequently reducing the ultimate load.
4. The behavior is not influenced by roughening the column surface indicating that the behavior depends on contact between the jacket and concrete rather than bond .
5. Jacket thickness may need to be increased along the column end regions to further improve the column performance. This practice becomes particularly important when the longitudinal bars are not continuous at the end cross section as in composite concrete-steel bridges.
6. The design equations recommended by the ACI 440-F guide provided a conservative estimate for the ultimate load .
7. Further testing is needed to study the column size effect and the role of longitudinal fibers in bi-directional fabrics.

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NOTATION AND SYMBOLS

A_g = gross sectional area , mm^2

A_{st} = longitudinal steel area, mm^2

b = column cross section width, mm

d = column cross section length, mm

f'_c = compressive strength of concrete, MPa

f'_{cc} = compressive strength of confined concrete

f_{ju} = tensile strength of FRP jacket, MPa

f_y = yield stress of reinforcement, MPa

K = cross-section effectiveness coefficient

n = number of jacket layers

r = corner rounding radius, mm

ρ_f = reinforcement ratio (A_{st} / bd)

ε_{cu} = ultimate confined concrete strain

ε'_{cu} = usable confined concrete strain

ε_{ja} = allowable FRP jacket strain

ε_{ju} = ultimate FRP jacket strain