JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT
2008
14(2): 115–120

BEHAVIOUR OF SQUARE CONCRETE COLUMN CONFINED WITH GFRP COMPOSITE WARP

Riad Benzaid[1,2], **Nasr-Eddine Chikh**[3], **Habib Mesbah**[4]
[1]*L. G. G. laboratory, Jijel University, BP 98, Cité Ouled Aissa, Jijel, 18000, Algeria*
[2,3]*L. M. D. C. laboratory, Dept of Civil Engineering, Mentouri University, Route Ain El Bey Constantine 25000, Algeria*
[4]*Dept of Civil Engineering, IUT, INSA de Rennes. 3, Rue Clos Courtel, BP.90422, 35704 Rennes cedex 7, France*
E-mail: [1]*Benzaid_Riad @ yahoo. Fr;* [3]*Chikh_ne@ yahoo.fr;*
[4]*habib-abdelhak.mesbah@ univ-rennes1.fr*

Received 22 Jan 2008, accepted 31 March 2008

Abstract. The behaviour of fibre reinforced polymer (FRP)-confined concrete in circular columns has been extensively studied, but much less is known about concrete in FRP-confined square columns, in which the concrete is non-uniformly confined and the effectiveness of confinement is much reduced. The present paper deals with the analysis of experimental results in terms of load-carrying capacity and strains, obtained from tests on square prismatic concrete column, strengthened with external glass fibre composite. The parameters considered are the number of composite layers and the corner radius for a square shape. A total of twenty-one prisms of size 100 × 100 × 300 mm were tested under strain control rate of loading.

Keywords: concrete column, square section, confinement, glass fibre, compressive strength, ultimate strain.

1. Introduction

The strengthening and seismic retrofit of existing reinforced concrete (RC) columns using fibre reinforced polymer (FRP) composite jackets is based on a well-established fact, that lateral confinement of concrete can substantially enhance its compressive strength and ultimate axial strain. In a circular column, subject to axial compression, the concrete is uniformly confined by the FRP jacket. The behaviour of such uniformly confined concrete has been extensively studied, leading to many models for both the compressive strength and the stress-strain behaviour. However, much less is known about the behaviour of concrete in FRP-confined square columns, in which the confining pressure provided by the FRP varies over the cross-section and only part of the concrete is effectively confined (Park, Paulay 1975). As a result, the effectiveness of confinement is much reduced (Mirmiran *et al.* 1998) and rounding the right angle corners is generally recommended both to enhance confinement effectiveness and to reduce the detrimental effect of a sharp corner on the tensile rupture strength of FRP.

In recent years, the use of externally bonded FRP has become increasingly popular for civil infrastructure applications, including wrapping of concrete columns. The behaviour of FRP wrapped concrete cylinders with different wrapping materials and bonding dimensions has been studied by Lau and Zhou (2001) using the finite element method (FEM) and analytical methods. It was found that the load-carrying capacity of the wrapped concrete structure is governed by mechanical properties such as modulus and Poisson's ratio of the wrapping sheet. The technique of wrapping thin, flexible, and high-strength fibre composite straps around the column for seismic strengthening, to improve the confinement and thereby its ductility and strength has been presented by Saadatmanesh *et al.* (1994). The analytical compressive behaviour of concrete members reinforced with FRP was examined by Campione and Miraglia (2003), Youssef *et al.* (2007) and the variation in the shape of the cross-section was analyzed. In a recent study, effect of corner radius on the performance of CFRP-confined square concrete columns has been studied by Wang and Wu (2008). The performance of wrapped concrete specimens subjected to severe environmental conditions such as wet, dry, and freeze-thaw cycles was investigated by Toutanji and Deng (2002).

A study on the compressive behaviour and strength of elliptical concrete specimens wrapped with carbon fibre reinforced polymer (CFRP) has been described by Teng and Lam (2002). It was found by the study that the axial compressive strength of FRP confined concrete in elliptical specimens is controlled by the amount of confining FRP and the major to minor axis length ratio a/b of the column section. The behaviour of FRP jacketed square concrete columns subjected to eccentric loading was studied by Parvin and Wang (2001). The confinement model describing the behaviour of rectangular concrete columns retrofitted with externally bonded fibre-

ISSN 1392–3730 print / ISSN 1822–3605 online
DOI: 10.3846/1392-3730.2008.14.6

reinforced polymer material and subjected to axial stress was presented by Chaallal (2003). It was found that the stiffness of the applied FRP jacket is the key parameter in the design of external jacket retrofits.

Significant research has been devoted to circular columns retrofitted with FRP and numerous models were proposed. FRP wrapping of circular columns has proven to be an effective retrofitting technique. In contrast, very limited data have been reported on square columns retrofitted with FRP wrap, even though square columns in need of a retrofit are very common. The objective of the present work is to study the behaviour of concrete square columns with 3 different corners radius strengthened with externally applied glass-fibre reinforced polymer (GFRP) jackets and subjected to axial compressive loading.

1.1. Research significance

The use of externally bonded FRP composite for strengthening and repair can be a cost-effective alternative for restoring or upgrading the performance of existing concrete columns. Even though a lot of research has been directed towards circular columns, relatively less work has been performed on square and rectangular columns, to examine the effects of FRP confinement on the structural performance. However, a vast majority of all columns in buildings are square or rectangular. Therefore their strength and rehabilitation need to be given attention to preserve the integrity of building infrastructure. This article is directed towards this endeavour. Effective wrapping can enhance both the confined concrete strength and the column load-carrying capacity.

1.2. Aims and scope

The main endeavour of this research is to experimentally scrutinise the effects of upgrading the load-carrying capacity of reinforced concrete square columns subjected to axial compression by jacketing with GFRP flexible wraps. The objectives of the study are as follows: 1) to evaluate the effectiveness of external GFRP strengthening for square concrete columns; 2) to evaluate the effect of the number of GFRP layers on the ultimate strength and ductility of confined concrete; and 3) to evaluate the effect of the corner radius of the column on the effectiveness of GFRP reinforcement.

2. External confinement with FRP

The application of FRP in the construction industry can eliminate some unwanted properties of concrete, such as the brittle behaviour of high-strength concrete. FRP is particularly useful for strengthening columns and other unusual shapes (Li, Hadi 2003).

As already mentioned, the use of FRP materials in concrete compression members produces an increase in strength depending on the FRP properties (material type, strength, thickness etc.), on the concrete properties, and prevalently on the shape of the transverse cross-section (Campione, Miraglia 2003). Bonding hoop FRP to the column surface enhances axial load capacity and ductility of columns. The hoop FRP resists lateral deformations due to the axial loading, resulting in a confining stress to the concrete core, delaying rupture of the concrete and thereby enhancing both the ultimate compressive strength and the ultimate compressive strain of the concrete as illustrated by Fig. 1 (Russell, Modi 2001).

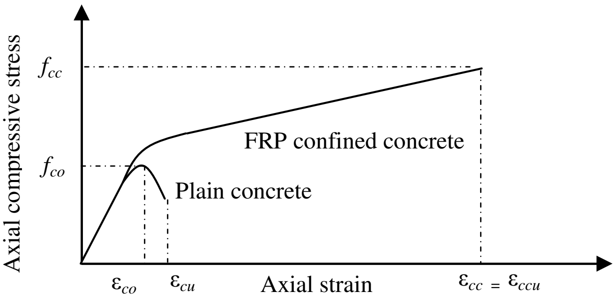


Fig. 1. Idealized stress-strain curve for FRP-confined concrete

3. FRP-confined concrete in square columns

A square column with rounded corners is shown in Fig. 2 (square columns are considered as a special case of rectangular columns with “width = depth”). To improve the effectiveness of FRP confinement, corner rounding is generally recommended. Due to the presence of internal steel reinforcement, the corner radius Rc is generally limited to small values. Existing studies on steel confined concrete (Park, Paulay 1975; Mander *et al.* 1988; Cusson, Paultre 1995) have led to the simple proposition that the concrete in a square or rectangular section is confined by the transverse reinforcement through arching actions, and only the concrete contained by the four second-degree parabolas (Fig. 2) is fully confined, while the confinement to the rest is negligible. These parabolas intersect the edges at 45°. While there are differences between steel and FRP in providing confinement, the observation that only a part of the section is well confined is obviously also valid in FRP confinement. The reduced effectiveness of an FRP jacket for a square or rectangular section than for a circular section has been confirmed by experimental results (Mirmiran *et al.* 1998; Rochette, Labossiere 2000; Chikh *et al.* 2006). Despite this reduced effectiveness, an FRP-confined square concrete column generally also fails by FRP rupture (Rochette, Labossiere 2000; Chikh *et al.* 2006).

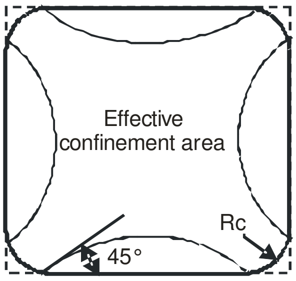


Fig. 2. Effectively confined concrete in a square column

It should be noted that due to the non-uniformity of confinement in a square section, for a given axial strain, the stress sustained by the concrete varies over the section. The commonly accepted approach is to define the stress as the average axial stress (= load divided by cross-sectional area).

4. Experimental program

4.1. Materials

The average standard of 28 days compressive strength of concrete f_{co} was approximately 54,80 MPa with a mix ratio of cement : dune sand : career sand Ø 0–5 mm: crushed gravel Ø 3–8 mm : Ø 8–15 mm : Ø 15–25 mm : water 1: 0,39 : 0,94 : 0,32 : 0,87 : 1,45 : 0,42. Concrete columns were confined by wrapping them with a plain weave E-glass manufactured with equal numbers of taws of fibres in the warp and weft directions. The typical characteristic properties of glass fibres are as follows: sheet width 600 mm, ply thickness 0,44 mm, ultimate tensile strength 383 MPa, elastic modulus 23,8 GPa, ultimate elongation 2,12 %. The resin system that was used to bond the FRP sheet over the columns in this work was the epoxy resin made of two parts, resin and hardener. The properties of the resin are in Table 1.

Table 1. The resin properties

Density about 1,3 at 20 °C
Compressive strength > 55 MPa in 2 days and 20 °C
Tensile strength > 30 MPa in 2 days and 20 °C
Flexural modulus E = 3800 MPa in 7 days and 23 °C

4.2. Specimen preparation

The experimental program was conducted in the laboratory of the Civil Engineering Department at the University of Constantine. Seven series of experiments were performed to investigate the behaviour of concrete square prisms confined by E-glass fibre composite. The dimensions of the specimens were (100 × 100 × 300) mm. The latter were divided into 3 representative groups: R1 sharp-edged square section, R2 square section with corner radius equal to 8 mm, and R3 square section with corner radius of 16 mm. The radius of the corners was guaranteed by the concrete formwork. Definition and details are in Table 2.

Table 2. Characteristics of specimens tested

Code	Section (mm)	Height (mm)	Corner radius (mm)	Number of GFRP layers
S0R1	100x100	300	0	–
S1R1			0	1
S2R1			0	2
S1R2			8	1
S2R2			8	2
S1R3			16	1
S2R3			16	2

4.3. Fibre-reinforced polymer wrapping

The resin system used in this work was made of two parts, namely, resin and hardener. The components were thoroughly hand mixed for at least 3 min. The concrete columns were cleaned and completely dried before the resin was applied. The first coat of a thin resin layer was applied and GFRP sheet was then wrapped directly on the surface. Special attention was paid to ensure the absence of voids between the GFRP sheet and concrete surface. A special roller was used to remove the entrapped air bubbles and press the resin to penetrate into the fabric. The roller was continuously used until the resin was reflected on the fabric surface, an indication of fully wetting. After the application of the first wrap of the GFRP sheet, a second layer of resin was applied on the first layer surface to allow the impregnation of the second layer of the GFRP sheet. Finally, a resin layer was used on the surface of wrapped columns. This system is a passive type where tensile stress in the FRP is gradually developed as the concrete dilates. This expansion is confined by the FRP jacket, which is loaded in tension in the hoop direction. Each layer was wrapped around the column with an overlap of ¼ of the perimeter to avoid sliding or debonding of fibres during tests and to ensure the development of full composite strength (Shahawy *et al.* 2000). The wrapped column specimens were left at room temperature for more than 2 weeks for the epoxy to harden adequately before testing.

4.4. Instrumentation and testing procedure

Specimens were loaded under a monotonic uni-axial compression load up to failure. The load was applied in a quasi-static displacement rate of 0,20 mm/min using an electro-hydraulic universal testing machine with a vertical load capacity of 2000 kN. Axial strains were measured using appreciable compressometer. Strains were noted for every 100 kN increment of load. For each series of specimen 3 samples were tested. The test setup for the columns is in Fig. 3.

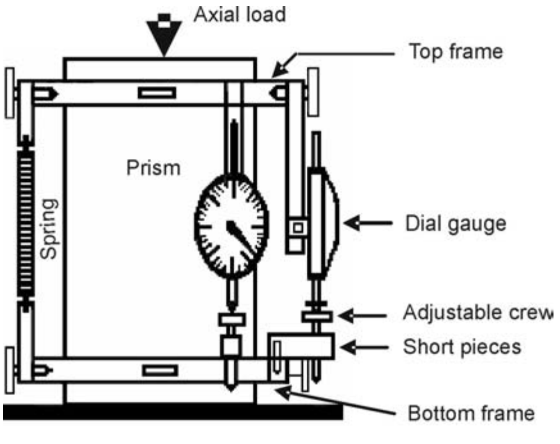


Fig. 3. Test set-up

5. Presentation and discussion of results

5.1. Overall behaviour

Table 3 indicates the results in terms of increase of the ultimate axial compressive strength and strain with respect to control specimens. The results show that the confinement of columns with GFRP wrap increases the load-carrying capacity of reinforced concrete columns. In addition, the greater the number of GFRP layers, the greater the gain in axial load-carrying capacity with respect to unconfined columns. The maximum increases achieved in series *S2R1*, *S2R2*, and *S2R3* with respect to control were 6, 20 and 36 % respectively, whereas those achieved for series *S1R1*, *S1R2*, and *S1R3* were only 2, 9, and 16 %. The gain in axial load carrying capacity is in Fig. 4.

Table 3. Experimental results

Code	N (kN)	f_{cc} (MPa)	$\frac{f_{cc}}{f_{co}}$	ε_{cc} (%)	$\frac{\varepsilon_{cc}}{\varepsilon_{co}}$
S0R1	548,00	54,80	1,00	0,25	1,00
S1R1	561,00	56,10	1,02	0,92	3,68
S2R1	582,00	58,20	1,06	1,46	5,84
S1R2	597,30	59, 73	1,09	0,99	3,96
S2R2	657,00	65,70	1,20	1,53	6,12
S1R3	635,60	63,56	1,16	1,04	4,16
S2R3	745,00	74,50	1,36	1,58	6,32

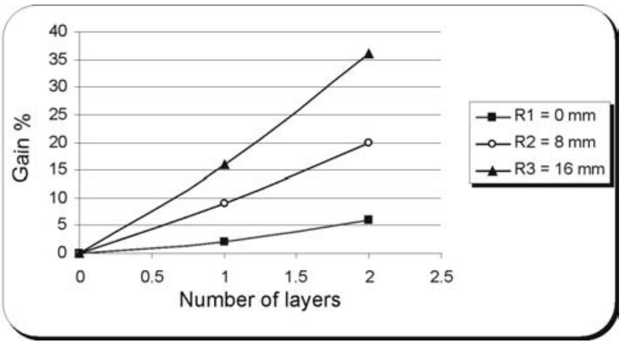


Fig. 4. Gain in compressive strength versus number of layers

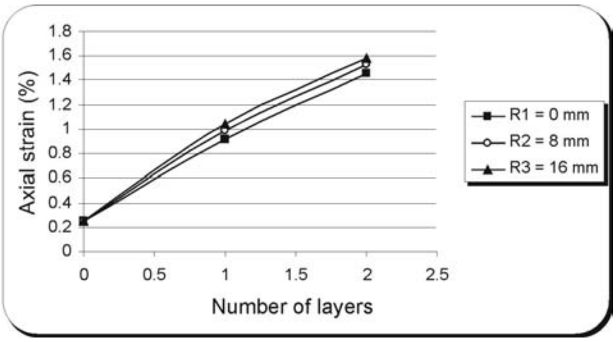
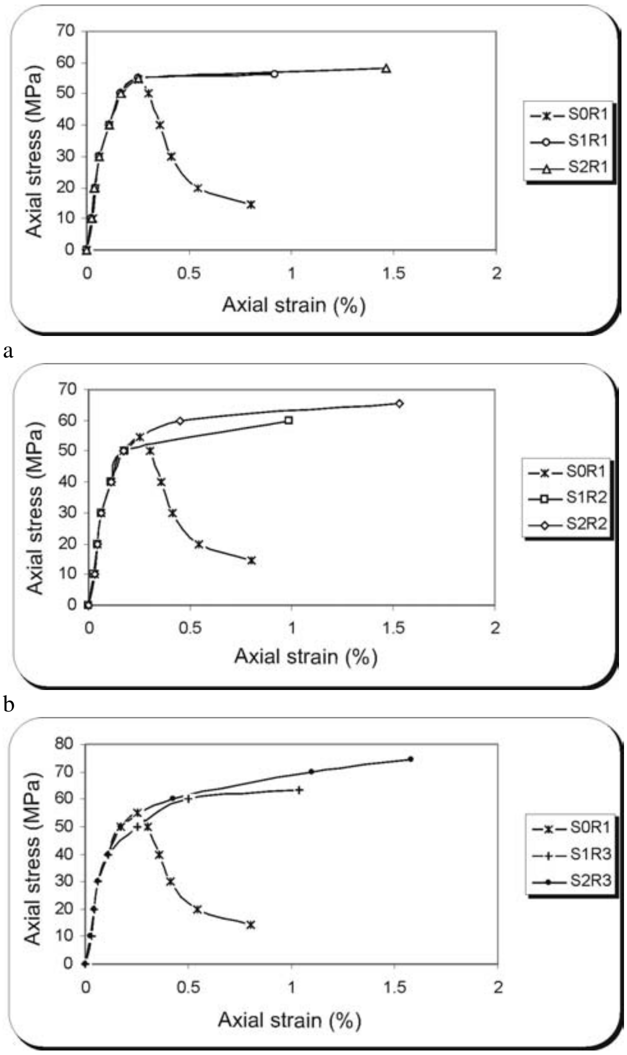


Fig. 5. Axial strains (ε_{cc}) versus number of layers

5.2. Ductility response

Fig. 5 shows the axial strain versus the number of layers. It is evident that confinement with GFRP wrap improved the column ductility. This increased ductility allows for a higher level of axial strain and a failure corresponding to rupture of the GFRP wrapping. In most cases, failure was initiated at or near a corner, because of the high stress concentrations in these locations. The columns ductility increased as the number of layers of wrapping increased. The maximum increases in axial strain achieved for specimens *S1R1*, *S1R2*, and *S1R3* with respect to control were 268, 296, and 316 % respectively, whereas those achieved for series *S2R1*, *S2R2*, and *S2R3* were 484, 512, and 532 % respectively.



a

b

c

Fig. 6. Stress-strain curves of square prismatic specimens: a –R1 = 0 mm , b – R2 = 8 mm, c – R3 = 16 mm

5.3. Stress-strain response

The bi-linear stress-strain curves for unconfined and GFRP wrapped columns are in Figs 6, 7. The figures give the axial stress versus the axial strains for the specimens with zero, one, and two layers. Examination of stress-strain curves clearly shows that confinement with GFRP can enhance the performance of concrete, both its strength and ductility, under axial load. Enhancement in ductility is more pronounced than the gain in ultimate load for GFRP wrapped columns, as compared to that of control specimens. The response in the first region was similar to that of unconfined concrete with high peak stress f_{co} and strain ε_{co}. The slope in the plastic region was function of the cross-sections geometry (effect of corner radius). Thus the efficiency of the FRP jacket confinement on square columns increases with decreasing corner sharpness (Fig. 7).

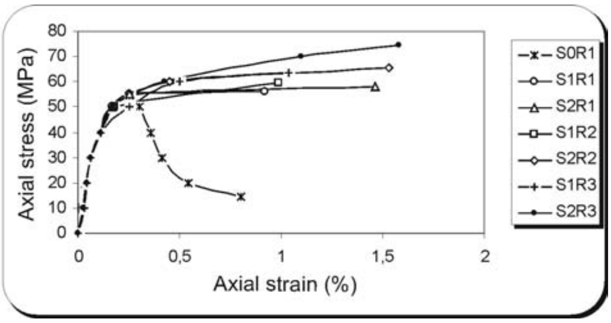


Fig. 7. Stress-strain curves (effect of corner radius)

5.4. Effect of corner radius

It was observed (Fig. 7) that the presence of GFRP reinforcement increases the strength of plain concrete, but this phenomenon is strongly influenced by the cross-section shape. The effectiveness of GFRP reinforcement is less in case of a square section (R = 0 mm) compared to a square cross-section with rounded corners (R = 8 or 16 mm). This is due to a high concentration of stresses at the corner of the square section with R = 0 mm also to the smaller effectively confined concrete core in this case compared to those with rounded corners.

Fig. 8. Failure modes of columns and GFRP torn at the level of corners

5.5. Failure modes

Glass fibre wrapped specimens typically failed by a fracture of GFRP composite at or near the corner of the specimens due to the stress concentration in those regions. In all cases, the columns failure was the result of the rupture of the FRP jacket. For most wrapped columns, it was associated with concrete crushing at or near the column ends and marked by wraps rupturing in the circumferential direction. Approaching failure load, the appearance of white patches was found, which indicated the yielding of E-glass and resin. After failure, disintegrated concrete was found. Failure of GFRP wraps was observed at or near a corner in all the specimens mainly due to stress concentrations. This may be expected since the column's sharp edges were not rounded off. In order to avoid stress concentration, an attempt should be made to round off sharp corners. One should also ensure that the failure will not happen at end regions by increasing the number of wrapping layers in the end regions. Failure modes of some specimens are shown in Fig. 8.

6. Conclusions

The experimental work involved in this study was mainly to evaluate the effectiveness of external reinforcement of concrete columns with glass fibre composite. Based on the analysis of experimental results, in terms of load-carrying capacity and strains, obtained from tests on square concrete column, strengthened with external E-glass fibre composite, it can be concluded that:

1. The external confinement with reinforced polymers composite can significantly increase the strength of the specimen under axial loading. The experimental results clearly demonstrate that composite wrapping can enhance the structural performance of concrete columns under axial loading.
2. The number of layers of FRP materials and the corner radius are the major parameters, having a significant influence on the behaviour of specimens. The test results from preliminary testing proved that the benefit of confinement could be enhanced by increasing the stiffness of external confinement applying multiple layers and by a good corner radius for square shape.
3. Bonding hoop FRP to the column surface enhances axial load capacity and ductility of columns. The hoop FRP resists lateral deformations due to the axial loading, resulting in a confining stress to the concrete core, delaying rupture of the concrete and thereby enhancing both the ultimate compressive strength and the ultimate compressive strain of the concrete.
4. The radius of the corner radius in square columns affected the behaviour. It determines stress concentration effect. A larger radius can expand the strong constraint zone and diminish the stress concentration. So the reduced confining pressure in a square section due to the concentration of stresses at the corners is solved by using a square section with circular corners.
5. The load–strain curve of FRP-confined concrete can be in one of several forms, but in a vast majority of cases, this curve is or can be approximated to a monotonically ascending bi-linear curve. Such FRP confined concrete is said to be sufficiently confined.
6. The results of experimental test showed that GFRP materials can produce a good lateral confinement pressure to column specimens. Then it can be used for strengthening or repairing structures.

References

Campione, G.; Miraglia, N. 2003. Strength and strain capacities of concrete compression members reinforced with FRP, *Cement and Concrete Composites* 25(1): 31–41.

Chaallal, O. 2003. Confinement Model for axially loaded short rectangular columns strengthened with fibre-reinforced polymer wrapping. American Concrete Institute, *Structural Journal* 100(2): 215–221.

Chikh, N. E.; Benzaid, R.; Bousalem, B.; Djebbar, N. 2006. Strengthening of high-strength concrete columns with external glass fibre composite, in *Proceedings of the Tenth Arab Structural Engineering Conference*, 13–15 November, Kuwait, 581–588.

Cusson, D.; Paultre, P. 1995. Stress-strain model for confined high-strength concrete. American Society of Civil Engineers, *Journal of Structural Engineering* 121(3): 468–477.

Youssef, M. N.; Feng, M. Q.; Mosallam, A. S. 2007. Stress-strain model for concrete confined by FRP composites, *Composites*, Part B 38: 614–628.

Lau, K. T.; Zhou, L. M. 2001. The mechanical behaviour of composite-wrapped concrete cylinders subjected to uniaxial compression load, *Composite Structures* 52: 189–198.

Li, J.; Hadi, M. N. S. 2003. Behaviour of externally confined high-strength concrete columns under eccentric loading, *Composite Structures* 62: 145–153.

Mander, J. B.; Priestley, M. J. N.; Park, R. 1988. Theoretical stress-strain model for confined concrete. American Society of Civil Engineers, *Journal of Structural Engineering* 114(8): 1804–1826.

Mirmiran, A.; Shahawy, M.; Samaan, M.; El Echary, H. 1998. Effect of column parameters on FRP-confined concrete. American Society of Civil Engineers, *Journal of Composites for Construction* 2(4): 175–185.

Park, R.; Paulay, T. 1975. *Reinforced Concrete Structures.* John Wiley & Sons, N.Y., U.S.A. 800 p.

Parvin, A.; Wang, W. 2001. Behaviour of FRP jacketed concrete columns under eccentric loading, *Journal of Composites for Construction* 5(3): 146–152.

Rochette, P.; Labossiere, P. 2000. Axial testing of rectangular column models confined with composites. American Society of Civil Engineers, *Journal of Composites for Construction* 4(3): 129–136.

Russell, P.; Modi, A. 2001. Wrapping the harbour city car park, *Manchester. Concrete* 35(6): 24.

Saadatmanesh, H.; Ehsani, M. R.; Li, M. W. 1994. Strength and ductility of concrete columns externally reinforced with fibre composite straps. American Concrete Institute, *Structural Journal* 91(4): 434–447.

Shahawy, M.; Mirmiran, A.; Beitelman, T. 2000. Tests and modeling of carbon-wrapped concrete columns, *Composites*: Part B 31(6): 471–480.

Teng, J. G.; Lam, L. 2002. Compressive behaviour of carbon fibre reinforced polymer-confined concrete in elliptical columns, *Journal of Structural Engineering* 128(12): 1535–1543.

Toutanji, H.; Deng, Y. 2002. Strength and ductility performance of concrete axially loaded members confined with AFRP composite sheets, *Composites Structures*: Part B 33(4): 255–261.

Wang, L. M.; Wu, Y. F. 2008. Effect of corner radius on the performance of CFRP-confined square concrete columns: Test, *Engineering Structures* 30: 493–505.

List of symbols

f_{co}	compressive strength (peak stress) of unconfined concrete,
f_{cc}	compressive strength (peak stress) of confined concrete,
ε_{co}	strain at maximum stress of unconfined concrete,
ε_{cc}	strain at maximum stress of confined concrete,
$\varepsilon_{cc,u}$	ultimate strain of confined concrete,
ε_{cu}	ultimate strain of unconfined concrete,
N	ultimate load,
FRP	fibre reinforced polymer,
GFRP	glass fibre reinforced polymer,
CFRP	carbon fibre reinforced polymer.

KOMPOZITINIAIS STIKLO PLUOŠTU ARMUOTO POLIMERO LAKŠTAIS SUSTIPRINTŲ KVADRATINIŲ BETONINIŲ KOLONŲ ELGSENA

R. Benzaid, N. E. Chikh, H. Mesbah

Santrauka

Pluoštu armuotu polimeru sustiprintų apskritų betoninių kolonų elgsena yra išsamiai išnagrinėta. Daug mažiau žinoma apie polimero pluoštu sustiprintų kvadratinių betoninių kolonų elgseną. Tokiuose elementuose betono deformacijos suvaržomos nevienodai. Dėl to mažėja sustiprinimo efektyvumas. Straipsnyje pateikiami išoriniais stiklo pluošto lakštais sustiprintų kvadratinių betoninių kolonų laikomosios galios, deformacijų eksperimentinių tyrimų rezultatai ir jų analizė. Eksperimentiniuose tyrimuose nagrinėta kompozitinių pluoštų sluoksnių skaičiaus, skerspjūvio kampo spindulio įtaka sustiprintų kolonų elgsenai. Iš viso išbandytos dvidešimt viena 100×100× 300 mm matmenų prizmės. Bandymai atlikti kontroliuojant apkrovimo greitį pagal deformacijas.

Reikšminiai žodžiai: betoninė kolona, kvadratinis skerspjūvis, sustiprinimas, stiklo pluoštas, gniuždomasis stipris, ribinė deformacija.

Riad BENZAID. Assistant Professor at the University of Jijel (Algeria). Researcher at the L.G.G laboratory at Jijel University and at the L.M.D.C laboratory of Materials at Mantouri University of Constantine (Algeria). His main research: strengthening the concrete elements with FRP materials.

Nasr-Eddine CHIKH. Professor at Mantouri University of Constantine, Algeria. Member of the Fédération Internationale du Béton (FIB). Member of both Scientific Committees of University. His research interests include: strengthening the concrete elements with FRP materials, behaviour of earthquake-resistant RC structures, and durability of concrete.

Habib MESBAH. Associate Professor at the University of Rennes1, IUT, INSA of Rennes1 (France). His research interests include: self-consolidating concrete, high performance concrete, fibre reinforced concrete, strengthening the concrete elements with FRP materials.