IMPROVEMENT OF LOAD BEARING CAPACITY OF CONCRETE COLUMNS THROUGH COMPOSITE MEMBRANE CONFINEMENT

Nicolae Taranu[1], Gabriel Oprisan[2],Vlad Munteanu[3], Ciprian Cozmanciuc[4], Ruxandra Oltean[5], Ioana Entuc[6]

Technical University "Gh. Asachi" of Iasi, Faculty of Civil Engineering and Building Services, Romania

Abstract: *Degradation of concrete columns due to their exposure to aggressive environmental factors and the increase of static and dynamic loads imposed by change in use require solutions for rehabilitation and strengthening of reinforced concrete (RC) columns. A modern approach to RC columns strengthening is their confining with composite membranes made of fiber reinforced polymer (FRP) composites. The confining effect of composite materials wraps upon concrete has been studied for cylindrical concrete specimens jacketed with 2, 3 and 4 carbon fibre reinforced polymer (CFRP) and glass fibre reinforced polymer (GFRP) layers. Experimental results have confirmed that increasing the number of composite layers improves the load carrying capacity and the ductility of the confined concrete columns. The authors identify the failure modes and the influence of material used towards confinement efficiency. A numerical analysis has been performed using LUSAS software in order to check and to confirm the benefit of the composite jacketing in multiple layers.*

Key words*: external reinforcement, FRP wrapping, axial loading, confining pressure, stress-strain response*

1. Introduction

By confining the concrete columns using glass fiber reinforced polymer (GFRP) or carbon fiber reinforced polymer (CFRP) composite membranes, an external reinforcement is obtained which leads to an increasing of the allowable axial force and to the ductility improvement of these structural members. Thus, the effect of concrete column wrapping with GFRP or CFRP

1 Nicolae Taranu, Prof. , M.Sc. (Eng), Ph.D., Technical University "Gh. Asachi" of Iasi, Faculty of Civil Engineering and Building Services, 43, Dimitrie Mangeron Blvd, Iasi, Romania, e-mail: taranu@ce.tuiasi.ro
2 Gabriel Oprisan, Associate Prof. , M.Sc. (Eng), Ph.D., Technical University "Gh. Asachi" of Iasi, Faculty of Civil Engineering and Building Services, 43, Dimitrie Mangeron Blvd, Romania, e-mail: oprisan@ce.tuiasi.ro
3 Vlad Munteanu, Lecturer, M.Sc. (Eng), Ph.D., Technical University "Gh. Asachi" of Iasi, Faculty of Civil Engineering and Building Services, 43, Dimitrie Mangeron Blvd, Iasi, Romania, e-mail: munteanu@ce.tuiasi.ro
4 Ciprian Cozmanciuc, Ph.D. student, Technical University "Gh. Asachi" of Iasi, Faculty of Civil Engineering and Building Services, 43, Dimitrie Mangeron Blvd, Iasi, Romania, e-mail: cozmanciucc@ce.tuiasi.ro
5 Ruxandra Oltean, Ph.D. student, Technical University "Gh. Asachi" of Iasi, Faculty of Civil Engineering and Building Services, 43, Dimitrie Mangeron Blvd, Iasi,Romania, e-mail: olteanr@ce.tuiasi.ro
6 Ioana Entuc, Lecturer, M.Sc. (Eng), Ph.D., Technical University "Gh. Asachi" of Iasi, Faculty of Civil Engineering and Building Services, 43, Dimitrie Mangeron Blvd, Iasi,Romania, e-mail: entuc@ce.tuiasi.ro

membranes generates a tri-axial stress state, that increases the concrete strength and minimizes the lateral expansion of the concrete [1], [2].

Many studies carried out by Saadatmanesh [3], Hoppel [4], Mirmiran [5], Thériault [6], Youssef [7], Teng [8] have demonstrated the efficiency of strengthening with composite membranes made of glass/carbon fabrics and epoxy matrix. Based on experimental results analytical strength models have been elaborated to predict the relationship between axial stresses, axial strains and lateral strains of confined concrete columns knowing the strength and strain of unconfined samples.

At the Faculty of Construction and Building Services in Iasi it is almost a tradition to use composite materials in structural applications [9-12]. Based on a long time experience in this field, a complex program on the possibility of performing structural rehabilitation with composite systems has been initiated and it is still in progress. To confirm the efficiency of reinforced concrete columns confined with GFRP and CFRP an experimental program has been carried out, comparing the structural response of the unconfined concrete columns with confined concrete columns subjected to axial loading.

2. Experimental program

To establish the mechanical characteristics of unconfined concrete, cylindrical specimens and standard cubes adequate to compression test have been cast. 9 concrete cylinders (100 mm in diameter and 250 mm high) and 9 cubes (100 mm in size) have been tested under uniaxial compression using standard conditions to determine the concrete class and the compressive strength. To avoid a rapid failure of the unconfined concrete cylinder and to determine the complete stress-strain curve including the post peak strength domain of the material a special installation for the post elastic testing of brittle materials designed and patented by the authors has been utilized. The experimental setups, for both unconfined and confined samples, are illustrated in Fig.1.

a. b.

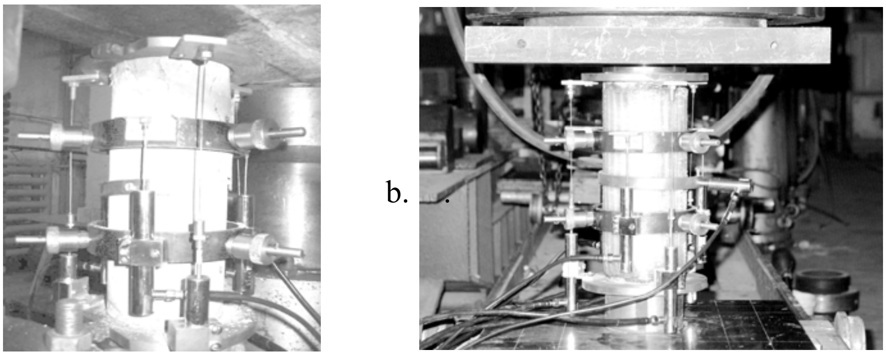
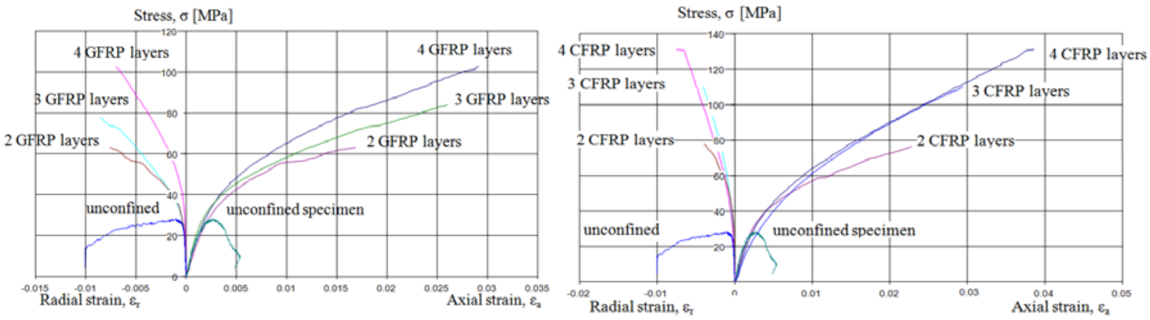


Fig. 1. Instrumentation of test samples: a. unconfined concrete cylinder specimen; b. confined concrete cylinder specimen with composite membranes

3. Experimental results

The compressive strengths determined on plain concrete samples, after 28 days was 31.64 N/mm^2 on the concrete cylinders and 32.16 N/mm^2 on the concrete cubes; a complete stress-strain curve for unconfined concrete is illustrated in Fig. 2.

Confined concrete specimens with glass fibre-reinforced polymer (GFRP), and carbon fibre-reinforced polymer (CFRP), have been tested with the same installation used for the unconfined concrete samples. A comparative set of stress-strain curves for plain and GFRP membranes confined concrete specimens is shown in Fig. 2a.



a. b.

Fig. 2. Stress-strain curves of compressed unconfined and confined concrete specimens with: a. GFRP membranes; b. CFRP membranes

A similar set of curves for unconfined and CFRP confined samples is illustrated in Fig.2b; the confined samples have been wrapped with 2, 3 and 4 layers of CFRP composites. The stress-strain curves of the concrete samples confined with CFRP composite jackets exhibit a bilinear shape with sharp softening in the transition area around the strength of the unconfined concrete. In the first stage the slope of the stress-strain curve is similar to that of the unconfined concrete. In the second stage the concrete is cracked and the confinement is activated. The stress of the confined concrete increases linearly with increasing the CFRP strain. A further step of the experimental program has been the cyclic loading of 3 CFRP layers confined samples as a first stage to seismic retrofit with polymeric composites. Some preliminary results are illustrated in Fig. 3.

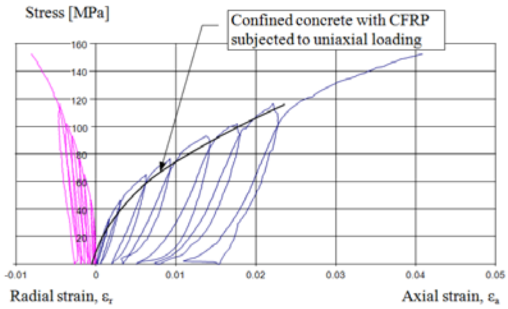


Fig. 3. Stress-strain curves of confined specimens subjected to cyclic loading

There were no major differences between the stress-strain curves obtained for concrete cylinders confined with 3 layers of CFRP, loaded in axial compression, and those obtained on concrete cylinders confined with 3 layers of CFRP axially loaded to 8 cycles.

4. Analytical interpretation

Analytical solution of column confining begun with Mander's formulation 1988 [13], which predicted the strength of confined concrete using steel hoops. The compressive strength of confined concrete specimen can be determined from the following equation:

$$f_{cc} = f_{c0}\left(2.254\sqrt{1+7.94\frac{\sigma_l}{f_{c0}}} - \frac{2\sigma_l}{f_{c0}} - 1.254\right) \tag{4.1}$$

where: f_{c0} is the compressive strength of unconfined concrete specimen, in [MPa], σ_l is the lateral confining pressure, $\sigma_l = \frac{4t_{frp}}{d}E_{frp}\varepsilon_{frp}$, in [MPa], t_{frp} is the thickness of FRP jacket, in

[mm], d is the diameter of confined concrete, in [mm], E_{frp} is the elastic modulus of FRP jacket, in [MPa], ε_{frp} is the strain in FRP jacket in the hoop direction in [%], taken as equal to the lateral strain of the concrete specimen.

The state of stress in case of FRP jacketed confinement is presented in Fig.4, the notations being specific for cylindrical coordinates. Lateral confining pressure can be defined using FRP volumetric ratio, ρ_{frp} (equation 4.4).

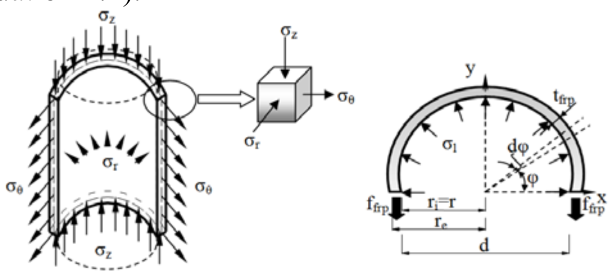


Fig. 4. Tri-axial state of stress in FRP:
σ_z – longitudinal stress, σ_r – radial stress, σ_θ – tangential stress (left)
and stress distribution in FRP jacket (right)

The tensile force in the FRP jacket can be calculated from the equilibrium condition. The projection equation along y axis gives the following expression:

(4.2) $$f_{frp} t_{frp} = \int_0^{\frac{\pi}{2}} \sigma_l r \sin\varphi d\varphi = \sigma_l r$$

where: f_{frp} is the tensile strength of FRP, σ_l is the confining pressure from lateral expansion of concrete equal with σ_r, r is the radius of the concrete specimen, φ the angle of the circular cross section with the horizontal line.

Expression of the confining pressure function of tensile strength of FRP becomes:

(4.3) $$\sigma_l = f_{frp} \frac{t_{frp}}{r} = f_{frp} \frac{2t_{frp}}{d} = f_{frp} \frac{\rho_{frp}}{2}$$

where: ρ_{frp} is FRP volumetric ratio given by the following equation:

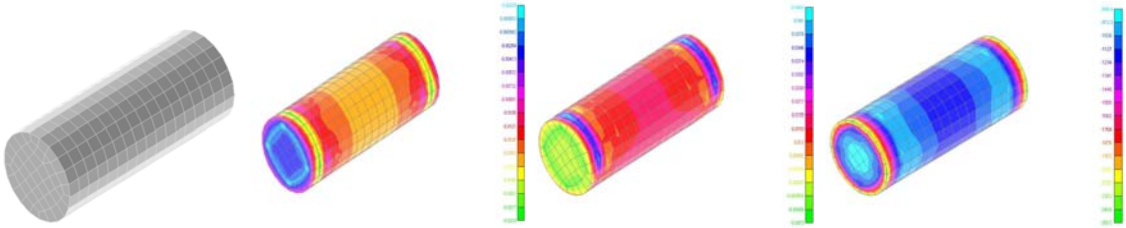
(4.4) $$\rho_{frp} = \frac{\pi d t_{frp}}{\frac{\pi d^2}{4}} = \frac{4t_{frp}}{d}$$

In addition, for a n number of FRP layers the expression of FRP volumetric ratio ρ_{frp} can be written as:

(4.5) $$\rho_{frp} = \frac{4nt_{frp}}{d}$$

5. Numerical analysis results

Using CADEC program [1], the following mechanical characteristics of FRP have been estimated: longitudinal modulus E_1, transverse modulus E_2, Poisson's ratio ν_{12}, shear modulus G_{12}, longitudinal tensile strength R_{tL}. These data were introduced as input data in finite element analysis (FEA) program used to compare the experimental and analytical values. All other characteristics introduced as input data correspond to a fibre volume fraction $V_f=0.45$ using the same program. Element types utilised in the modeling were: an eight-node solid element used to model concrete cylinder and a membrane element type was used to model FRP composite cylindrical jackets (for carbon fibers and glass fibers reinforced membranes).



a. b. c. d.

Fig. 7. Stress strain map corresponding to concrete cylinder specimen confined with 4 layers with GFRP: a. initial mesh of concrete specimen; b. longitudinal strains; c. transverse strains; d. longitudinal stress σ_z in confined concrete solid (in 0.1MPa).

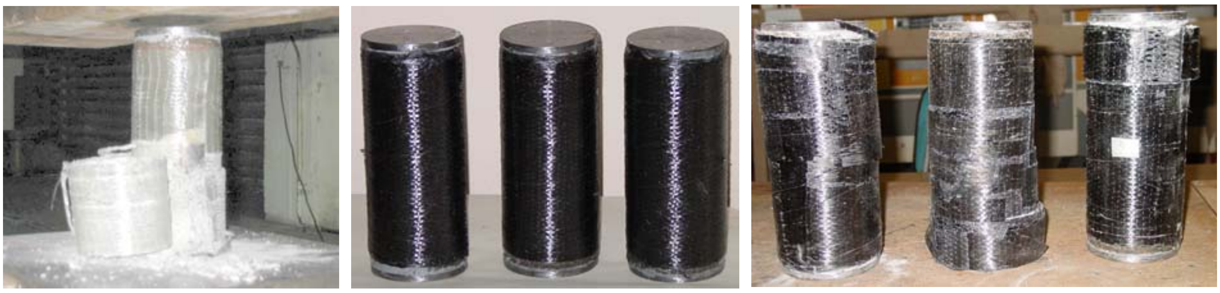
In this finite element modelling study, the Mohr-Coulomb yield criteria combined with isotropic hardening rule have been utilized to simulate the nonlinear behaviour of confined concrete cylinder. The GFRP exhibits a linear elastic behaviour governed by the generalized Hooke's law until failure. The variable of GFRP was the jacket thickness modified by choosing the number of layers (in our case 2, 3 and 4 unidirectional layers were considered).

Fig.7 illustrates the distribution of stress and strain in the confined concrete cylinder specimen with GFRP composites.

From the analysis of the models on concrete specimens confined with FRP the following observations have been formulated: FRP exhibits a tough behaviour that prevents crack initiation and its propagation in concrete; FRP membranes efficiently increase the compressive strength and the ductility of the concrete cylinder, especially in case of 4 CFRP confinement layers; confinement of concrete cylinder using CFRP or GFRP prevent/delay the failure process in concrete; tensile strength of FRP enables the increase of compressive strength of the concrete specimen; the stress-strain response obtained with FEA modeling could be visualized for every FRP layer in any chosen point; the FRP confinement method becomes very efficient in case of using at least 3 FRP layers.

6. Failure modes

The failure modes are different, depending on the type of confinement, the number of layers and the quality of wrap installation.



a. b. c.

Fig. 8. Failure modes: a. concrete destruction and explosive rupture of GFRP at the lower part of specimen b. CFRP concrete specimens initial stage (before loading); c. explosive failure modes of the concrete specimen in case of wrapping with 3 CFRP layers

The numerical results obtained from experimental stress-strain curves shows gradually increasing until the FRP jacket fails (explosive rupture occurring). A failure mode for concrete specimens confined with GFRP is presented in Fig.8 a; Fig.8c illustrates the failure modes of confined concrete cylinder with 3 layers of CFRP.

Conclusions

The experimental and numerically obtained results clearly demonstrate the beneficial influence of confining compressed concrete elements with FRP composite jackets.

The FRP composite wrapping prevents the concrete lateral expansion improving its structural response. A certain delay and blockage of the crack occurrence is achieved.

The efficiency of confining is improved with increasing the number of composite layers.

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