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Experimental and numerical analysis of compressed concrete elements confined with FRP composites

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Summary

Confinement of concrete by suitable selection of transverse internal reinforcement or by externally bonded reinforcement results in significant increase in both the compressive strength and the ductility of concrete subjected to compressive loading. Traditional confinement solutions have been developed using steel hoops or steel jackets and only recently fibre reinforced polymer composites (FRP) have been perceived as reliable confinement solutions for concrete elements. Extensive research projects have been performed since 1990s and theoretical and experimental results confirm the validity of confinement with FRP composites jackets. An experimental program has been initiated at the Faculty of Civil Engineering, the Technical University of Iasi, to evaluate the confining effect with glass fibre/epoxy and carbon fibre/epoxy composites. The influence of the material type and the thickness of FRP confining jacket were the variables involved.

The results obtained have proven the effectiveness of confinement solutions based on FRP composites. Both compressive strength and ductility of the confined specimens have shown dramatic increase compared to unconfined concrete specimens. The experimental set-up, the testing procedure and the main results are presented, emphasizing the influence of the composite nature and the thickness of the confining jacket.

KEYWORDS: confining, FRP jackets, compressive strength, ductility

1. INTRODUCTION

To establish the mechanical characteristics of unconfined concrete, cylindrical specimen and standard cubes adequate to compression test were cast. Also in order to determine the concrete class and the compressive strength, 9 concrete cylinders, 100 mm in diameter and 250 mm high, and 9 cubes, 100 mm in side, have been tested in uniaxial compression under standard condition. To avoid a rapid failure of the unconfined concrete cylinder and determine the complete stress-strain curve including the post peak strength domain of the material it was necessary to use a special installation for the post elastic testing of brittle materials. The arrangement

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of all transducers is illustrated in figure 1, for both unconfined and confined samples.

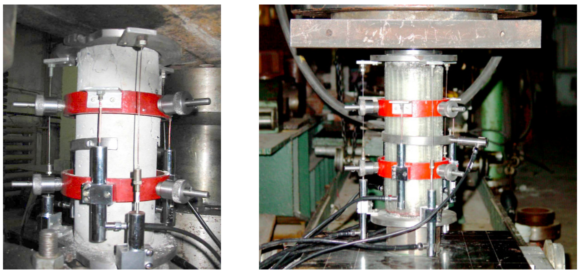
a. b.

Figure 1. Instrumentation of test samples with LVDTs a. unconfined concrete cylinder specimen; b. confined concrete cylinder specimen

The compressive strength determined on plain concrete samples, after 28 days is 31.64 N/mm2 on the concrete cylinders and 32.16 N/mm2 on the concrete cubes, and a complete stress-strain curve for unconfined concrete is illustrated in Figure 2.

2. EXPERIMENTAL PROGRAM

To avoid a rapid failure of the unconfined concrete cylinder and determine the complete stress-strain curve including the post-yielding domain of the material it was necessary to use a genuine installation for the post elastic testing of brittle materials. Before the experimental testing of the specimen, the testing machine had been calibrated and the equipment had been prepared for data acquisition, fig. 2. Data processing was done with a developed soft based on “Test Point” program.

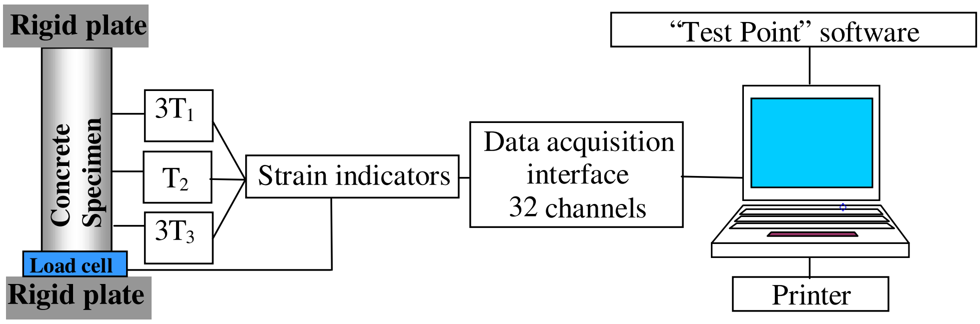

Figure 2. Acquisition and processing experimental data

Stress-strain curve obtained on unconfined concrete cylinders (fig.3) has two branches, a rising one associated with elastic, viscous and plastic strains, and a falling one corresponding to pseudo plastic strain and characterized by an accelerated decrease in load and increase in strain over time. The maximum value on the curve corresponds to the ultimate compressive strength of concrete. The compressive strength 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.

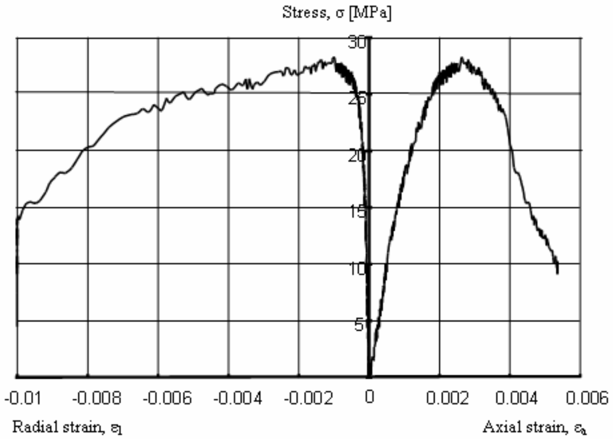

Figure 3. The complete stress-strain curves for unconfined concrete specimens

Nine specimens with 2, 3 and 4 unidirectional CFRP and GFRP layers (three of each type) with main fibers orientated in the hoop direction have been prepared using a wet hand lay-up technique. Prior to the application of the FRP layers the surface of the samples has been properly prepared to provide a hard, dry and clean surface. The main characteristics of GFRP for epoxy resins are presented in table 1 whilst the properties for glass and carbon fibers are given in table 2 and table 3.

Table 1 - Properties of epoxy resin

Appearance	Component A: light/yellow to amber Component B: pale yellow to clear liquid
Mixing ratio	A:B = 100:34,5
Density	1,16 g/cm^3
Tensile strength (ASTM D 638)	7 days at +21 ^{0}C: 55N/mm^2
Tensile modulus (ASTM D 638)	7 days at +21 ^{0}C: 2000N/mm^2
Fracture elongation (ASTM D 638)	7 days at +21 ^{0}C: 3,2%

Confined concrete specimens with GFRP and CFRP have been tested with the same installation used for the unconfined concrete samples. The confined specimens have been kept under laboratory conditions kept for 7 days to enable the complete cure of the polymeric resin after confinement.

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Table 2 - Properties of glass fiber reinforcement

Fiber type	E-Glass fibers
Fiber orientation	0^0C (unidirectional)
Construction	93% warp, 7% weft
Areal weight	920 g/m^2
Fabric thickness	0,36 mm
Density of glass fibers	2,58 g/cm^3
Tensile strength of fibers	2250 N/mm^2
Tensile E-modulus	72400 N/mm^2
Ultimate fiber strain	3,7 %

Table 3 - Properties of carbon fiber reinforcement

Fiber type	Carbon fibers - high modulus
Fiber orientation	0^0C (unidirectional)
Construction	97% warp, 3% weft
Areal weight, [g/m^2]	610
Fabric thickness, [mm]	0,34
Tensile strength of fibers, [N/mm^2]	3900 (nominal) 3700 (minimal)
Tensile E-modulus, [N/mm^2]	231000
Ultimate fiber strain, [%]	1,5

Three stages have been observed on the stress-strain curve of confined concrete specimens:

- the first stage is linear and it corresponds to the stiffness of the unconfined concrete specimens, fig.4;
- in the second stage the concrete specimen exhibits larger lateral strains and the GFRP jacket creates a confining pressure on the concrete core. When the concrete specimen is cracked, a dramatic change in curve configuration occurs. At this stage much higher stresses and strains are attained than in the case of unconfined concrete;
- in the third stage, the concrete specimen is thoroughly cracked and the GFRP maintain the concrete confined specimen intact till the explosive failure of the jacket occurs. The stress-strain curve increases by a constant angle up to the rupture, fig.4.

A comparative set of curves for unconfined and CFRP confined samples is illustrated in fig.5; the confined samples have been wrapped with 2, 3 and 4 layers of CFRP composites.

The stress-strain curves of the CFRP composites have 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 linearly increases with increasing the

CFRP strain. All experimental results confirm the similar work published in the field of structural rehabilitation with composites [1].

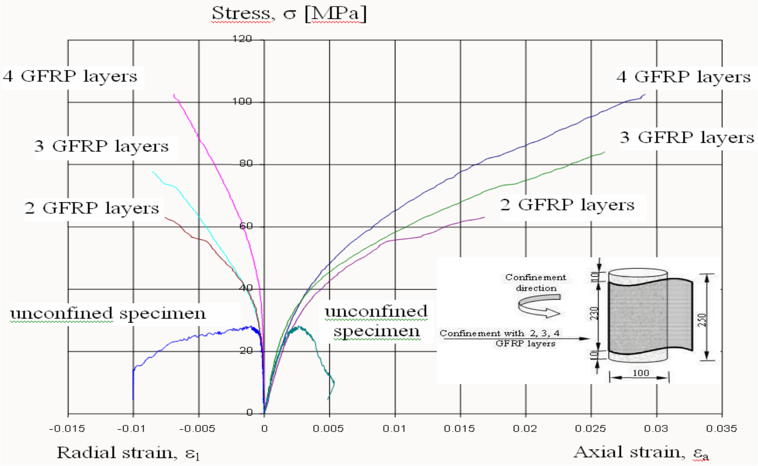

Figure 4 - Stress-strain curves of compressed unconfined and confined concrete specimens with GFRP

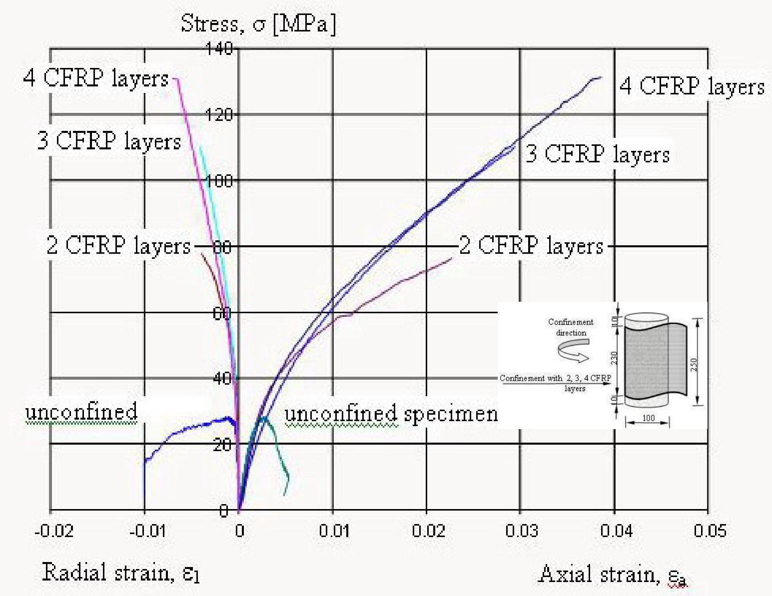

Figure 5 - Stress-strain curves of compressed unconfined and confined concrete specimens with CFRP

When the test is properly carried out the maximum stress is reached at the CFRP rupture. Some samples failed prematurely due to separation of the composite layers at the lap joints. A step forward of the experimental program has been the cyclic loading of the confined samples as a first stage to seismic retrofit with polymeric composites. Some preliminary results are shown in fig.6 [2].

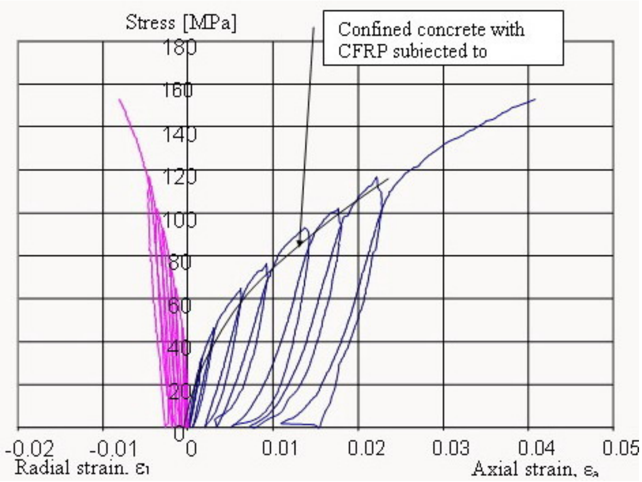

Figure 6 - Stress-strain curves of confined specimens subjected to cyclic load

3. NUMERICAL ANALYSIS

In order to verify the suitability of a FEM based software (LUSAS) for modelling concrete confinement problems, a numerical analysis was performed.

A statical non-linear analysis was conducted on a model that was built under the same dimensional conditions with the experimental program.

The concrete cylinder was modelled as a 3D solid element. In order to obtain a radial regular meshing it was first modelled a quarter of the final concrete element. The CFRP jacket was modelled as a sum of thick shell elements, “glued” onto the concrete surface using the SLIDELINE option, proper for contact problems, as in this case. The attributed thickness of the jacket was equivalent to a 3 layers disposal of CFRP sheets.

3D solid elements were used for the concrete cylinder meshing, as long as for the jacket, 3D surface elements were used. Although the software allows the use of higher order finite elements, only linear interpolation between nodes option was used in order to reduce the total number of elements and nodes for having a reasonable solving time.

The cylinder was considered as simply supported at the top end and totally restrained at the bottom end. The load was applied as a uniformly distributed force at the top end of the concrete element. In order to ensure a good convergence of the load increments, an initial value of 1 N/mm^2 was used and variable load increments (3 and 10) were used afterwards in the Solution Software Manager.

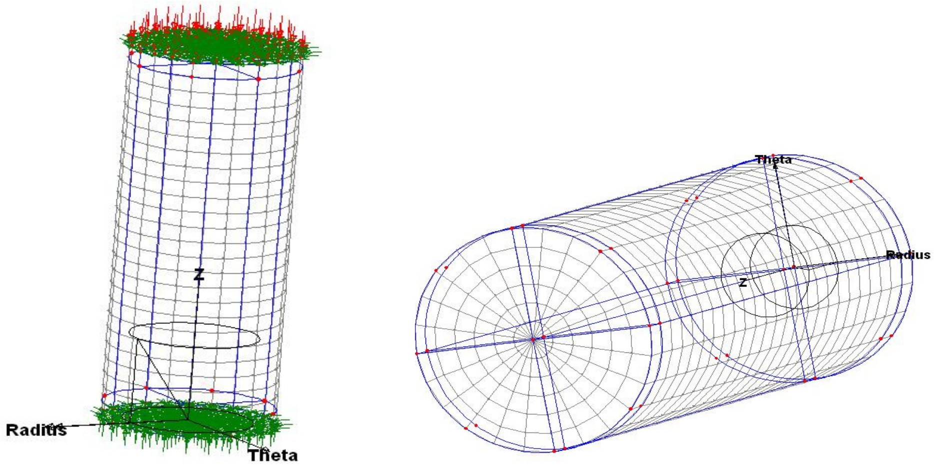

Figure 7 Support and load conditions of the concrete cylinder; radial meshing of the concrete volume

A Ducker-Prager material model based was used for defining the material properties for concrete as long as for the composite CFRP jacket an orthotropic material model available in the software's material options was used.

The mechanical properties for both concrete and composite jacket were defined in accordance with the materials that were used in the laboratory tests, and then attributed to the geometric elements.

From the large range of numerical and graphical results available after performing the run of the program, representative data charts and maps were selected and presented below. They are related to stresses, strains, displacements data needed in order to realise a good picture of the confined concrete cylinder behaviour under axial loading.

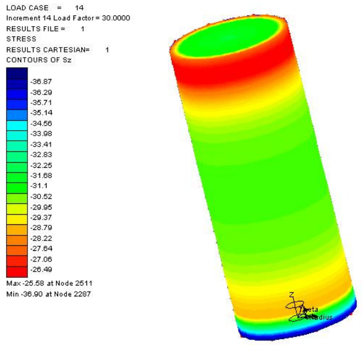

Figure 8. Normal stresses (unconfined concrete cylinder)

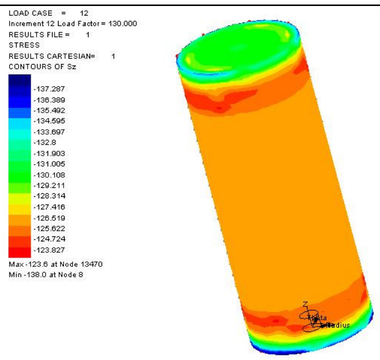

Figure 9. Normal stresses (CFRP confined concrete cylinder)

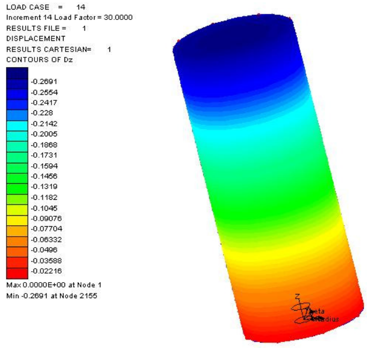

Figure 10. Longitudinal displacements (unconfined concrete cylinder)

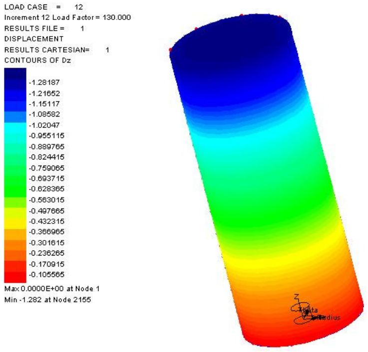

Figure 11. Longitudinal displacements (CFRP confined concrete cylinder)

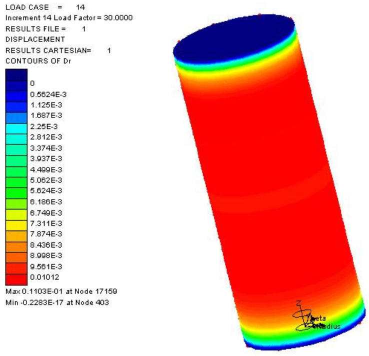

Figure 12. Transversal displacements (unconfined concrete cylinder)

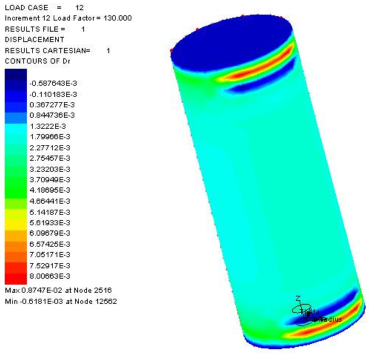

Figure 13. Transversal displacements (CFRP confined concrete cylinder)

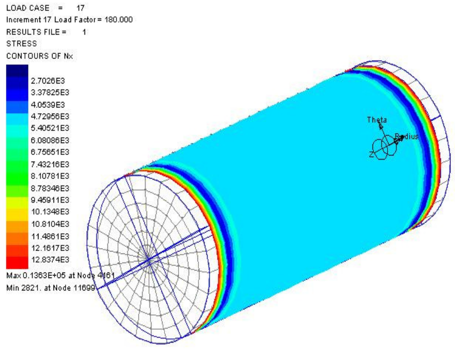

Figure 14. Longitudinal stress resultants in the CFRP jacket

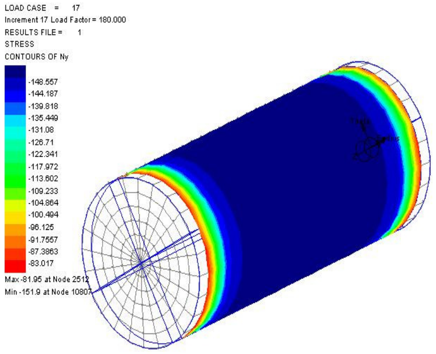

Figure 15. Transversal stress resultants in the CFRP jacket

Characteristic stress-strain curves for both confined and unconfined concrete were obtained; they are very similar to those obtained from the experimental analysis.

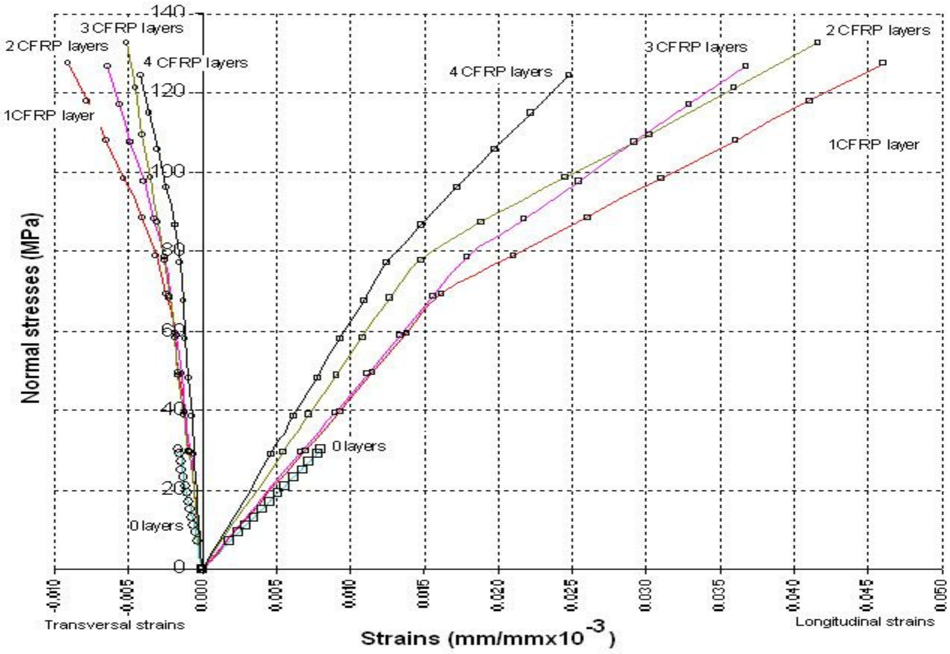

Figure 16. Stress-strain characteristic curves (CFRP confined / unconfined cylinder)

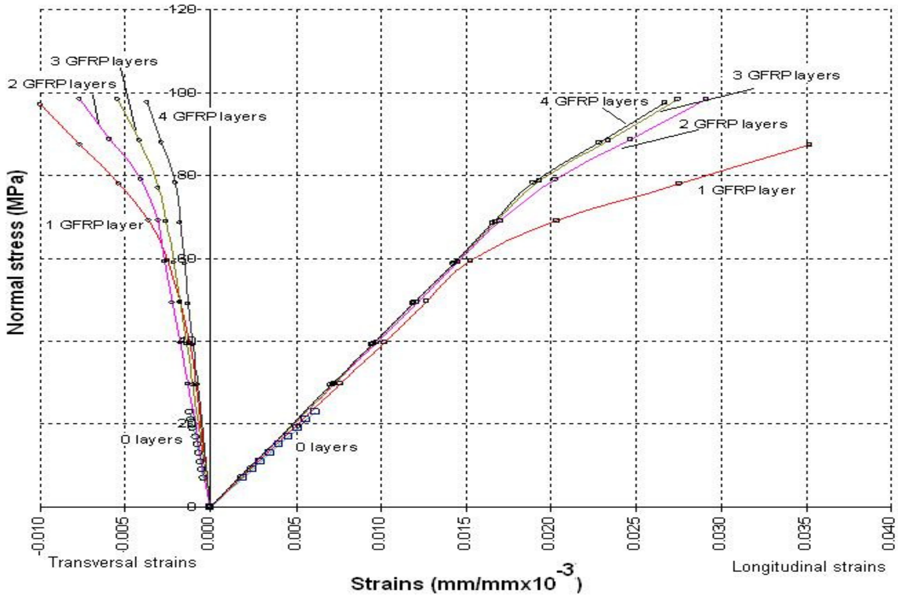

Figure 17. Stress-strain characteristic curves (GFRP confined / unconfined cylinder)

4. CONCLUSIONS

The use of FRP confinement significantly improves compressive strength and ductility of concrete. It should be noted that epoxy resins adhere well to the concrete surface, being also an excellent adhesive. Strengthening solutions with FRP used for reinforced concrete columns prove to be very good for several reasons. On the one hand, the strength and ductility values obtained are favourable and on the other hand, the weight of the consolidated system and the cost related to execution time and work are considerably reduced. Experience has shown that the failure modes of FRP are different and they depend on a series of factors which can influence the results obtained, such as: the characteristics of the concrete to be confined, casting moulds and vibration methods, fibre volume fraction, confinement techniques and accurate application by qualified workers.

References

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2. Oprisan, G. Soluţii moderne de consolidare a structurilor penrtu construcţii industriale, Teză de doctorat (PhD Thesis) - U.T. Iasi, (2002). (in Romanian)