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COMPOSITE STRENGTHENING SOLUTIONS FOR REINFORCED CONCRETE LOAD BEARING ELEMENTS

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Rezumat. *În lucrare se prezintă rezultatele unui program complex de cercetare-dezvoltare referitor la aplicarea soluțiilor de consolidare bazate pe compozite polimerice armate cu fibre, organizat la Facultatea de Construcții și Instalații din Iași. Programul a inclus concepția sistemelor de reabilitare structurală, alcătuirea constructivă și testarea experimentală a unor soluții aplicate la grinzi, plăci și stâlpi (cu secțiune circulară și pătrată). În cazul fiecărui element portant s-a urmărit utilizarea eficientă a materialelor pentru creșterea performanțelor structurale ale elementelor din beton armat, concretizate prin creșterea eforturilor capabile, îmbunătățirea răspunsului structural și controlul modurilor de rupere.*

Abstract. *The results of a complex research and development program relating to the use of fiber reinforced polymeric composite strengthening solutions carried out at the Faculty of Civil Engineering and Building Services Iasi, are presented in this paper. The program has included the conceiving of the structural rehabilitation systems, the detailing and experimental testing of some solutions applied to reinforced concrete beams, slabs and columns (with circular and square cross-section). An efficient use of the component materials to improve the structural performance of the studied reinforced concrete element has been the main target of the research program. The main benefits resulted from the research program refer to the increase of the load capacities, the improvement of the structural response of all strengthened elements and a better control of the failure modes.*

Keywords: polymeric composites, structural rehabilitation, beams, slabs, columns

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1. Introduction

Ageing infrastructures constructed from a variety of traditional building materials such as concrete and reinforced concrete (RC) include a wide range of structural members that, after a long period of use may require strengthening to extend their life span. The main reasons for strengthening load bearing elements are illustrated in Figure 1 [1, 2, 3].

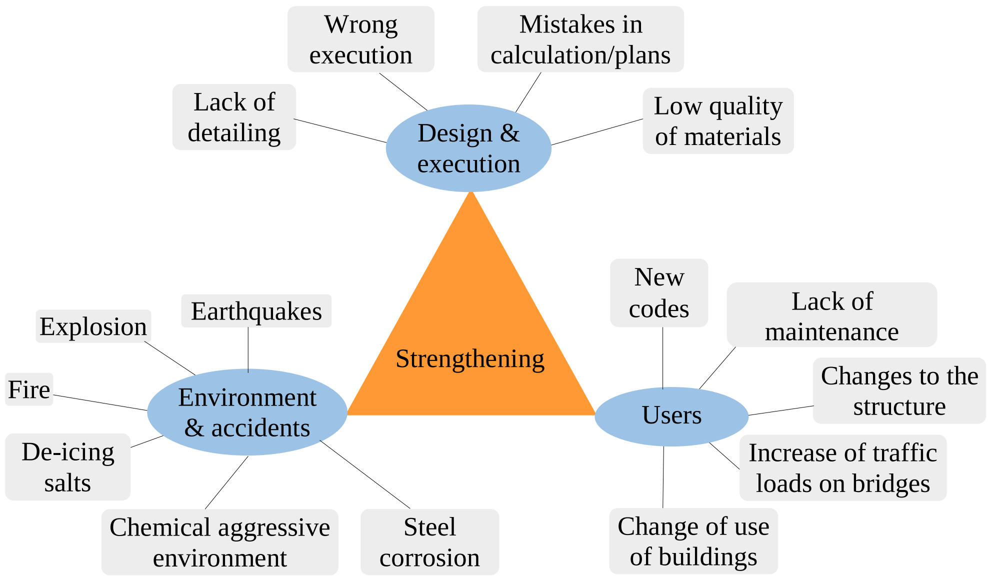


Fig. 1. The main reasons requiring structural rehabilitation [1, 2, 3].

Over the past forty years different approaches have been tried to mitigate or combat the corrosion problem, using Fibre Reinforced Polymer (FRP) composite products for strengthening systems applied externally or embedded in concrete structural members. The current and the future economic climate in all countries indicates a certain decline in new buildings, therefore the need for upgrading existing infrastructure becomes more demanding [2].

An important research effort has been targeted at the Faculty of Civil Engineering and Building Services Iasi, since 2001, to the development of modern strengthening solutions based on FRP composites for RC structural members. Expanding the initial system with steel plate bonding attached to the RC beams with epoxy adhesives [4], new strengthening solutions have been developed for RC beams and plates. The plate bonding techniques, with FRP externally bonded reinforcement, (EBR), [5, 6] and the near surface mounted solution, (NSM), [7, 8] to improve the load bearing capacity of RC beams have been further researched to evaluate the components bonding [9] and to improve the overall structural response. Some research and development projects dealing with the FRP strengthening solutions of plate elements [10, 11] have also been performed. A particular attention has been given to increasing the load bearing capacity and ductility of reinforced concrete columns. Research programs have been carried out on circular cross section columns [12, 13] and rectangular cross section columns [14, 15] to evaluate the efficiency of composite membranes in structural strengthening of reinforced concrete members subjected to compression.

2. Properties of fibre reinforced polymeric composites for strengthening solutions of RC members

In fibrous polymeric composites, the fibres with high strength and high stiffness are embedded in a low modulus continuous polymeric matrix. The reinforcing fibres constitute the backbone of the material, determining most of its strength and stiffness in the direction of fibres, although "lateral" contributions are also possible.

The polymeric matrix, chemically and thermally compatible with the reinforcing fibres, binds the fibres together and protects their surfaces from damage during composite handling, fabrication and service life. In addition, the matrix disperses and separates the fibres, also providing the transfer of stresses to the reinforcing component. The interface region has the prevailing role in controlling the overall stress-strain behaviour of composites and their fracture toughness.

Most FRP composites in construction are made of thermosetting polymeric resins (epoxy, vinylester, polyester) reinforced with glass fibres (GFRP), carbon fibres (CFRP) or aramid fibres (AFRP). The usual fibre volume fractions (V_f) of polymeric composites are in the range of 0.3 to 0.75.

The advantages of FRP composites for strengthening solutions compared to conventional building materials include higher strength, lower weight, the ability to provide tailored properties, Figure 2, corrosion resistance to numerous aggressive agents and reduced fabrication costs.

The same advantages have facilitated the development of efficient strengthening solutions of reinforced concrete structures, with little additional permanent loading [16], including seismic retrofitting of deteriorated structural members.

The most important disadvantages of FRP composites utilised for strengthening RC load bearing elements include: lower ductility than steel, high initial material costs, as well as potential adverse effects of temperature and moisture.

It can be stated that, for instance, GFRP reinforcing bars are about three times more expensive than steel bars, while aramid or carbon-fibre based composites can go up to ten times the cost of basic steel reinforcement, [17, 18].

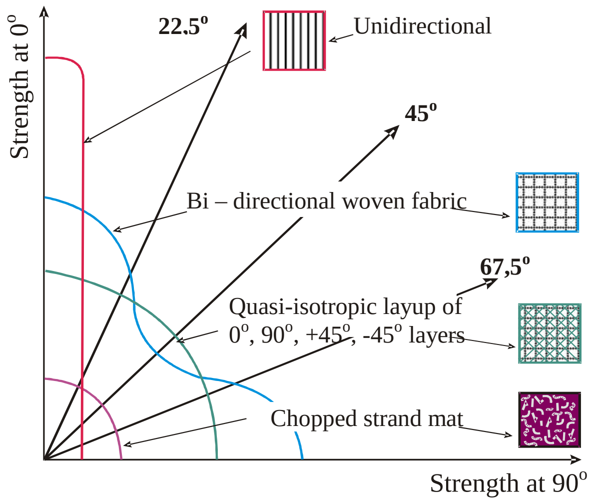


Fig. 2. Variation of FRP composites strength with loading direction.

Unlike steel, FRP composites have an almost brittle, linear behaviour for the whole range of loading. In many cases the yield and ultimate strengths are almost the same and they can be considered to be identical, Figure 3. Due to the absence of plastic flow at yield, some FRP composites are incapable of relieving stress concentrations leading to brittle failure.

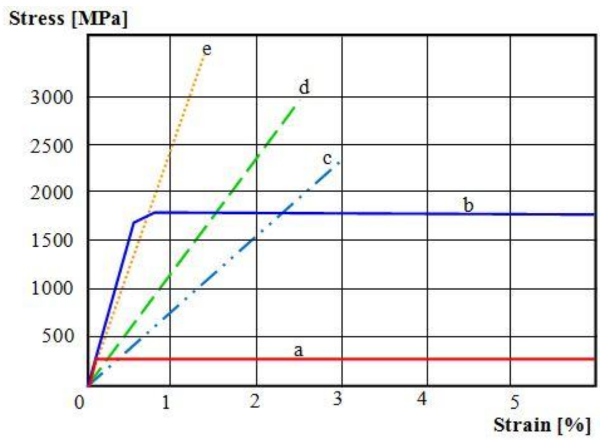
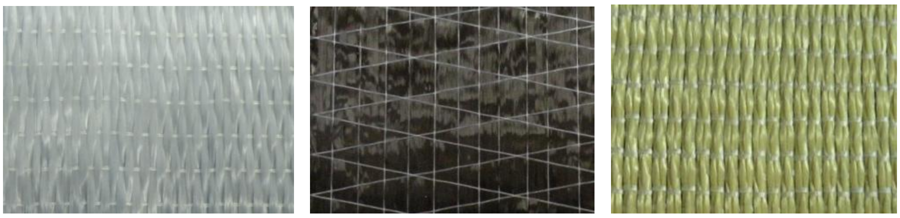


Fig. 3. Stress-strain curves of FRP composites utilized in civil engineering compared to steel: a) mild steel; b) high strength steel; c) GFRP; d) AFRP; e) CFRP

FRP composites have different values of strength and modulus in tension and compression. Experimental work has proved that compressive strengths of FRPs are lower than the tensile strengths, introducing relative difficulties in structural design work.

They are orthotropic when reinforced with unidirectional fibres, woven roving and cloth. Special attention should be given to transverse properties which are mainly determined by the polymeric matrices. Both mechanical and thermal properties vary with direction and fibres volume fraction.

The composite materials and products utilised for strengthening of reinforced concrete load bearing elements can be fabricated using different manufacturing procedures. Two methods are, however, mainly used, and these are: the wet lay-up system for column wrapping or plate bonding, and the pultrusion that enables the fabrication of composites plates and/or strips. Unidirectional and balanced fabrics, Figure 4 and Figure 5, are utilised for wrappings which are formed by impregnation of reinforcing fibres with polymeric resins.



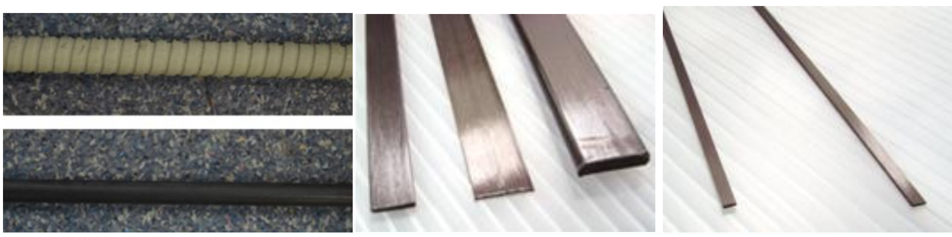
a. b. c.

Fig. 4. Unidirectional fabrics for FRP composite wrappings:
a –glass fibres; b –carbon fibres; c – aramid fibres

a. b. c.

Fig. 5. Balanced fabrics for FRP composite wrappings:
a –glass fibres; b –carbon fibres; c – aramid fibres

Pultrusion is a continuous process for manufacturing composite elements that have a constant cross-sectional shape. The FRP composite plates and strips, Figure 6, can be easily fabricated by this technique.



a b c

Fig. 6. Composite products for structural rehabilitation: a) reinforcing bars with glass and carbon fibres; b) carbon fibres/epoxy composite plates; c) narrow composite strips.

3. Strengthening composite solutions for reinforced concrete load bearing elements

3.1. Strengthening RC beams using EBR/ NSM FRP composites

Strengthening of the reinforced concrete members subjected to bending aims to supplementing the existing initial steel reinforcement. This effect is achieved by providing additional composite reinforcing elements to the tensioned side of the RC bent member. The attached composite products are prefabricated quasi-unidirectional reinforced plates, composite membranes obtained by impregnating reinforcing fabrics, or embedding near surface composite narrow strips, [6].

The bond between concrete and the FRP plate has a major influence on the failure mode and on the load bearing capability of the strengthened RC beams [9, 19]. The bending of the reinforced concrete beams plated with CFRP strips, has led to the identification of the following specific modes of failure: concrete compressive failure before the yield of steel reinforcement, concrete compressive failure after the yield of steel reinforcing bars, fracture of the CFRP plate, shear failure, debonding of the CFRP plate, delamination of the composite plate and failure within concrete cover layer.

In a preliminary study on the FRP strengthening of the reinforced concrete beams, the bent members subjected to a four point loading scheme have been tested. The tested samples were 1200 mm long, 100 mm wide and 150 mm high. They were reinforced with two 10 mm diameter longitudinal steel bars, placed on the tensioned part of the beam with a 20 mm concrete cover. The reinforced concrete beams, were strengthened with steel plates and CFRP strips, respectively. The structural responses of reinforced concrete beams, namely unstrengthened reinforced concrete (RC) beams, RC beams bonded with steel plates and RC beams plated with CFRP strips, are illustrated in Figure 7 which also includes a detail of the initial failure caused by the shear effect. This type of failure imposes the shear strengthening of the reinforced concrete beam to avoid premature cracking of the bent element, [6, 18].

The research work carried out until now has revealed that the full tensile strength of the CFRP product is almost impossible to be achieved with the EBR solution. The stress concentrations at the adhesive – concrete interface has led to premature debonding, which has been shown to be one of the most common failure modes of the EBR technique [7].

Therefore the study on the strengthening solutions with CFRP elements has been extended on a number of 18 reinforced concrete beams. All tested beams have been selected with the cross-sectional area 200x300 mm, the length equal to 3000 mm and the span of 2700 mm.

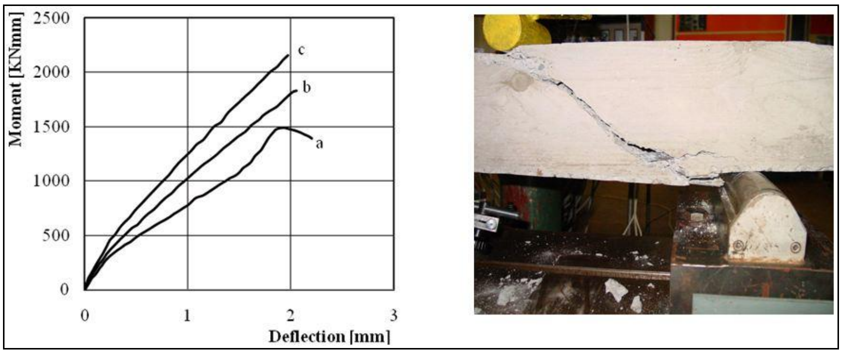


Fig. 7. Structural response of reinforced concrete beams: a) unstrengthened beam; b) beam strengthened with steel plate; c) CFRP strengthened beam [left]; failure of a CFRP plated beam near support due to shear force [right].

They were tested under a constant bending moment on the central portion using the four point loading scheme. A reference unstrengthened beam, type A, has been selected to compare the results of all EBR and NSM strengthening solutions. The EBR concrete beams, type E and type F, have been strengthened with two different widths of CFRP plates, Figure 8. The failure mode illustrated in Figure 9 strongly recommends the improving the CFRP plate / concrete bonding.

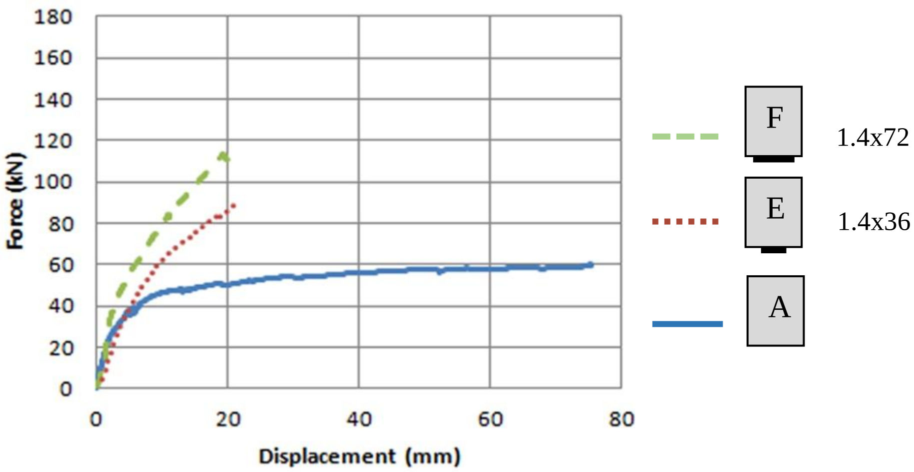


Fig. 8. Structural response of reinforced concrete beams:
A- unstrengthened beam; E – CFRP strengthened beam with an EBR narrow plate;
F - CFRP strengthened beam with an EBR wide plate.

The NSM FRP strengthening technique involves bonding of FRP bars / strips into pre – cut grooves in the concrete cover of the structural element to be strengthened.

The main advantages of the NSM technique are: mitigated risk of premature debonding, lower exposure to exterior factors or vandalism and undisturbed aesthetics [7].

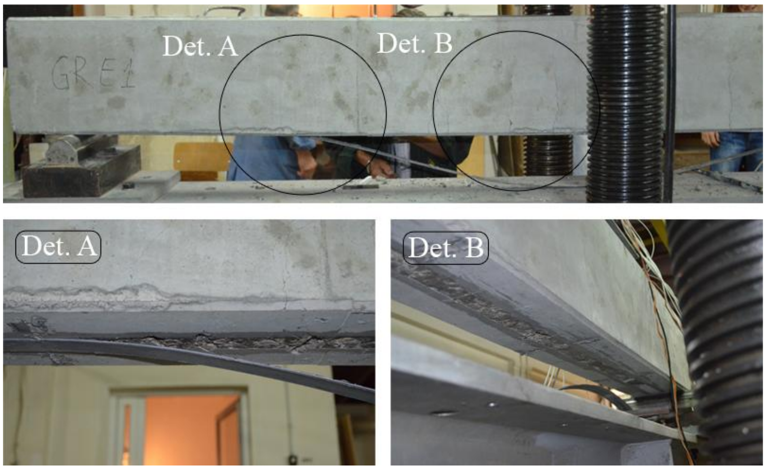


Fig. 9. Typical failure mode for EBR strengthening technique.

Nine CFRP strips NSM strengthened beams (type B, C, D) have been testes to prove the efficacy of this solution. The results are summarized in Figure 10 which illustrates the structural response for each strengthening scheme. The details of the failure modes are shown in Figure 11.

As it can be seen from Figures 9 and 11, the failure details suggest a much better bonding between embedded narrow composite strips and concrete compared to the weak bond at the interface between CFRP plates and concrete surface in the EBR solution.

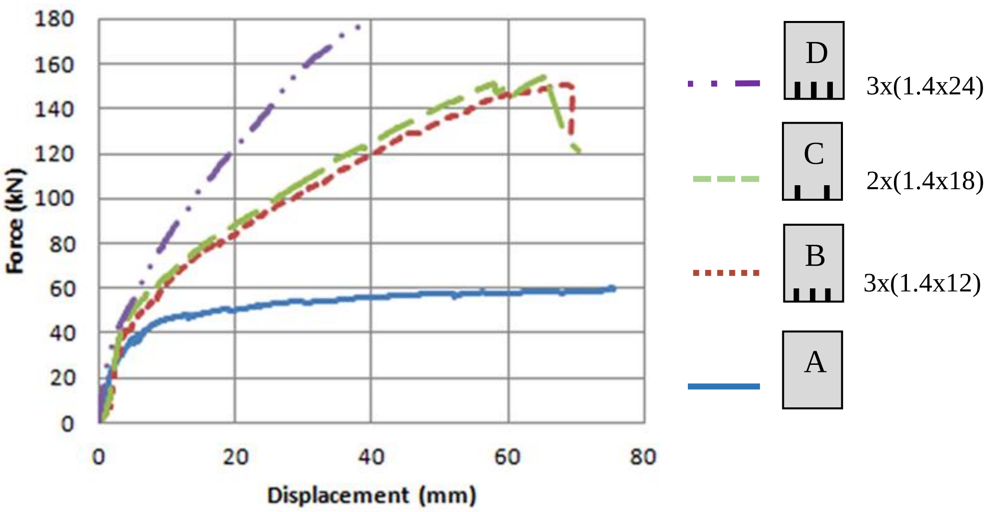


Fig. 10. Structural response of unstrengthened and NSM strengthened reinforced concrete beams:
A – unstrengthened beam;
B – CFRP strengthened beam with three narrow NSM strips;
C – CFRP strengthened beam with two NSM strips;
D - CFRP strengthened beam with three NSM wide strips.

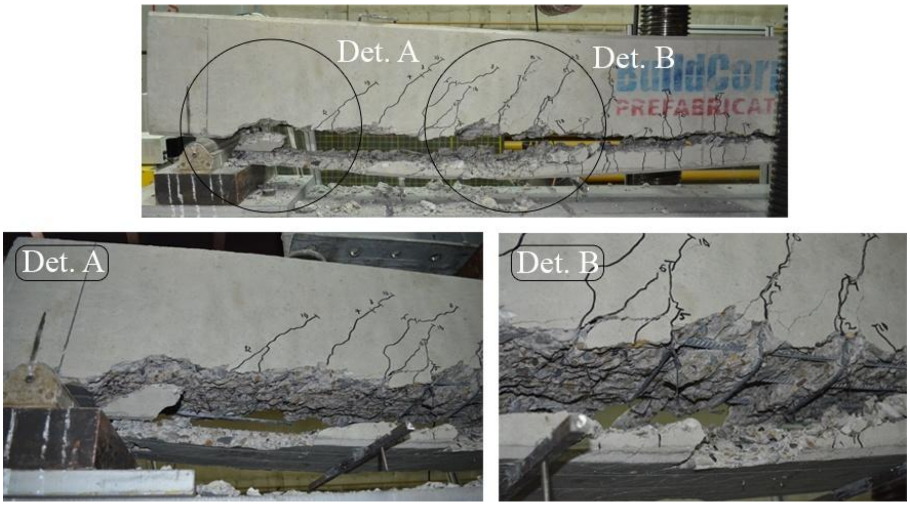


Fig. 11 Typical failure mode for NSM strengthening technique

3.2. Strengthening RC slabs using externally bonded composite reinforcement

The effectiveness of FRP strengthening solutions for reinforced concrete slabs has been proven by several experimental investigations performed in our laboratory [10, 11].

It has been found out that the result obtained from beams cannot be extrapolated to concrete plates due to the biaxial response of normally utilised RC slabs.

Strengthening with CFRP strips can be also used to effectively recover the strength of the slab before the cut-out [2]. The experimental program carried out by our team [10, 11] included the testing of RC slabs (unstrengthened and strengthened) with dimensions 1100 mm×1100 mm×50 mm.

The strengthening solutions using CFRP strips are illustrated in Figure 12a, b (slab without opening) and Figure 12c, d (slab with opening). The strengthening of the RC slabs was provided with CFRP strips bonded to the tensioned face.

The RC slabs (unstrengthened and strengthened) have been tested under static loading up to failure. The comparative load-displacement curves for two slabs (unstrengthened and strengthened as shown in Figure 12b) without opening are represented in Figure 13, illustrating the effect of the strengthening solutions on the structural response.

The failure mode of the strengthened slabs has been induced by the debonding of the composite strips, accompanied by their flexural cracking. The debonding of the CFRP strips occurred through the concrete cover near the surface of the RC element, Figure 14.

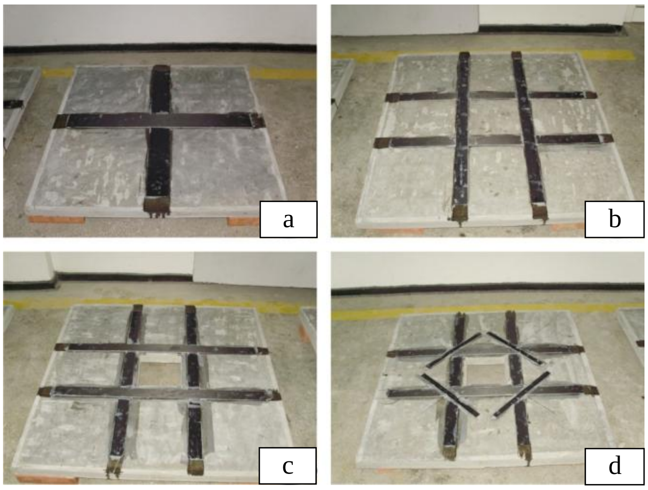


Fig. 12. CFRP strengthening solutions of the RC slabs:
a, b) slab without opening; c, d) slab with opening

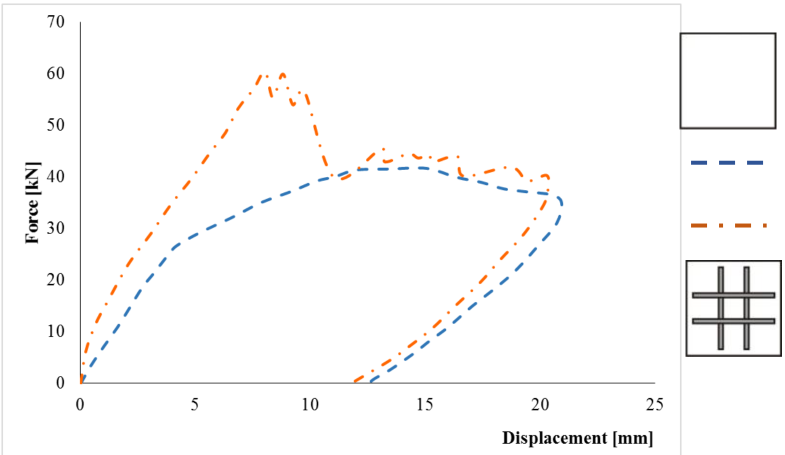


Fig. 13. Comparative load-deflection diagrams for unstrengthened
and CFRP strengthened slab without opening.

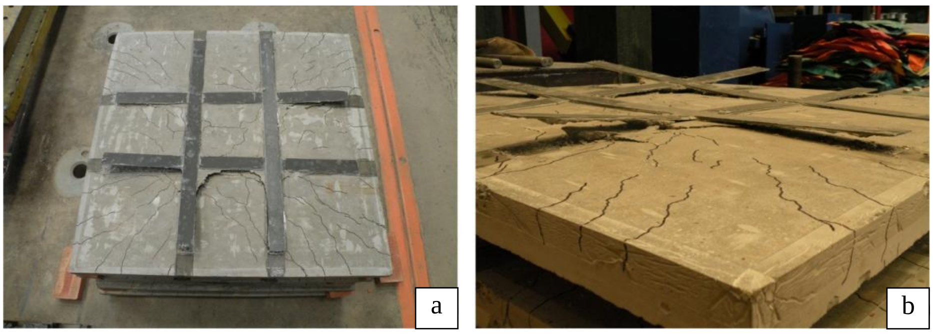


Fig. 14 The failure of the strengthened plate without openings:
a) the cracking pattern; b) debonding of the CFRP strips.

Figure 15 illustrates the comparative structural responses in case of two slabs (unstrengthened and strengthened as shown in Figure 12d) with opening; the pick load recorded during testing reveals the stiffening effect of the diagonal CFRP strips attached near the corners of the opening. The mechanism of failure is quite similar to that occurred in the previous case, Figure 16.

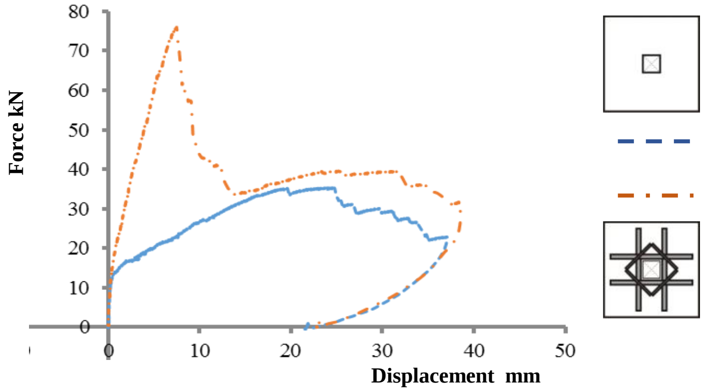


Fig. 15. Comparative load-deflection diagrams for unstrengthened and CFRP strengthened slab with opening.

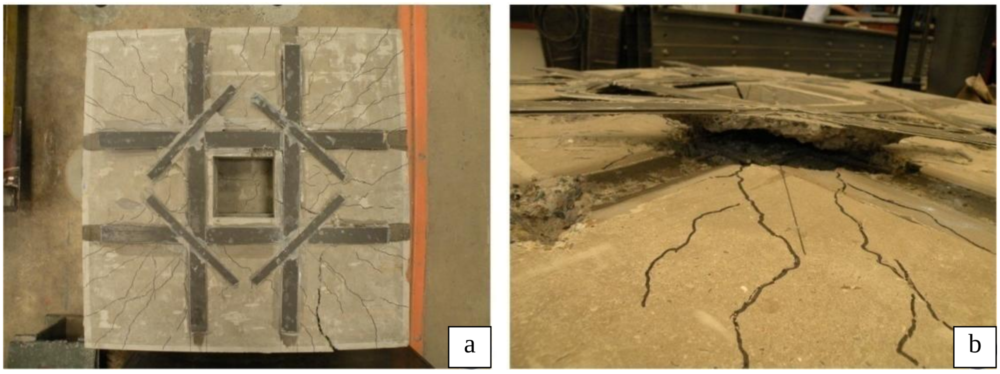


Fig. 16 The failure of the strengthened plate with openings:
a) the cracking pattern; b) debonding of the CFRP strips

3.3. FRP confinement systems for reinforced concrete columns

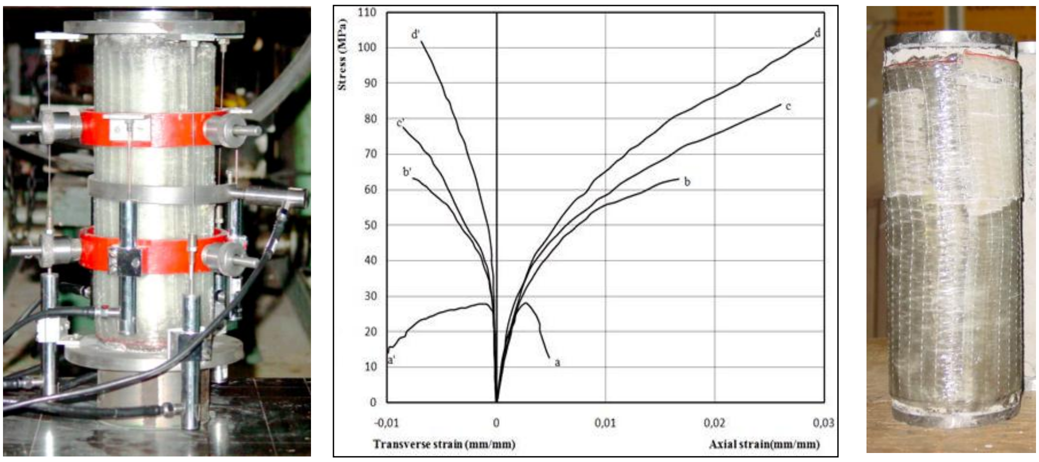
FRP composites can be successfully utilised to provide confinement to RC columns enhancing their load bearing capacity and ductility. The strengthening solutions applied to members subjected to axial compression is based on the significant increase of the axial compression strength and the axial compressive strain of concrete through lateral confinement. The most common utilised technique is the *in situ* application of the FRP composites; the unidirectional fiber sheets or the impregnated fabrics are wrapped around columns in a wet lay-up process. The main reinforcing fibres are orientated in the hoop direction [2].

It has been established that structural efficiency is mainly dependent on the extent of concrete volume subjected to the confinement pressure induced by the FRP externally applied system.

The study of FRP composites based confinement of RC columns has focused upon identifying and quantification of specific aspects of this problem. The following characteristics were monitored: the improvement of the overall load-bearing capacity of members, variation of the confined concrete strengths, efficiency parameters and particularities in the failure mechanisms. Typical results were expressed in stress – axial/ transverse strain diagrams. An initial stage in the research was represented by the study of cylindrical members, 100 mm in diameter and 250 mm in height, made of plain concrete. Variability of the externally applied FRP confinement system was given by the use of different layer numbers of GFRP, Figure 14, and CFRP, Figure 15.

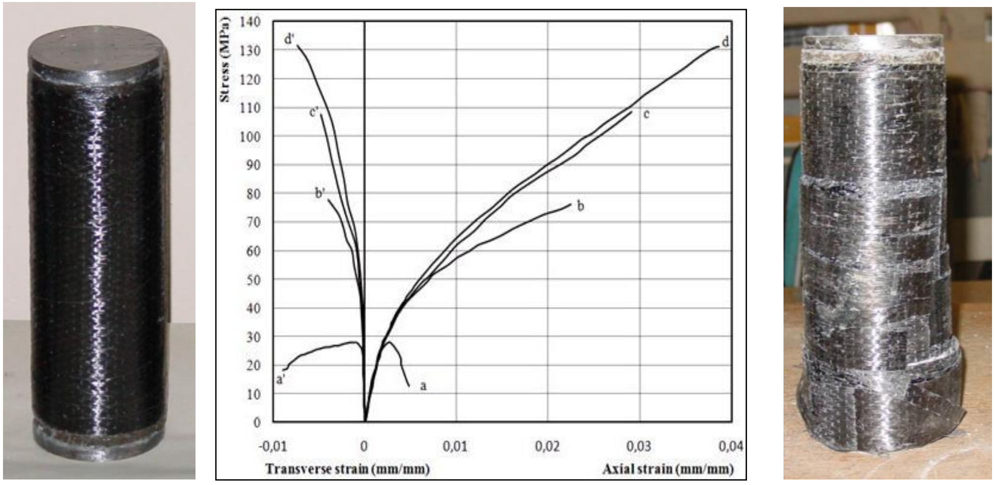
An original equipment patented by some authors of the research team [20] was utilised to enable the development of characteristic curves throughout the entire loading process.

The resulted stress-strain curves reveal the activation of the FRP confinement pressure in the second stage, after the unconfined concrete strength having been surpassed. Once the confining pressure was activated, a quasi-linear dependency was noticed between the stresses within the confined concrete and the FRP jacket strains [12, 13].



A) B) C)

Fig. 14. Effect of confining cylindrical concrete columns with GFRP membranes:
A) the instrumented cylindrical sample;
B) the assembly of the stress-strain curves
[a) stress-axial strain curve for unconfined concrete; b), c), d) stress-axial strain curves for samples confined with 2, 3, 4 GFRP jackets; a') stress-transverse strain curve for unconfined concrete;
b'), c'), d'), stress-transverse strain curves for samples confined with 2, 3, 4 GFRP jackets];
C) failure of the cylindrical specimen.



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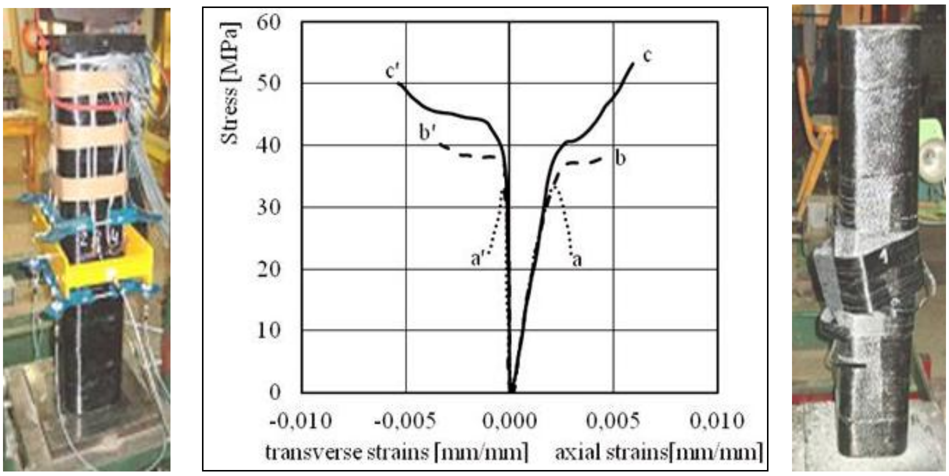
b'), c'), d') stress-transverse strain curves for samples confined with 2, 3, 4 CFRP jackets];
C) failure of the cylindrical specimen.

The research and development program has been extended to CFRP confined concrete in square RC columns. Although the confinement technique is less efficient than the case of circular sections, it still remains one of the most suitable strengthening technique against exceptional loads such as earthquake, impact and terrorism [17].

The experimental program dealt with 1000 mm high and 200x200 mm cross-sectioned RC square columns, in unconfined (UC) and confined (CC) configurations. A composite membrane made of epoxy resin reinforced with unidirectional carbon fiber fabric was formed by wet-up technology and was wrapped around the column.

A uniaxial compressive test has been performed on instrumented unconfined and confined columns, Figure 16A, to establish the stress-strain curves along the axis of the column and perpendicular to the longitudinal axis. The experimental results are illustrated in Figure 16B, which includes the above mentioned diagrams. As it can be seen the confined concrete columns have a much higher compressive strength and increased axial/transverse strains than the unconfined concrete columns. The figure also reveals the beneficial influence of the increase of number of CFRP layers. Failure of FRP confined specimens was characterized by composite delamination rather than actual FRP tensile fracture and revealed extensive crushing of the tri-axially stressed confined concrete, Figure 16C.



A) B) C)

Fig. 16. Structural response of square RC column confined with CFRP membranes:
A) instrumentation of CFRP confined RC column with square section;
B) structural responses of unconfined and FRP confined RC columns
[a), a') unconfined RC column; b), b') one layer CFRP membrane confined RC column;
c), c') two layer CFRP membrane confined RC column] C) failure of the square specimen.

Conclusions

The strengthening solutions based on FRP composites have gained a large recognition due to a multitude of advantages. They are light weight, corrosion resistant, tailorable according to strength and stiffness requirements, can be easily applied and do not usually interrupt the functioning of infrastructure components thus avoiding important economic loss.

FRP structural rehabilitation systems do not decrease the useful space for living or production in civil and industrial buildings. Due to their low thickness and reduced stiffness, the structural rehabilitation solutions based on FRP composites do not substantially modify the dynamic and seismic characteristics of framing systems for buildings.

The structural rehabilitation of the reinforced concrete members subjected to bending and shear can be achieved by supplementing the existing steel reinforcement using the plate bonding or near surface mounted composite reinforcing elements. Strengthening of reinforced concrete columns is based on the beneficial influence of the confining phenomenon that forces the concrete to work under triaxial state of stress. The confining solutions are more efficient in case of circular columns than in case of square columns.

Rethinking the building rehabilitation techniques is a must and composite materials have to be included in order to fulfil the performance requirements, minimizing the structural defects, reducing the material waste, preserving the environment and eventually leading to sustainable development.

R E F E R E N C E S

[1] K. Pilakoutas, M. Guadagnini, *CIV 6170 – FRP composites in construction* (Course Notes, The University of Sheffield, UK, **2015**).

[2] L.C. Hollaway, J.G. Teng, (Eds.), *Strengthening and Rehabilitation of Civil Infrastructures Using Fibre-Reinforced Polymer (FRP) Composites* (CRC Press, Boca Raton, USA, **2008**).

[3] N. Taranu, G. Oprişan, D. Isopescu, I. Entuc, Vl. Munteanu, *Soluţii compozite de reabilitare a structurilor inginereşti* (*Composite Strengthening Solutions for Engineering Structures)*, (Ed. STEF, Iasi, Romania, **2006**).

[4] I. Gosav, *Influenta durabilitatii asupra nivelului sigurantei structurale. Solutii de reabilitare. (The Influence of Durability on Structural Safety Level. Rehabilitation Solutions.)* Teza de doctorat, PhD Thesis, "Gheorghe Asachi" Technical University of Iasi, Romania, (**1996**).

[5] C. Saftiuc, *Contribuţii privind utilizarea materialelor compozite la consolidarea construcţiilor industriale*, *(Contributions to the Use of Composite Materials for Strengthening the Industrial Buildings)* Teză de doctorat, PhD Thesis, "Gheorghe Asachi" Technical University of Iasi, Romania, (**2005**).

[6] G. Oprisan, N. Taranu, M. Budescu, I. Entuc, *Structural behaviour of reinforced concrete beams strengthened by CFRP plate bonding*, Romanian Journal of Materials, 387-398, Issue 4, Vol. **42**, (**2012**).

[7] P. Ciobanu, *Consolidarea grinzilor din beton armat cu materiale compozite aplicate lângă fețele exterioare (Strengthening reinforced concrete beams with near surface mounted – NSM - composite materials)* Teză de doctorat, PhD Thesis, "Gheorghe Asachi" Technical University of Iasi, Romania, (**2014**).

[8] N.Taranu, P. Ciobanu, P.Mihai, S. Popoaei, M. Budescu, V. Lupasteanu, *Improving structural response of reinforced concrete beams strengthened with NSM composite strips*, Romanian Journal of Materials, 325-340, Issue 4, Vol. **43**, (**2014**).

[9] R. Oltean (Cozmanciuc), *Studiul fenomenelor de conlucrare dintre materiale compozite și materiale tradiționale la structuri hibride*. (*Study of the bonding phenomena between composites and traditional materials in hybrid structures*) Teză de doctorat, PhD Thesis, "Gheorghe Asachi" Technical University of Iasi, Romania, (**2011**).

[10] D. Banu, *Consolidarea placilor din beton armat folosind compozite polimerice armate cu fibre*, *(Strengthening of the Reinforced Concrete Plates Using Fibre Reinforced Polymer Composites)* Teză de doctorat, PhD Thesis, "Gheorghe Asachi" Technical University of Iasi, Romania, (**2012**).

[11] N. Taranu, D. Banu, G. Oprisan, M. Budescu, L. Bejan, *Strengthening of thin reinforced concrete slabs with composite strips*, Romanian Journal of Materials, 3-13, Issue 1, Vol. **43**, (**2013**).

[12] G. Oprişan, *Soluții moderne pentru consolidarea structurilor pentru construcții industriale (Modern Solutions for Strengthening of Framing Systems for Industrial Buildings*, Teză de doctorat, PhD Thesis, "Gheorghe Asachi" Technical University of Iasi, Romania, (**2002**).

[13] G. Oprişan, N. Taranu, V. Munteanu, M. Budescu, C. Cozmanciuc, R. Oltean, *Improvement of concrete strength through confining with composite membranes*, Romanian Journal of Materials, 302-315, Issue 4, Vol. **41**, (**2011**).

[14] V. Munteanu, *Îmbunătățirea capacității portante a stâlpilor din beton armat folosind soluții compozite, (Improving the Load Bearing Capacity of RC Columns Using Composite Systems)*, Teză de doctorat, PhD Thesis, "Gheorghe Asachi" Technical University of Iasi, Romania, (**2008**).

[15] C.I. Cozmanciuc, *Consolidarea stâlpilor din beton armat cu secțiune necirculară prin confinare cu materiale compozite, (Strengthening reinforced concrete noncircular cross section columns by confining with composite materials)*, Teză de doctorat, PhD Thesis, "Gheorghe Asachi" Technical University of Iasi, Romania, (**2011**).

[16] N. Taranu, L. Bejan, R. Cozmanciuc, R. Hohan, *Materiale si elemente compozite*, (Composite Materials and Elements), (Politehnium Iasi, Romania, **2013**).

[17] C. Burgoyne, *Fibre reinforced polymers – strengths, weaknesses, opportunities and threats*, 9th International Symposium on Fiber Reinforced Polymer Reinforcement for Concrete Structures, FRPRCS-9, 1-9, Sydney, Australia (**2009**).

[18] N. Taranu, G. Oprisan, I. Entuc, M. Budescu, V. Munteanu, G. Taranu, *Composite and hybrid solutions for sustainable development in civil engineering*, Environmental Engineering and Management Journal, 783-793, Vol. **11**, No 4, (**2012**).

[19] N. Taranu, R. Cozmanciuc, I. Entuc, M. Budescu, V. Munteanu, D. Isopescu, *The behaviour of the interface between carbon fibre reinforced polymer composite plates and concrete*, Romanian Journal of Materials, 232 -239, Issue 3, Vol. **45**, (**2015**).

[20] M. Budescu, P. Mihai, N. Taranu, I. Lungu, O.M. Banu, I.O. Toma, *Establishing the complete characteristic curve of concrete loaded in compression*. Romanian Journal of Materials, 43-54, Issue 1, Vol. **44**, (**2015**).