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EXPERIMENTAL STUDY OF REINFORCED CONCRETE COLUMNS CONFINED WITH COMPOSITE MEMBRANES

BY

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Abstract. Composite materials made of fibres embedded in a polymeric resin, also known as fiber-reinforced polymers (FRP), have emerged as an alternative solution to traditional materials for strengthening and retrofitting structures. In attempt to increase strength and ductility of reinforced concrete (RC) load bearing elements through confining systems the FRP membranes have become a familiar solution. Extensive studies (experimental, finite element modelling and analytical modelling) were carried out on the analysis of confining effect in case of concentrically loaded RC columns. In all real framing systems, columns are not only axially loaded, they can be subjected to various loads and combination of loads. Currently, the study of RC columns confined with composite materials subjected to eccentric compression is relatively new and limited. FRP confinement systems are less effective under eccentric loading compared to concentric one, but this solution is still applied and it can be efficiently utilized. An extensive experimental program on testing the performance of eccentrically loaded RC columns externally strengthened with FRP membranes was carried out and results are presented in this paper.

Key words: RC columns; external strengthening; FRP wrapping; eccentrical compression; experimental investigation.

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1. Introduction

The structural strengthening and rehabilitation of deficient structures to restore or enhance load bearing performance, to improve the structural behaviour and repair of damaged framing systems have become current practices (Ţăranu *et al*., 2009). The significant number of advantages, such as light weight, high tensile strength, highly versatile, noncorrosive, nonmagnetic and the ease of application procedure, made from FRP materials, in certain cases, the ideal materials for strengthening applications (Ţăranu *et al*., 2010; Cozmanciuc *et al*., 2009).

Currently, strengthening of RC columns with externally bonded FRP composite products is a commonly accepted and widespread technique. The numerous studies developed over the last three decades have proven that lateral confinement of concrete can substantially increase its compressive axial load bearing capacity and ultimate axial strain (Sun & Wang, 2011). Generally the experimental programs focused on the analysis of confining effect in case of concentrically loaded RC columns. In practice, in real RC framing systems for buildings, all columns are subjected to axial loading, shear forces and bending moments leading to some eccentricities in load application. Studies on eccentrically loaded FRP-wrapping confined concrete columns are relatively new and limited in number making clear the need of investigating the behaviour of columns under eccentric loads (Cozmanciuc *et al*., 2011).

In literature there can be found several experimental studies concerned with the analysis of the behaviour of FRP confined concrete cylinders, prisms and columns subjected to eccentric compression or combined axial and bending loads. Parvin & Wang (2001) developed a numerical and experimental analysis of small-scale FRP jacketed square columns subjected to compression with various eccentricities. It was noticed that the efficiency of the confining system is proportional to the stiffness of the FRP membrane, which controls the dilatation of the concrete cross-section and leads to a larger axial deformation capacity. Also, the load bearing capacity of the element is higher when the number of confinement layers are increased, but it decreases with the increasing of the eccentricity (Parvin & Wang, 2001; El Maaddawy, 2009; Bisby & Ranger, 2010).

In the experimental program performed by Ghali *et al*. (2003) there were tested eighteen FRP-confined circular concrete columns of various heigths subjected to small eccentric compression loads until failure. In case of columns having the height-to-diameter ratio of 4 there was reported a strength reduction of 26% and for columns with height-to-diameter ratio of 8, a strength reduction of 70%. It can be concluded that column slenderness and load eccentricity have a negative effect on the efficiency of FRP confining systems (Bisby & Ranger, 2010; Ghali *et al*., 2003; Ranger &Bisby, 2007).

Hadi *et al*. (2003; 2004; 2006; 2007; 2009) have published over the last decade several studies on the analysis of eccentrically-loaded FRP confined concrete concluding that the improvement of ductility was more obvious than the gains in strength. Application of multiple layers of composite material increases the stiffness of the external confinement and enhances the efficiency of the confining system (Hadi, 2003, 2006). The increase of eccentricity has a direct impact on the maximum load capacity, while for the lateral deflection there is no influence with the eccentricities. Carbon fibres (CFRP) embedded in a polymeric matrix provided the highest amount of confinement compared to other types of fibres or steel reinforcement (Hadi, 2004, 2006; 2007; 2009).

In the experimental programmes carried out by Tao *et al*. (2004) and Fitzwilliam & Bisby (2006) were as well studied the behaviour of FRP confined circular RC columns subjected to compression with various eccentricities. These studies highlighted that increasing of load eccentricity and slenderness is producing a reduction of confinement efficiency (Bisby & Ranger, 2010; Ranger & Bisby, 2007; Tao *et al*., 2004; Fitzwilliam & Bisby, 2006)).

Ranger and Bisby (2007) tested at eccentric compression up to failure fourteen pin-ended small-scale circular RC columns. At the extreme compression fibre was recorded the maximum hoop strains, while at the extreme tension fibre are developed minor hoop strains. This is related to the strain gradient produced by eccentric loading which is developing uneven hoop confinement on the column cross-section (Bisby & Ranger, 2010; Ranger & Bisby, 2007).

An extensive experimental and analytical program was carried out by El Maaddawy *et al*. (2008, 2009, 2010). The gain in load capacity under eccentric loading due to the CFRP-confinement depends on the degree of eccentricity and to some extent on the shape of the cross-section. The members with rectangular cross-section subjected to eccentrical compression provided lower gain in ductility compared to the ones with circular and square cross-sections. The gain in ductility due to the CFRP-confinement under eccentric loading is inversely proportional with the eccentricity (El Maaddawy, 2008, 2009, 2010).

The performance of eccentrically loaded columns strengthened with different CFRP systems was studied by Quiertant & Clement (2011), combining longitudinal flexural reinforcement and lateral confinement. Various arrangements of plates, unidirectional and bi-directional composite fabrics were investigated. Depending on the CFRP strengthening system, significant deformation capacity and ductility improvement was achieved for columns subjected to eccentric compression. However, for the tested strengthening configuration the contribution of flexural reinforcement to strength enhancement was not clearly established (Quiertant & Clement, 2011).

2. Experimental Program

In the experimental program there were designed six square RC columns which were subjected to eccentric compression. The specimens were assembled in two groups of three identical columns, each group being tested with a different load eccentricity. The first group was designed with the cross-section side of 250 mm and noted C1, while for the second group the cross-section dimension was of 300 mm, being noted C2. In each group one specimen was unconfined and the other two specimens were confined with one, and two layers of CFRP.

2.1. Test Specimens

The RC columns were cast and tested within an experimental program developed at the Faculty of Civil Engineering and Building Services of Iaşi. The specimens were designed alike, with the height of 1,000 mm and with an identical distribution of the internal reinforcement. As longitudinal reinforcement there were used four deformed rebars 12 mm diameter. There were set, for transversal reinforcement, steel stirrups of 6 mm diameter plain

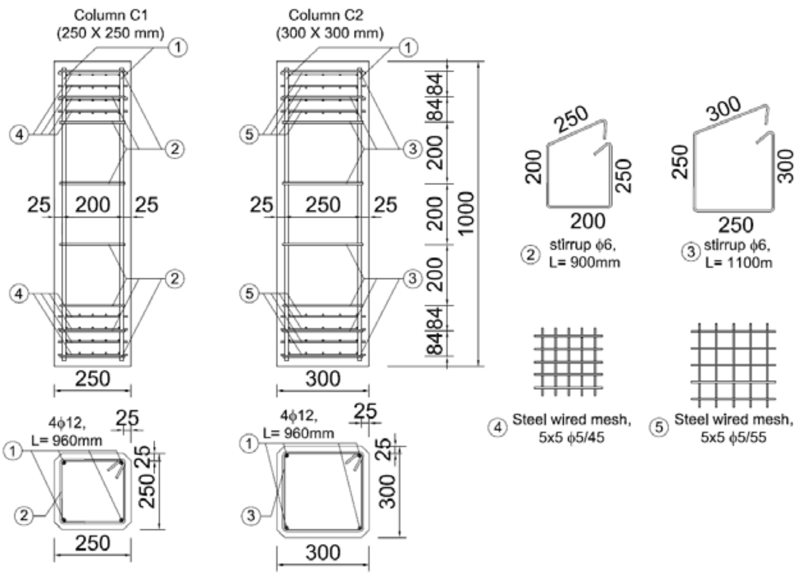


Fig. 1 – Details of test specimens.

bars, spaced at 200 mm in the middle region and at 84 mm to the ends of the columns. Using steel wired mesh, an additional internal reinforcement in the transverse direction was placed at both ends of the columns to prevent any undesired failure. In order to enhance the confining effect of the wrap and to prevent premature rupture of the CFRP membrane the columns were cast in moulds with chamfered corners, resulting a radius of 35 mm for the rounded corners. The concrete cover up to the surface of the longitudinal steel bars was of 25 mm. The specimens dimensions and details of internal reinforcement are shown in Fig. 1.

2.2. Material Properties

The mechanical characteristics of concrete were experimentally determined on six cylinders and six cubes. The average concrete compressive strength determined on cylinders was of 30.55 MPa and 37.30 MPa on cubes. In case of internal reinforcement, the longitudinal steel bars were made of high strength low alloy steel bars with f_y = 300 MPa, while the transverse reinforcement was mild steel stirrups with f_y = 210 MPa. For confinement was used unidirectional CFRP sheets with non-structural weaves in the secondary direction to hold the fabric together.

The unidirectional carbon fibre fabric (Sika Wrap Hex 103C), according to the data sheet provided by the manufacturer, has a tensile strength of 3,793 MPa, an elastic modulus of 231,000 MPa and an elongation at break of 1.5%. The fabric was glued to the specimens with an epoxy resin (Sikadur 300VP) having the tensile strength of 55 MPa, an elastic modulus of 1,724 MPa and an elongation at break of 3%.

2.3. CFRP Application Technique

In the present experimental program the wet lay-up technique was applied in order to obtain a full CFRP confining system. The CFRP wrapping process included surface preparation and unidirectional CFRP application. At the mid-height of the column was applied a 600 mm wide CFRP and at both ends there was applied a 300 mm wide CFRP strip, resulting an overlap of 100 mm reffering to the longitudinal direction of the column. The overlap of the CFRP strips in the transversal direction of the member was equal with the side of the cross-section. At both ends of the specimens one additional 200 mm wide CFRP strip was applied in order to avoid premature failure.

In the process of CFRP application, first the specimen corners were rounded and the concrete surface was grounded. Then, using an industrial vacuum cleaner, dust and any foreign particles have been removed from the concrete surface. The CFRP fabrics were precut at the desired dimensions and were impregnated into the resin. The epoxy resin was then applied straight on the prepared substrate and the composite strips were placed transversally to the column. Adequate pressure was applied until the resin squeezed out between the fabrics.

2.4. Test Set-up

All columns were subjected to eccentric compression, with the eccentricity of 50 mm in case of the first group of specimens, and of 75 mm for the second one. In order to apply the eccentric load there was designed and manufactured a set of loading plates which were positioned at column ends and at both grips of the universal testing machine as it can be seen in Fig. 2.

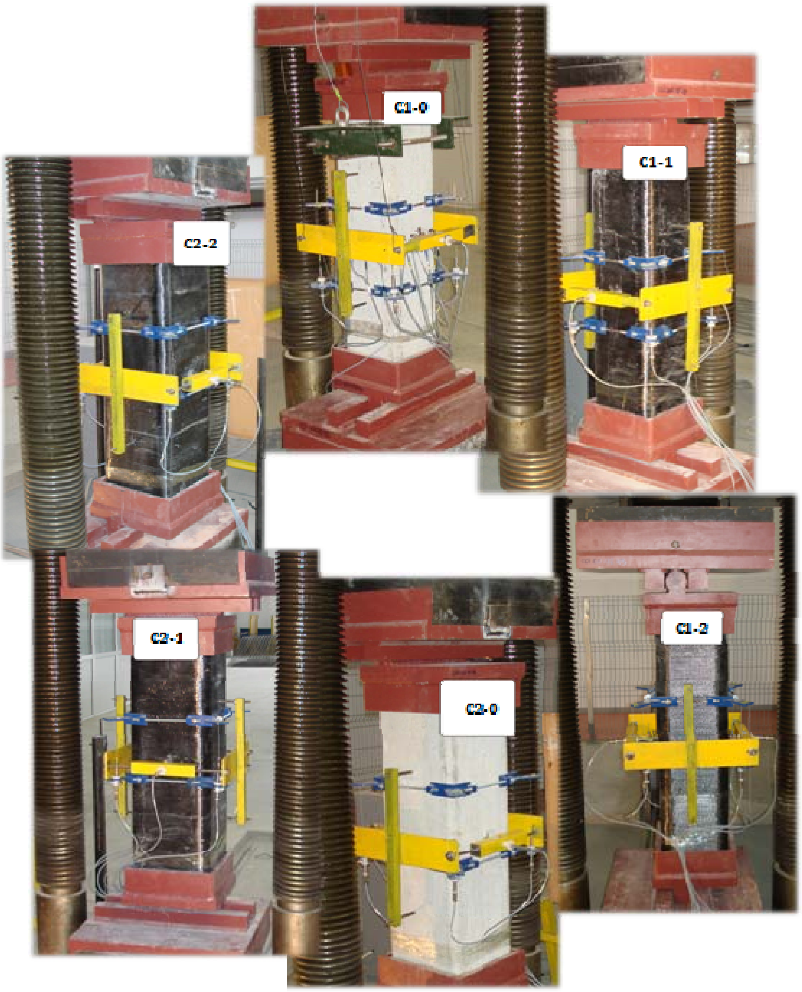


Fig. 2 – Test set-up and instrumentation of the columns.

To read the transversal and longitudinal displacements at the midheight of the specimen there were fixed six linear variable differential transducers (LVDTs) using a special device mounted on specimen. Four of them were used to measure the longitudinal displacement, while the other two LVDTs were used for measuring the transversal displacement at the midheight of the column.

3. Experimental Results

The experimental study was performed under static loading, the specimens being subjected to a monotonous and uniform load up to the peak load. From safety reasons the LVDTs were removed from the specimens when the maximum allowable displacement was recorded, after which the loading process was continued until the failure of the columns. A summary of column specimens configuration and the resulted experimental maximum load are given in Table 1.

Table 1
Configuration of Column Specimens and the Experimental Maximum Load

Group (cross-section) mm	Specimen	Confinement condition	Load eccentricity mm	Maximum load kN
C1 (250 × 250)	C1-0	No wrapping	50	1,391.1
	C1-1	1 layer CFRP	50	2,133.8
	C1-2	2 layers CFRP	50	2,004.9
C2 (300 × 300)	C2-0	No wrapping	75	2,121.1
	C2-1	1 layer CFRP	75	2,295.5
	C2-2	2 layers CFRP	75	2,480.7

3.1. Group C1 of Columns

The failure of the unconfined specimen (C1-0) is due to crushing of concrete at the compressive side. Cracks propagation, both in compression and tension side, were visible before occuring the crushing of the RC member. At the tensioned side cracks were developing in the transverse direction of the member, while in the compressed region was noticed the buckling of the longitudinal steel reinforcing bars (Fig. 3 *a*).

By applying one layer of CFRP (C1-1) there was obtained an enhance of the maximum load with 53.4% compared to the unconfined specimen. During the loading process was noticed the noise produced by the composite membrane due to the service of the composite jacket. At the compressed side, near the midheight of the element, due to vertical shrinkage of the element were visible wrinkles in the FRP membrane. This wrinkles features the unbonding of the FRP material from the concrete substrate in the end on this areas came the failure of the CFRP jacket. Failure of composite material was transversaly to the tensioned carbon fibres. After removing the composite wrap fragments, an advanced degree of concrete crushing was noticed as well as the buckled longitudinal steel bars, meaning that failure of the element occurred as a direct consequence of the jacket rupture (Fig. 3 *b*).

a.

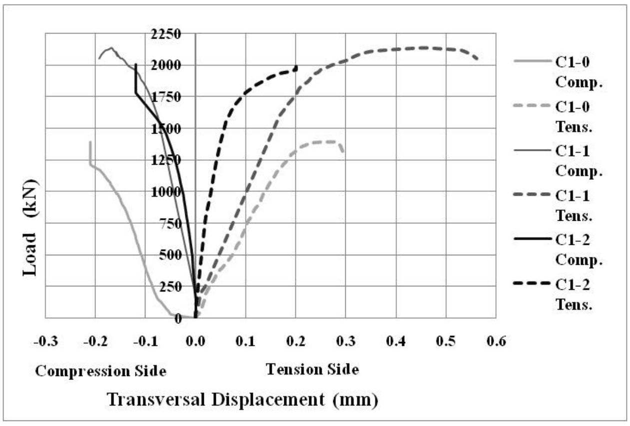
b.

c.

Fig. 3 – Modes of failure in case of specimens from group C1:
a – C1-0; *b* – C1-1; *c* – C1-2.

In case of the element confined with two layers of CFRP (C1-2) the maximum experimental load was of 2,004.9 kN, resulting an enhance of 44.1% compared to the unconfined specimen. The behaviour of this element was similar to the one of the specimen confined with one layer of CFRP, except that the failure occurred at the corners from the compressed side and not due to the wrinkles in the FRP membrane (Fig. 3 *c*).

In Fig. 4 there are presented the experimental load *versus* the mid-height transversal and longitudinal displacement curves for C1 group of columns.



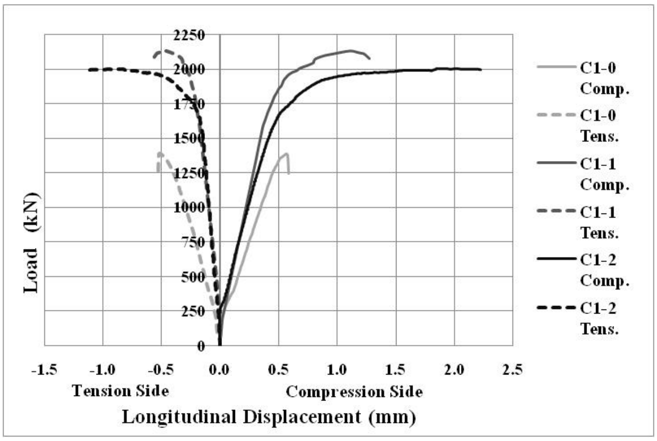
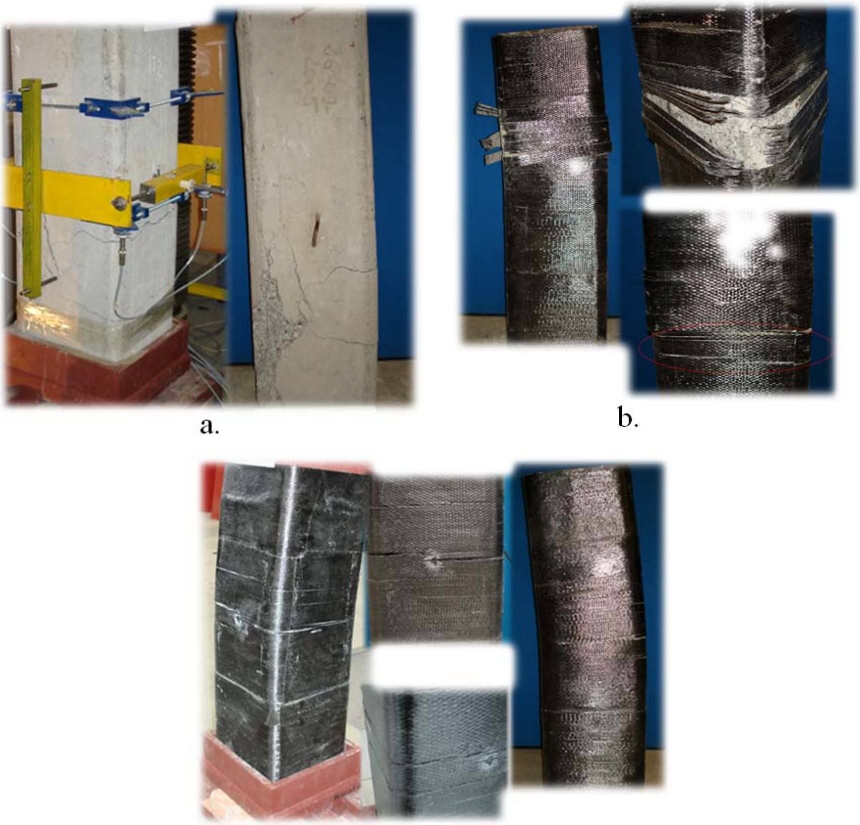


Fig. 4 – Load *vs.* transversal and longitudinal displacement curves; group C1.

3.2. Group C2 of Columns

The specimen C2-0 failed in a brittle manner, without acoustical or visual clear warnings at a load level of 2,121.1 kN. The mode of rip is similar to the one of specimen C1-0. The first cracks were produced at the inferior compressed side of the column. At the compressed side the cracks propagation were by the longitudinal direction of the element, whereat there were cracks expanding transversally at the tensioned side of the specimen. Finally, after removing the crushed concrete, was noticed the buckled longitudinal steel bars (Fig. 5 *a*).

In case of the specimen confined with one layer of CFRP (C2-1), the maximum experimental load was of 2,295.5 kN, an enhance of 8.2% compared to the unconfined column. Even if at the compressed side there were developed wrinkles, the failure of the element was produced due to the rip of the composite membrane in the corner area. The ript was sudden and violent, with heavy noise (Fig. 5 *b*).



a. b.

c.

Fig. 5 – Modes of failure in case of specimens from group C2:
a – C2-0; *b* – C2-1; *c* – C2-2.

The peak load obtained for the column confined with two layers of CFRP (C2-2) was of 2,480.7 kN, an increase of 17% compared to the unconfined column. From safety reasons the loading process was stoped before the rip of the composite membrane. The behaviour of this element was similar with the other confined specimens. At the compressed side there were noticed wrinkles in the CFRP material, but because the stiffness of the composite membrane was enhanced by applying two layers of CFRP at the tensioned side of the element was observed the failure of the unidirectional CFRP membrane on the transversal direction of fibres (Fig. 5 *c*).

In Fig. 6 there are presented the experimental load *versus* the mid-height transversal and longitudinal displacement curves for C2 group of columns.

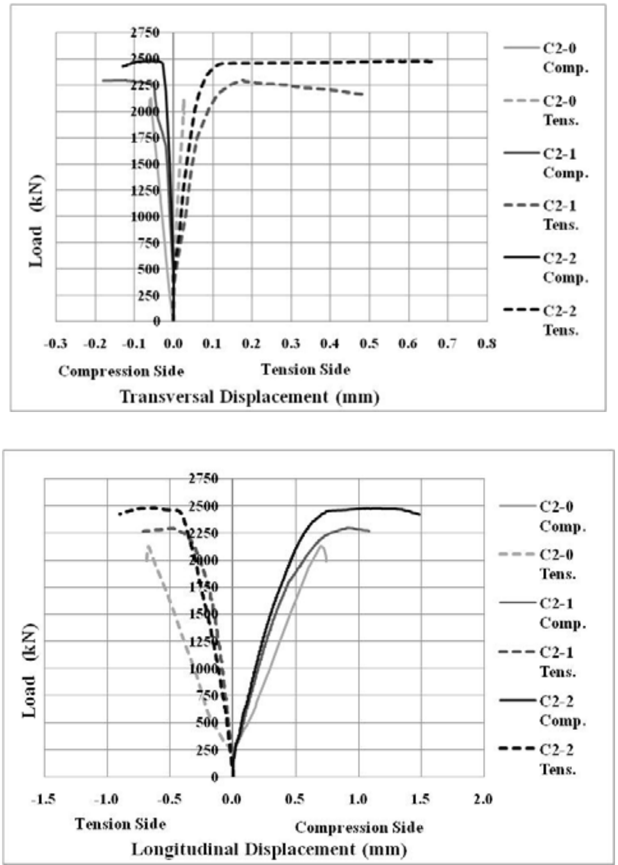


Fig. 6 – Load *vs.* transversal and longitudinal displacement curves; group C2.

4. Conclusions

The use of FRP materials can improve significantly the behaviour of the RC columns. The efficiency of the RC columns confined with CFRP membranes is reduced if the load eccentricity and slenderness are increased. During the experimental program was noticed that the failure of the eccentrically loaded elements occurred at the compressed side. Failure of the FRP confined RC elements depends on the failure of the FRP composite membrane. Further research programmes are required for determining the efficient form of confining eccentrically loaded RC columns.

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STUDIUL EXPERIMENTAL AL STÂLPILOR DIN BETON ARMAT CONFINAŢI CU MEMBRANE COMPOZITE

(Rezumat)

Materialele compozite realizate din fibre imersate într-o răşină polimerică, cunoscute şi sub denumirea de polimeri armaţi cu fibre (PAF), s-au identificat ca o soluţie alternativă la materialele tradiţionale pentru consolidarea şi reabilitarea structurilor. În încercarea de îmbunătăţire a rezistenţei şi ductilităţii elementelor portante din beton armat (BA), aplicând sistemele de confinare, membranele PAF au devenit o soluţie frecvent întâlnită. Studii extinse (experimentale, modelări cu elemente finite şi modele analitice) au fost desfăşurate în vederea determinării efectului de confinare la stâlpii din BA încărcaţi centric. În sistemele structurale pe cadre reale, stâlpii nu sunt solicitaţi doar axial, ei fiind supuşi la variate încărcări şi combinaţii de încărcări. În prezent, studiul stâlpilor din BA confinaţi cu materiale compozite supuşi la compresiune excentrică, reprezintă o noutate şi are un caracter limitat. Sistemele de confinare cu PAF sunt mai puţin eficiente în cazul solicitărilor excentrice faţă de cele centrice, dar chiar şi aşa soluţia este aplicată şi utilizată în mod eficient. Un program experimental extins cu privire la testarea performanţelor stâlpilor din BA consolidaţi la exterior cu membrane PAF, supuşi la compresiune excentrică, este în desfăşurare iar rezultatele parţiale sunt prezentate în acestă lucrare.