Abstract: - The Composite in Construction Research Group (CCRG) developed within the Faculty of Civil Engineering and Building Services Iasi, Romania has a good expertise in implementing Fiber Reinforced Polymer (FRP) composites based solutions for strengthening structures made of traditional materials such as reinforced concrete, masonry, timber and, more recently, steel. In an extended research program, the effects of external carbon FRP wrapping of non-circular reinforced concrete (RC) columns loaded in axial/eccentric compression have been studied. Results obtained on square, RC, externally CFRP wrapped columns loaded in eccentric compression are presented and commented. Experimental laboratory works are backed-up by a numerical Finite Element Method (FEM) based modeling. Although the FRP confined columns have an improved overall structural response, the effectiveness is diminished due to the load eccentricity.

Key-Words: - FRP confinement; square RC columns; Eccentric loading, FEM Modeling

1 Introduction
Fiber Reinforced Polymers (FRP) based confinement efficiency has been extensively studied and validated in case of centrically loaded circular concrete columns. However, this type of elements in real practice cases is relatively rare.

The interest in structural strengthening procedures based on using FRP in case of non-circular cross-sectioned, eccentrically loaded RC columns, yet of less efficiency, is fully justified against “traditional”, heavy steel caging/plating techniques [1].

Natural scale, RC square cross-sectioned columns have been studied under eccentric loading conditions and various external carbon FRP confinement configurations. The experimental program consists of tests performed on two sets of square RC columns (250x250mm and 300x300mm in cross-section, 1000mm in height) under eccentric compression loading conditions.

The 250x250mm cross section columns have also been studied in a finite element method (FEM) based modeling using the specialized LUSAS software, with positive results.

This study brings a contribution to understanding the structural behavior of FRP confined concrete columns under eccentrically loading conditions. It adds useful information on this new strengthening technique.

2 Experimental tests
Two sets of columns, C1 and C2, as described in Fig.1 and Table 1 have been tested.

![Fig.1 Internal reinforcement layout of the RC square columns](image)

Table 1 - Column specimens

<table>
<thead>
<tr>
<th>Column set</th>
<th>Name</th>
<th>No. of CFRP layers</th>
<th>Load eccentricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 250x250mm</td>
<td>C1-0</td>
<td>0</td>
<td>50mm</td>
</tr>
<tr>
<td></td>
<td>C1-1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C1-2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>C2 300x300mm</td>
<td>C2-0</td>
<td>0</td>
<td>75mm</td>
</tr>
<tr>
<td></td>
<td>C2-1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C2-2</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>
2.1 Materials
C30/37 grade concrete, with $f_{\text{cylinder}}=30.55\text{MPa}$, $f_{\text{cube}}=37.30\text{MPa}$ experimentally determined characteristics has been utilized [2].

The internal steel conventional reinforcement consisted of $4\phi 12$ high strength low alloyed deformed steel longitudinal bars ($f_{yk}=355\text{MPa}$) and $\phi 6$ mild steel stirrups ($f_{yk}=255\text{MPa}$) (Fig.1).

The external CFRP membrane was made of SikaWrap Hex 103C unidirectional carbon fiber fabric (3,793 MPa – tensile strength; 234,500 MPa – elastic modulus; 1.5% elongation at break) [3] and Sikadur 300 epoxy resin (55 MPa – tensile strength; 1,724 MPa – elastic modulus; 3% elongation at break) [4].

The wet lay-up procedure was used and led to a 1.016mm thickness per applied layer.

2.2 Test set-up
The eccentric loading was performed under an incremental monotonic manner, up to failure.

Especially designed steel boxes have been used to obtain the specified eccentricities.

![Fig.2 Experimental set-up of columns](image)

Four longitudinal linear variable differential transducers (LVDT) – disposed at corners – and two LVDTs – placed on opposite faces – at columns mid-height (Fig.2) have been utilized to monitor the deformation process.

3 Results
Maximum load values as well as LVDT recordings during the loading procedure have been processed and presented herein.

Notes regarding structural events have been done and discussed in the subsequent subsections.

A first set of results, in terms of maximum load values (Fig.3) and load-displacement curves (Fig.4) are presented herein.

![Fig.3 Maximum load values for the two set of columns](image)

The results reveal the substantial influence of eccentricity in reducing the ultimate load of all specimens. As a comparison, the authors have obtained, in case of a 200x200mm square section, 1 layer wrapped RC axially loaded column an ultimate load level of near 3000KN.

![Fig.4 Load – longitudinal displacement for the 1st set of columns (Tension - Compression side)](image)

3.1 C1 set of columns
The failed C1 columns are presented in Fig.5.

![Fig.5 C1 columns feature after testing](image)

An increase with 53.4% in the maximum load value was gained in case of C1-1 as compared to the C1-0 column.
For the C1-2 column, an increase of 44.1% in maximum load level was obtained (Fig. 3).

In this context, the axial stress – axial/ transverse strain curves are considered to depict the behavior of the studied elements.

In the C1 columns case, the obtained curves are presented in Fig.6 and Fig.7.

3.2 C2 set of columns
Increases with 8.2% and 17% in the maximum load values were gained in case of C2-1 and C2-2 columns, when compared to the C2-0 column. These values may not recommend the FRP strengthening solution when analyzed in terms of economical efficiency.

In this case, alternative strengthening systems might be considered for cost reductions [5].

Details of the failed C2 columns are presented in Fig. 8.

Fig. 8 C2 columns set after testing
Axial stress – axial/ transverse strain curves for the C2 columns set are shown in Fig.9 and Fig.10.
3.3 Modes of failure

3.3.1 Un-strengthened specimens (C1-0, C2-0)
The failure of the un-strengthened columns, C1-0 and C2-0, was of a brittle, rather sudden manner. Transverse fine cracks were initiated at the tensioned faces; these cracks developed towards the compressed faces over approximately the mid-heights of the columns.
In a final stage, for both columns, failure was characterized by concrete spalling in the compressed side with clear internal reinforcement buckling (Fig.11).

Fig.11 Close-ups of the failed C1-0 (left) and C2-0 (right) columns

3.3.2 Strengthened specimens (C1-1/2, C2-1/2)
The structural response of the non-strengthened columns up to the unconfined concrete strength is similar to the structural response of the strengthened columns up to the same concrete stress level (Figs.6, 9). This behavior is based on the fact that the composite membrane is passive up to this level [6].
Loss of interfacial bonding to concrete substrate (suggested by development of wrinkles – for C1-1, C2-1 columns, prior to corner region failure, as for C1-2, C2-2 columns) is preventing the composite membrane to exhibit its total structural potential.
An additional comment may be done related to the fact that the stiffer the CFRP wrapping, the higher degree of crushed concrete.

4 FEM Modeling
The finite element modeling of the studied RC square columns is based on the licensed LUSAS software capabilities.
Given the symmetry of the column geometry, support and loading conditions, only half of the volume was modeled, with adequate support conditions (Fig.12). Perfect bond conditions between interacting materials are assumed.
This is not the case of actual hybrid structures behavior [7] but it represents a common approach in modeling practice.

Analyses developed on micro-scale modeling may reduce discrepancies between laboratory and numerical results.

4.1 Finite elements
The later on presented Drucker-Prager material model for concrete imposed, for compatibility issues, the 8 noded, HX8 type 3D solid finite elements.
2 noded BRS3 bar elements have been used for the internal steel reinforcement modeling.
CFRP external membrane is modeled with 4 noded QTS4 type 2D thick shell finite elements.
Details of these elements are presented in Fig.13.

4.2 Material models
4.2.1 Material model for concrete
The LUSAS material library supplies a version of the Drucker-Prager material that is suitable for frictional materials such as soils, rocks or concrete.
The Drucker-Prager form for the yielding function is defined by cohesion ($c$) and friction ($\phi$) parameters. The concrete material parameters are
calibrated against the experimental results and fall within values reported in literature.

In this particular study, \( c = 2.80 - 3.70 \text{MPa} \) and \( \varnothing = 25^\circ - 35^\circ \) have been used as guiding values [8].

4.2.2 Material model for steel reinforcement
Standard stress-strain curves were used for modelling the internal steel reinforcement, with characteristic values as presented in Sub-section 2.1.

4.2.3 Material model for CFRP membrane
A linear elastic material model was adopted for the external composite membrane.

The material parameters have been established using the micro-mechanics of composite media and experimental checking on standard flat coupons [9].

4.3 FEM analysis
4.3.1 Stress distributions
Colored maps of stress distributions obtained in the LUSAS FEM analysis are able to picture the actual behavior of the studied phenomenon. These contours are to complete the laboratory test, associating areas of apparently large stress concentrations to the concrete crushing parts of the column volumes.

Stiffer corner regions are noticeable (Fig.14), as a specific feature of confinement effect exerted by the FRP wrapping.

4.3.2 Strain distributions
Gradual axial strain development over the column height is to be observed in Fig.15. The deformed FEM model follows the overall shape of the laboratory tested column.

4.3.3 Stress-Strain relationship
The FE modeling obtained axial stress-strain curves for studied columns are plotted in Fig.16.

It is worth mentioning that, unlike the case of experimental results, the common elastic modulus for concrete in tension and compression stress states is noticeable.

Fig.16 Axial stress – axial strain curves for the C1 columns set (LUSAS FEM)

Fig.17 compares the experimentally and numerically obtained results for the compressed side of the C1 set of columns.
4.4.4 CFRP membrane behavior

Strain distributions associated to the principal stress directions for the CFRP external membrane are able to match the longitudinal (related to the column) discontinuities in the transversal (related to the membrane) direction that were experimentally noticed (Fig. 18 vs. Fig. 5).

The stress distributions for longitudinal fibre directions reveal an inefficient use of the material confining characteristics.

5 Conclusions

The paper presents the results obtained from an experimental and numerical study on eccentrically loaded CFRP confined square RC columns. The eccentricity of the axial loading severely diminishes the ultimate load levels of studied elements.

As a common concept, it is considered that providing additional lateral confinement would increase the ductility of columns. Although no detailed quantitative assessment has been presently performed, clear increases in this direction may be noticed (Fig. 4).

LUSAS software is able to predict the structural behavior of un-strengthened - FRP strengthened square RC columns in eccentric loading. With proper model parameters calibrations, there may be obtained stress/strain distributions that may be used in further studies. The inability to use the entire FRP structural potential requires optimization procedures for cost reductions. FEM based studies, such as the LUSAS present results, may serve this purpose.

References: