Prediction of structural behavior of FRP confined square RC columns using numerical modeling

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Abstract: - The paper presents the capabilities of LUSAS software in predicting the structural behavior of FRP confined square columns by the use of the nonlinear concrete Drucker-Prager material model. The numerical modeling study was intended to accompany laboratory tests in describing the structural behavior of the analyzed structural elements. Results obtained on 1000mm high, 200mmx200mm cross-sectioned, ordinarily reinforced concrete (RC) square columns, in unconfined (UC) and confined (CC) configurations are discussed. Concrete was modeled with 8 nodded, HX8 type 3D solid elements while for internal steel reinforcements 2 nodded BRS3 bar elements were used. For the CFRP confined column, the external membrane was modeled with 4 nodded QTS4 type 2D thick shell finite elements (FE). Appropriate nonlinear material laws were used for steel and concrete, with modeling parameters calibrated based on the experimental results. The results show that LUSAS software can successfully be used for predicting the structural behavior of natural scale RC square cross-sectioned columns confined with external carbon fiber reinforced polymer (CFRP) membranes. Specific characteristics, such as the active area, stress concentrations, stress-strain relationships are satisfactorily highlighted.

Key-Words: - FRP confinement; square RC columns; Drucker-Prager; FE modeling

1 Introduction
The use of external FRP confinement systems for ordinary reinforced concrete columns is one of the most efficient uses of composites in civil engineering. The beneficial effects in terms of strength and ductility enhancement were extensively studied over the last decades in the case of circular concrete columns.

The initial enthusiasm due to spectacular results in case of low strength unreinforced concrete small scale circular cross-sectioned specimens was later on tempered when dealing with more complex actual column configurations.

The paper deals with natural scale square cross-section columns and explores the capabilities of the specialized LUSAS software to capture specific features such as the active area, stress concentrations, stress-strain relationships.

2 Experimental tests
The LUSAS FE modeling experimental work companion was conducted on two 1000mm high, 200mm x 200mm cross-sectioned RC square columns, in unconfined (UC) and confined (CC) configurations.

Normal strength C30/37, with f_cylinder=30.55MPa and f_cube=37.30MPa experimentally determined characteristics was used [1].

The internal steel conventional reinforcement consisted of 4Ø12 high strength low alloyed profiled steel longitudinal bars (f_yk=355MPa) and Ø6 mild steel stirrups (f_yk=255MPa) as in Fig.1.

Fig.1 Internal reinforcement of the RC square columns
In the case of the confined column, the external wrapping was performed using the wet lay-up procedure out of an epoxy resin-unidirectional carbon fiber fabric composite (Sika Wrap Hex 103C [2] – Sikadur 300 [3]).

Both UC and CC specimens were identically instrumented with LVDT type displacement transducers (t0 – t5) and electric strain gauges (m0 – m10) disposed as presented in Fig. 2.

For safety reasons, all the LVDT transducers were removed prior to specimens’ failure.

2.1 Unconfined column, UC
The unconfined column, UC failed at a load level of 1750KN, in a brittle manner, Fig.3b. Feeble acoustical and visual warnings were noticed prior to failure.

The examined concrete volume revealed the loss of the cement paste – aggregate bond, suggesting an inappropriate use of the latter’s potential (Fig.4).

The rupture mode was characterized by progressive crack propagation leading to rapid concrete spalling at the corners. The unprotected longitudinal reinforcement consequently buckled.

2.2 Confined specimen
The confined column, CC failed at a load level of 2750KN, in an explosive, brittle manner, Fig. 5. The examined concrete volume revealed a large amount of aggregate crushing zones, suggesting a better use of its potential, Fig.6.

As shown in Fig.7, there are no significant differences between the behaviors of the two columns up to the failure load level of the UC specimen. The passive type of the external confinement system and its inactivity up to important concrete deformations [4] is assumed to be the cause.

As the load increased, acoustical signs of epoxy matrix cracking marked the engagement of the CFRP wrapping.
2.3 Results

Based on the LVDT longitudinally disposed transducers data and assuming uniform compression stress distribution over the columns cross-section, axial load – displacement curves were developed, Fig.7.

![Axial force-displacement curves experimentally obtained for the two columns](image)

These results were used to calibrate the materials model parameters in the FE modeling.

Readings of the m5 to m8 electric strain gauges attached to the composite wrapping (Fig. 2) point out, in Fig. 8, the uneven engagement of the CFRP membrane in providing lateral concrete confinement.

![Strain distribution along the monitored CFRP membrane surface (m5 to m8)](image)

3 Finite element approach

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 1/4 of the volume was modeled, with adequate support conditions (Fig. 9). This represents a common modeling approach with obvious advantages in reducing the overall model size as well as the running time of the software [5].

![FE LUSAS model structure (concrete/ internal steel reinforcement/ external CFRP membrane)](image)

3.1 Finite elements

Concrete has been modeled with 8 nodded, HX8 type 3D solid elements that are compatible to the later on presented Drucker-Prager material model.

For the internal steel reinforcement modeling, 2 nodded BRS3 bar elements have been used.

In the case of the confined column, the CFRP external membrane is modeled with 4 nodded QTS4 type 2D thick shell finite elements. Details of these elements are presented in Fig.10.

![Finite elements used for concrete, steel and CFRP membrane](image)

Previous uses of this set of elements have been reported to fit, in case of smaller scale columns, quite well the experimental results [6].

3.2 Material models

3.2.1 Material model for concrete

The utilized Drucker-Prager material model available in the LUSAS material library is reported.
to be suitable for frictional materials such as soils, rocks or concrete.

The Drucker-Prager form for the yielding function is given by Equation 1:

$$F(\sigma, k) = \alpha I_1 + \sqrt{J_2} - k \quad (1)$$

where $I_1$ and $J_2$ are the first and the second stress invariants while $\alpha$ and $k$ are constants defining the yield surface, governed by cohesion $- c$ and friction $- \varphi$ parameters. $c = 2.80 - 3.70$ MPa and $\varphi = 25^\circ - 35^\circ$ are recommended to suit reasonably [7].

However, for concrete strength similar to the present case, values up to 10 MPa for cohesion are reported [8]. In the present FE modelling, the concrete material parameters are calibrated to the experimental results and fall within the above mentioned values.

3.2.2 Material model for steel reinforcement
Standard stress-strain curves were used for modelling the internal steel reinforcement, with characteristic values as presented in Section 2.

3.2.3 Material model for CFRP membrane
A linear elastic material model was adopted for the external. The material parameters were set based on the micro-mechanics of composite media and experimental checking on standard flat coupons [9], Fig.11.

Perfect bond conditions between interacting materials are assumed.

4 Results and discussions
4.1 Stress distributions
As it can be noticed from the contours (Fig.12 a, b), the uneven axial stress distributions suggest the uneven engagement of concrete in undertaking the axial compressive stresses.

Unlike the confined circular concrete sections, where uniform confinement pressure is present, square/rectangular confined sections are characterized by the presence of the so-called “active area”. This “active area” is noticeable in case of the two modeled columns, with specific features for the different confinement systems. Similar results are reported in Ref. [10].

In the case of internal steel stirrups confinement, the suggested active area is inscribed in the stirrup contour only. In the case of the external CFRP membrane, the active area spreads over almost the entire concrete section.

The axial stress concentrations around the longitudinal reinforcement bars for the UC specimen are similar to the axial stress distributions in actual RC columns. The absence of these concentrations in the case of the CC specimen suggests the failure of the steel reinforcement.

4.2 Strain distributions
The FE modeling obtained axial stress distributions for both UC and CC specimens are shown in Figs.13 and 14.

Fig.11 Stress-strain curve for CFRP

Fig.12 Axial stress distributions over the mid-height cross-sections of UC (a) and CC columns (b)
The change in overall deformation shape is to be remarked. The characteristic barrel shape presents a larger deformations zone in the middle part of the UC (Fig.13). This is to be compared to the apparently unaffected column extremities observed in the laboratory test.

Fig.13 Axial strains distribution over the deformed UC specimen height

Fig.14 Axial strains distribution over the deformed CC specimen height

In the case of the CFRP confined column, the deformed shape reveals a smoother deformation distribution, as in Fig.14. This is assumed to be in good accordance with the larger crushed concrete volume found when removing the failed wrapping.

4.3 Stress-Strain relationship
The FE modeling obtained axial stress-strain curves for the central point (Point 1) of the column are in good accordance with the experimental results, Fig.15.

4.4 CFRP membrane behavior
The strain and stress distribution maps are in accordance with the experimentally determined CFRP properties. The stiffer corner regions may be noticed again (Fig.17).

Fig.15 Comparative stress-strain curves for the central column point

Middle corner (Point 3) and face (Point 2) nodes were particularly monitored. As it can be seen in Fig.16, stiffer corner regions are also to be observed, as previously reported in Ref [11].

Fig.16 Comparative stress-strain curves for the face (Point 2) and corner (Point 3) column points

Fig.17 Longitudinal strain and stress distributions over the CFRP wrapping
5 Conclusions

LUSAS software is reasonably capable to predict the structural behavior of both unconfined and FRP confined square RC columns in terms of stress/strain distributions.

The LUSAS FEM obtained axial stress distributions over the columns cross-sections highlight the non-uniform confinement effect of both internal steel stirrups and external CFRP membrane.

Results of such type should however be regarded with appropriate reserves given the perfect bond conditions between adjacent materials. This assumption is one of the shortcomings of similar FE modeling approaches.

Nevertheless, the numerical modeling study presented in this paper provides an initial reliable picture on the structural behavior of the approached RC elements avoiding expensive laboratory tests.

References: