Analytical and Experimental Behavior of a Novel Anchorage Layout for FRP Confined Rectangular Columns

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ABSTRACT

In the last two decades, FRP systems have been largely used to improve the performance of structural members, due to their high strength to weight ratio and corrosion resistance. Application of this strengthening procedure in circular columns has resulted quite beneficial in increasing their seismic and axial capacity. Whereas in the rectangular ones, strength enhancement was considerably less. Hence this paper aims in introducing the FRP strengthening mechanism of rectangular columns and highlighting its limitations in strength enhancement when compared to the circular counterparts. The corner radii, aspect ratio and concrete compressive strength effect on the capacity increase rate are evaluated as well, based on the results of the large database provided by different experimental studies performed until now. A novel anchorage configuration is suggested to overcome the existing limitations for enhancement of axial strength in this column category. Analysis of the improvement that this solution provides to the confinement pressure distribution was performed by ANSYS Software. Experimental and analytical results supported the increase of stress distribution uniformity in the anchored rectangular column section.

INTRODUCTION

Structures are in continuous need for strengthening, due to increase in demand, code revision or damages suffered. Their repair and strengthening has been performed with different techniques, from reinforced concrete jacketing (Julio, et al., 2003) (Stoppenhagen, et al., 1995) (Austin, et al., 1995), to steel jacketing (Li, et al., 2005) (Adam, et al., 2009) and recently with FRP materials (Samaan, et al., 1998) (Wu, et al., 2005) (Turgay, et al., 2009) (Doran, et al., 2009). In terms of cost and structural performance efficiency, FRP materials have proven to be superior to other methods in strengthening structural members (Fukuyama, et al., 2000). They are characterized by high strength to weight ratio, low corrosion and ease of installation. Their application has resulted successful in flexural and shear strengthening of slabs (Smith, et al., 2009) (Mosallam, et al., 2003) and beams (Al-Zaid, et al., 2012) (Toutanji, et al., 2006) . On the other hand, column confinement has provided considerable increase in axial (Wang, et al., 2008) and lateral (Zaki, 2013) deformation capacity. However, the increase in axial strength of columns reached the highest levels in circular columns, where the confining pressure is applied uniformly throughout the section. In rectangular columns, though, the strength enhancement reached considerably lower levels, despite the same confinement ratio used (Hu, 2013). This is due to the concentration of stresses in the sharp corners, where the FRP failure in most of the cases occurs. This concentration occurs due to the non-uniform distribution of stresses in rectangular sections. Considering the importance of columns in their structural function and the high rate of occurrence of rectangular columns in most of the buildings, a lot of study and research in improving the strength enhancement in non-circular columns has been going on for the last two decades. Several approaches have been taken, which were focused mainly in the column shape modification. The corner effect was avoided either by rounding them in the desired corner radius, in order to provide a larger area where the corner stresses can be distributed, or by modifying the column shape from rectangular to circular or elliptical by adding extra material, as expansive cement grout in Pantelides and Yan study. Yet, these methods are not completely efficient due to structural condition and cost restrictions. Currently the most used method of strengthening columns is rounding the corners with radii varying from 20mm to 30mm, and installing FRP sheets with a dry or wet procedure. In order to reach a considerable increase in strength either large corner radii (~30mm) or high confinement ratio (layer thickness up to 1.5mm) were used. Investigation of the above mentioned parameters was done on small scale specimens by Rochette Labosiere (Rochette, et al., 2000) producing an increase in strength up to 60%, but with the usage of 0.9-1.5mm thick CFRP layers, and 25-38mm rounded corners. Harris and Carey (Harris, 2003) used GFRP layers for confinement, and with the specimen providing the least confinement (thickness 0.9mm) they got an increase of only 18%. Rousakis (Rousakis, et al., 2007) as well with the least confined specimen with CFRP layer of 0.18mm thickness, and corner radius of 30mm obtained an increase in strength of only 16%. Al-Salloum (Al-Salloum, 2007) used thick CFRP 1.2mm and obtained increase percentages varying from 43%-131% for corner radii of 5mm-50mm, respectively. Wang and Wu (Wang, et al., 2008) tested 150mmx150mmx300mm specimens and for no or 15mm corner radius, with only one layer of CFRP they achieved an increase in strength of about 3%, whereas when the confinement increased to two layers (0.34mm thick) the increase in strength reached the value of 30%. Considering the FRP capacity, more research should be done in effectively using the confinement provided to the columns. This paper aims in presenting the possible improvement of axial strength of columns by providing a novel anchorage configuration to overcome the existing limitation in increasing the axial capacity of rectangular columns. Anchors are employed to distribute the corner stress concentration of rectangular columns into the faces. Experimental and FEM modeling by ANSYS were used to investigate effects of anchors in FRP strengthened rectangular columns.

PARAMETERS AFFECTING THE STRENGTH ENHANCEMENT

Strengthening of non-circular columns has proven to be less efficient when compared to the circular ones (Hu, 2013). Despite the shape effect, even among the rectangular sections set, there is a difference in columns behavior based on their aspect ratio. The higher the aspect ratio of the column, the less efficient is the confinement (Wu, et al., 2010). The faces may be acted upon bending forces due to lateral expansion of concrete, which fall out of only the tensile capacity of the fibers. The stresses are more concentrated in the corners, and failure occurs earlier. As previously mentioned, the corner radius has a considerable effect in improving the confinement efficiency in a proportional relationship. Concrete properties are affecting as well the performance of confinement (Binici, et al., 2007). The lower grade concrete shows a beneficial effect on the confinement process, when compared to high strength concrete. Considering the above mentioned parameters in the confinement efficiency, it can be deduced that the rectangular columns, with high aspect ratio, small corner radius are the most critical ones. Hence improvement in the confining techniques should be implemented, in order to achieve a higher efficiency from the confinement used with them.

FINITE ELEMENT ANALYSIS

Modeling Procedure

Finite element modeling and analysis of the confined columns has been considered the best approach to accurately obtain the stresses and strains distributions, in any section of the specimen. Several models of the confined columns have been produced, simulating the behavior of FRP confined concrete specimens. The most used Software is ANSYS, which has accurately modeled the behavior of different strengthened structural members (Mirmiran, et al., 2000) (Kachlakev, et al., 2001) (Pantelides, et al., 2004). Hence, in order to obtain a thorough view of stress and strain state in the specimen, a specimen confined with CFRP sheet, modeled with ANSYS Software is presented in this section. The specimen dimensions used are 15x15x30cm. Modeling was performed based on Mirmiran approach, using a non-associative Drucker-Prager Plasticity Model. Concrete was modeled with *Solid65*, capable of cracking (in three orthogonal directions), crushing, plastic deformation and creep. CFRP sheet was modeled with *Shell41* membrane element, which has membrane (in-plane) stiffness but no bending (out-of-plane) stiffness. The element has three degrees of freedom at each node: translation in the nodal x, y, and z directions. Previous studies have shown that due to symmetry condition only a quarter of the model can be analyzed and be representative enough of the full model (Pantelides, et al., 2004). Boundary conditions were applied on both ends of the column to simulate the support in the compressive test, by restraining translation in x, y and z directions. Axial load was applied as structural displacement in one end area, and 100 sub-steps were used to perform the analysis.

Analysis Results

In order to obtain a clear view of the stress state with confinement presence, the points where maximum stresses concentrate and the strain distribution pattern, the finite element analysis results are presented here.

i. Distribution of axial stress at the column section plane

Full confinement effectiveness is observed in the section corners, where the maximum stresses are developed as well, as it can be seen in *Fig.1*. Hence corners can be considered as the highest constraint zones, and drop gradually along the diagonal. On both sides of the diagonal, the constraint decreases, reaching the minimum values in the middle of the edges. It’s like an X-shaped stress ridge occurring under the compression load, similar to square concrete columns confined by steel hoops.

Figure 8 Axial Stresses in Midsections

ii. Strain Distribution

In the longitudinal direction, the distribution of axial strain is uniform in the first phase of loading. When approaching the ultimate load the strain is concentrated in the column mid-height. Whereas in the cross section, the fiber strains are always lower in the corners when compared to the faces. This strain state proves again that the confinement in the corners is more efficient than in the faces.

The section- stress distribution in square FRP confined columns is similar to the case when confined with steel hoops. A confining stress distribution in the columns confined with steel hoops is as shown in *Fig.2*. The maximum pressure is concentrated in the corners. The confining pressure in the corners is considerably higher than in the mid-faces, showing that the confinement is not uniform throughout the section. The presence of the X-shaped stress ridge in the FRP confined column, proves the similar behavior of these two categories of confined columns.

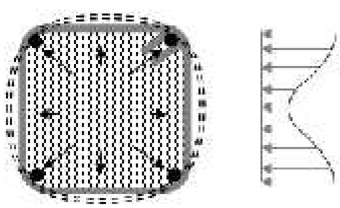


Figure 10 Lateral Pressure Built up in a Square Column (Yalcin, 2000)

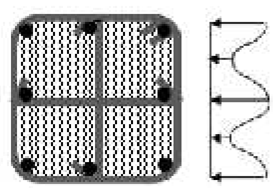


Figure 9 Distribution of Confining Stresses with Additional Hoops (Yalcin, 2000)

Different configurations of steel hoops in the reinforced concrete columns, produce different stress distributions, hence different confining pressures as well. Smaller hoops overlapping each-other within the sections are sometimes used. The addition of these partially confining hoops can affect the section stresses as shown in *Fig.3*. The corner stresses are reduced and the pressure is distributed also to the center of the faces in a more uniform pattern (Yalcin, 2000). This happens due to the increase of the confined area provided by the added steel hoops. This situation can be simulated as well in the FRP confined rectangular columns if the proper distribution of stresses and confinement is provided.

FRP ANCHORAGES WORKING MECHANISM

Previous researches have shown that anchorages can transfer stresses quite successfully from FRP to concrete. They have been generally used to prevent debonding failures, quite common in flexural and shear behavior of FRP strengthened structural members. Different types of anchorages have been used as: *embedded metal threads* (Sharif, et al., 1994) (Shahrooz, et al., 2002), *embedded FRP threads*, *surface mounted rods* (Gose, et al., 2000), and *anchors made using FRP* (Eshwar, et al., 2005) (Orton, et al., 2007). FRP anchors are particularly attractive as they are non-corrosive and can be easily applied to beams, slabs and walls. Anchorages are composed of an embedded portion (dowel) acting in friction, and a fan part which is responsible for accumulating the fiber stresses into the embedded part, and transferring them to the concrete core. The layout of an anchorage is as shown in *Fig.4*. Despite improving the structural performance in flexure and shear, by avoiding debonding failures, FRP anchors have been used also to transfer the fiber forces to other parts of the structure (Ceroni, et al., 2008).

Figure 11 Dry CFRP

The anchor fan can accumulate the corner stresses, and transfer them by the dowel part to the inner core, the confined part, hence increasing the confined area, as addition of steel hoops does. In order to prove this stress distribution, an anchorage strip (*1.25cm wide*)is placed in the middle section of the quarter of the CFRP confined column model as shown in *Fig.5*.

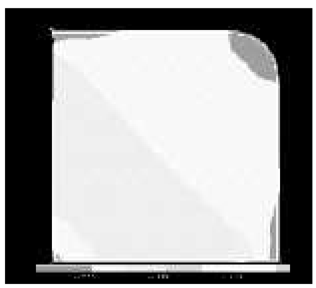
(c) 3-D Anchored Specimen with 1 one Strip

(b) Axial Stress in Anchored Specimen Section

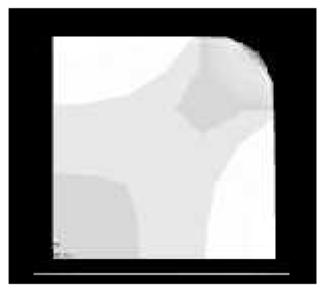
(a) Axial Stress in Un-anchored Specimen Section

Figure 5 Axial Stress Distribution in Mid-section of Column

The axial stress distribution in the midsection of the column, where the anchorage strip is placed changes from the un-anchored model, as shown in *Fig.5*. It is obvious, that the stress concentration only in corner is changed after placing the anchorage strip. It is seen another stress increase near the anchorage (*blue part*) which belongs to the mid-face of the full scale model. Hence the low confinement produced by the faces in the unanchored model is improved with anchorage presence. In the case when two strips are placed in the model, the stress distribution is as shown in *Fig.6*. This stress distribution pattern is quite similar to the reinforced column when steel hoop is placed, as previously assumed. The difference of stress concentration of *corner-midface* parts, is reduced by placing the anchorage. This yields an increase in the confinement area, the stresses can be distributed more uniformly within the section, as in the case of added steel hoops. Moreover the maximum stress in the corner is reduced by 25 % by placing these anchorage strips. With the increase in uniformity of confining pressure distribution, the axial strength enhancement which is directly related to this stress state, can be enhanced as well. Namely when the first cracks occurs, and the concrete starts to dilate the confining pressure acts more uniformly on the surface, decreasing more efficiently the lateral expansion, and due to the Poison Ratio effect also the axial deformation, hence allowing the section to be acted by a higher axial stress level.



(a) Two –strips Anchored Specimen



(b) Un-anchored Specimen

Figure 6 Axial Stress in Specimen Midsection

EXPERIMENTAL PROCEDURE

Specimen Properties

In order to evaluate the changes in stress distribution in the FRP wrapped column, 4 specimens were tested, with two different anchorage layouts. The specimens tested had dimensions of 15cmx15cmx30cm, corner radius 1.5cm, with concrete grade 31MPa. FRP layer properties are shown in *Table.1*.

Table 1 FRP properties

- Fiber Stiffness	230GPa
- Areal weight	230g/m2
- Fabric thickness	0.127
- Ultimate strain	1.6%

The anchorage layouts of the specimens are defined in *Table.2*.

Table 2 Anchorage Properties

Anchorage Properties	**Type 1** *(Fig.7)*	**Type 2** *(Fig.8)*
Embedment depth	4 cm	7cm
Embedment angle	0°	40°
Fan	5cm	9cm
Nr of anchorage per face	1	2
Anchorage Type	Bow	One-direction

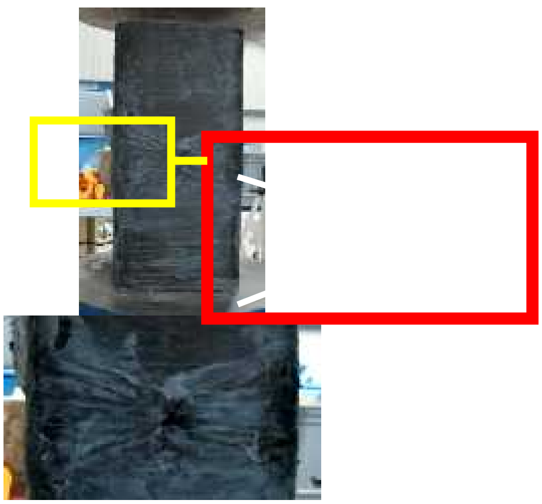


Figure 7 Type 1 Anchorage (*Bow type*)

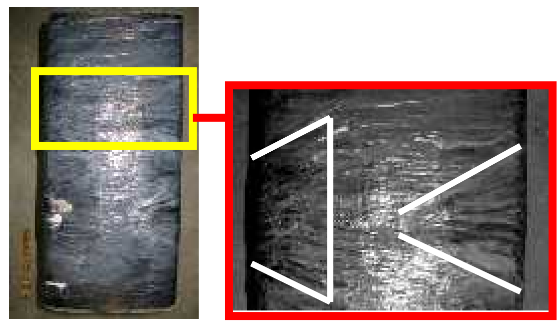


Figure 8 Type 2 Anchorage (*Fan type*)

Experiment Setup

Concrete specimens are first surface grinded, in order to reach a better adhesion of the epoxy to the concrete aggregate. Then holes of the anchorages are drilled and the dust is removed. The FRP layer is placed first after covering the surface with epoxy, and then anchorages are placed as shown in *Fig.9*.

(a) Drilling (b) Grinding (c) Filling holes with epoxy (d) Apply FRP layer over epoxy (e) Anchorage placement

Figure 9 FRP Application Procedure

The resulting anchorages layouts are as shown in *Fig.7* and *Fig.8*. Testing of the specimens is done only in compression with the U-Test Compressive Machine.

Type of failure

In all specimens failure occurred in the mid-face, not in the corner as in *Fig.10.c*, which is the common failure of the specimen without anchorage, but in vicinity of the anchorage (above or below it). The concrete has also crushed in this section. The typical failure mode is shown in *Fig.10*. This proves that the stresses are distributed from the corner to the specimen mid-face, which was the aim of the anchorage in the first place. As previously depicted in *Fig.5* and *Fig.6* stresses which are accumulated in the corner, are reduced and distributed more uniformly within the section.

(a) Type 1 Anchorage (b) Type 2 Anchorage (c) No anchorage failure

Figure 10 Failure of FRP wrapped specimens

CONCLUSION

Rectangular columns confined with FRP, provide only a relatively low enhancement in axial strength when considering the FRP strength capacity, and the quite good performance that FRP shows in the circular columns. This low increase is due to the presence of sharp corners, where the concentration of stresses is maximum, and the low confinement in the faces, which causes the fibers to prematurely rupture in the mid-height of the column in the corners. When analyzing the stress distribution in the FRP confined columns sections, the X-shaped stress layout is similar to the steel hoop confined ones. When adding steel hoops, that wrap a part of the column, the confinement is enhanced with the stresses being distributed more uniformly and not concentrated in the corners, with a high difference with the faces confinement. Hence the confinement is considerably improved. In order to simulate a similar behavior in the FRP confined column as well, FRP anchorages can be used. The fan part of the anchorage can accumulate the stresses of the corner and transfer them to the inner confined concrete core, by proving a hoop-like confinement for that portion where the anchorage is placed. In this case the pressure is distributed more uniformly, with reducing the corner stresses. This behavior is proved with the experimental approach as well, where the failure of FRP did not occur in any part of the corner, even in the places where no anchorage fan was present, but in the mid-face, below or above the anchorage embedding portion. Hence anchorage can transfer the stresses form the corner to the mid-face and based on the embedment depth it reaches it can transfer them in the confined area of the section as well.

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