BEHAVIOUR OF REINFORCED CONCRETE COLUMNS CONFINED WITHCFRP (CARBON FIBRE REINFORCED POLYMER)

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Abstract

In modern world the retrofitting of structures is promoted rather than demolishing and reconstruction of deteriorated structures.Attentionhas also given to increase the load carrying capacity of existing structures to increase the usage capacity or to change the intended usage. Retrofitting of structures using Carbon Fibre Reinforced Polymer materials is accepted as a sustainable and effective method comparatively to most of other well-known methods like steel plate bonding and external post tensioning. This paper presents anexperimental study carried out to understand the effectiveness of external CFRP confinement for square reinforced concrete columns and validation of ananalytical stress strain model,using experimental results. Four reinforced concrete columns, one control specimen without external confinement and three specimens with full external confinement were tested for compression to monitor the strength gain against axial loading. The results showed a considerable increase of the axial strength, about 50% and improved ductility, up to about 20% for the columns with external confinement. The analyticalstress stain modelpresented anacceptable agreement with obtained experimental results.

Keywords: CFRP, reinforced concrete columns, confinement, repair

1. Introduction

As the world is moving towards sustainability aspects more and more daily, sustainability concepts are massivelyapplied for construction industry also. Hence considerable attention has been paid for retrofitting of old structures for increased usability or for alterations of usagerather than demolishing and reconstruction. Thereforesignificant levels of researches have been carried out to find new methods and materials that are more effective in terms of sustainability.

The major materials that could be used for structures are timber, steel and reinforced concrete. In Sri Lanka reinforced concrete is more popular than other materials because of lower labour cost, and hence most of the structures have been built using reinforced concrete.

Although columns vary in physical shape and size depending on their application, typically they are circular or rectangular for the ease of construction. In most cases columns play a major role in structural stability and failure of one such element will incur greater loss than a failure of other elements. Therefore the retrofitting of structural columns should be carried with greater care and experience.

The traditional column strengthening techniques such as steel plate bonding and external post tensioning have their own disadvantages like heavy weight and corrosion of steel.The external bonding of Fiber Reinforced Polymers(FRP) sheets on the surface of concrete columns has gained worldwide interest as a mode of strengthening and retrofitting reinforced concrete structures mainly due to its high strength/stiffness to weight ratio and excellent corrosion resistance. Since the use of FRPs in the civil infrastructures has utilized mostly in the past few years, many of the studies have been carried out through out in the recent past, ranging from design methods, construction techniques, and mechanical properties characterization to durability, etc.

This paper discusses the experimental program that was carried out to study the effectiveness of the CFRP on axial confinement of the reinforced concrete columns and analytical model verification to use in future studies.

2. Objectives and Methodology

Although CFRP retrofitting is accepted as a very effective technology in worldwide, in Sri Lankan context,using CFRP as a retrofitting material is a completely new aspect.Another concern is,lessnumber of researches has been carried out to study the effectiveness of CFRP technology in tropical countries like Sri Lanka.Objectiveof the research is to carry out experimental study to find out strength and ductility enhancement due to external CFRP confinement for axially loaded reinforced concrete columns and comparing the experimental results with an existing analytical model for stress strain behavior of confined columns. Four column specimens, one control specimen and three fully laterally confined specimens were tested for axial compression and results were compared with an analytical model proposed by Harajli[1].

3. Strength enhancement with CFRP

Referring to the case of confinement effects of compressed members externally wrapped with CFRP unidirectional sheets, several theoretical and experimental investigations given in literature [1-9] have stressed the effectiveness of the retrofitting techniques in terms of both strength and ductility improvement. The strength and ductility enhancement is related to the choice of the best type of reinforcing material and its thickness, the shape of the transverse cross section to be wrapped, the height of the member, the grade of the concrete and the presence of the steel reinforcements constituted by the longitudinal and transverse steel bars, the presence of round fillets at the corners of the square of rectangular cross section, the local strengthening technique at the corner with single strips of CFRP before wrapping[1].

Normally the procedure used in strengthening of columns is wrapping the full column with CFRP. However in practice, most of the columns deterioration occurs only in small segments. Hua Wei et al.[2] carried out an experimental study on the strengthening of partially deteriorated columns using CFRP. They studied the possibility of installing partially wrapped external CFRP jackets for strengthening of partially deteriorated columns. An experimental study has carried out for both plain concrete columns and for columns with steel reinforcement. The results show that the both strength and ultimate behaviours of the deteriorated parts have been improved. The load carrying capacity of the entire column improved significantly and significant increase of ductility has also noted.

An experimental study was carried out by Silva[3] about behaviour of square and circular columns strengthened with carbon fibres or aramid fibres. In this study prismatic columns with square cross sections were divided in to three categories according to corner radius of the column. Columns have been tested for axial loading and results showed that an equal strength gain for almost all the cylindrical columns. Columns with square cross sections and sharp corners have shown no improvement of strength nor ductility. It has occurred due to less confinement on flat sides of the columns. This gives a clue that corner radius of square cross sectioned columns will influence directly for the strength gain due to external CFRP reinforcement.

In the tests of Hadi [4], the column specimens were non prismatic, having haunches on one side of either ends. When the load was applied concentrically on the haunches, it created eccentric loads on the test area. The concrete strength of these columns was 100 MPa. Two different wrapping materials, Carbon and E-glass FRP were used. The main finding of the study was that the wrapping column with FRP is an efficient method to increase the strength and ductility of high strength concrete columns when loaded eccentrically.

As strain gauges are used to measure the strain at mid height of the columns in the experimental study it is important to select appropriate gauge length for strain gauges. Brandon and Hamilton [5]have carried out experimental programme to study the effective strain gauge lengths for testing limestone and granite aggregate concrete. Under the experimental programme the attention has given for gauge length, concrete maximum aggregate size, and aggregate type. Theresults have revealed the accuracy of strain gauge improves as the ratio of gauge length to aggregate size increases. However improvements in accuracy are less pronounced for gauge to aggregate size ratio greater than about 2.5. As the concrete used for this test series was made with a maximum aggregate size of 20 mm, minimum gauge length used was 60mm strain gauges. For concrete surfaces 90 mm gauge length strain gauges used while 60mm gauges were used for CFRP surfaces. Accuracy was expected to be higher in CFRP layers because CFRP jacket is more uniform than concrete.

Lot of studies have been carried out with the topic of developing analytical models for axially loaded columns confined with carbon fibber reinforced polymer.Campione&Miraglia[6] has proposed some analytical models to find stress strain relation, ultimate load carrying capacity and ultimate failure strain of CFRP confined reinforced concrete columns. The study has mainly focused on circular columns under axial loading.

Stress Strain relation for CFRP confined rectangular columns has proposed by Harajli[1] and was used in this paper for analytical study as this model takes in to account almost all the parameters that influence the behavior of rectangular reinforced concrete columns confined with carbon fiber polymers.

4. Experimental Study

Under experimental study,four reinforced concrete columns with square cross sections were tested for pure compression. One column was tested as a control specimen (C1) without external CFRP confinement and the other three columns (C2, C3& C4) were tested for full external confinement. All the concrete columns were 175 x 175 x 890 mm in size, confined columns were fully wrapped by single layer of CFRP sheets.CFRP wraps were constituted by unidirectional carbon fibers and fixing was done in such a way that the fiber orientation was perpendicular to the axis of the column. They were glued to the external concrete surface with a special high strength epoxy resin.

4.1 Materials and Specimen Details

Grade 30 concrete was used to cast all the test specimens. Tor steel of 10mm diameter having yield strength of 460N/mm^2 was used in the columns as the longitudinal reinforcement and 6mm diameter mild steel having yield strength of 250N/mm^2 at 120 mm spacing was used for the stirrups in the columns. CFRP properties are illustrated in Tables 1 and 2, respectively.

Table 1:Typical dry fibre properties

Parameter	*Value*
Tensile Strength	*3.79 GPa*
Tensile Modulus	*230 GPa*
Ultimate Elongation	*1.7%*
Density	*1.74 g/cm^3*
Weight per sq.meter	*644 g/m^2*

Table 2: Composite Gross Laminate Properties

Parameter	*Value*
Ultimate tensile strength	*986 MPa*
Elongation at break	*1.0%*
Tensile Modulus	*95.8 GPa*
Laminate thickness	*1.00 mm*

Parameter	*Value*

Table 3: Epoxy Properties

Ultimate tensile strength	*72.4MPa*
Elongation at break	*5.0%*
Tensile Modulus	*3.18GPa*
Flexural strength	*3.12GPa*

The reinforcement details for both confined and unconfined columns are shown in Figure 1.

4.2 Preparation of Test Specimens

CFRP were bonded to the columns after carrying out the surface preparation.All the surfaces of the Columns were made smooth using a rotary grinder. It is important to make the top and bottom surfaces of columns exactly flat to apply uniform load on both surfaces. Then the saturated CFRP layers with epoxy were pasted on to the column surfaces.

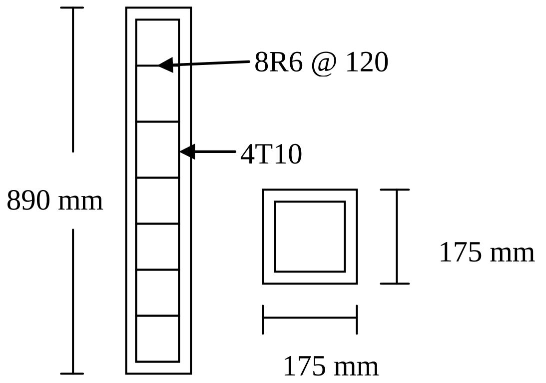

Figure 1: Reinforcement arrangement of test specimens

Figure 2: Fully and partially fibre wrapped test specimens

4.3 Loading arrangement and experimental setup

The loading arrangement and the experimental setup are shown in Figures 3,4 and 5.

Columns were tested using Amsler testing machine with 200 ton capacity under a pure axial compression loading.

To monitor the behavior of columns under loading, two strain gauges and two LVDTs (Linear Variable Deformation Transducers) and one dial gauge were placed accordingly to measure the vertical and lateral strain and vertical and lateral deformation of the columns (Figure 5)**.**

When selecting strain gauges to measure strains in concrete surfaces, gauges with 90mm length was used.Tomeasure strains in CFRP surfaces gauges with 60 mm length was used. The measurements were taken using TDS530 data logger.

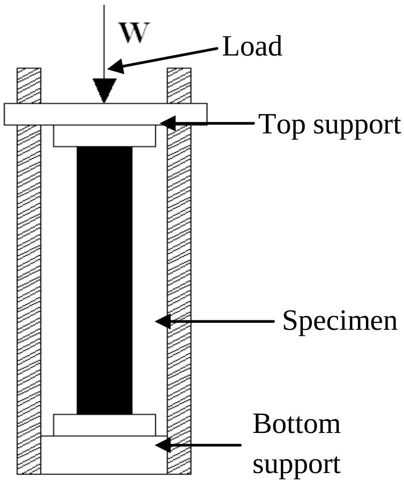

Figure 3: Loading arrangement

Figure 4: Strain gauge arrangement

Figure 5: LVDT and Dial gauge arrangement

4. The Analytical Study

Ananalytical study was carried out to verify a numerical model proposed by Harajli[1]. The intension was to validate the model to be used in future studies in CFRP technology. The proposed analytical model can be used to predict the stress strain curve for CFRP confined concrete columns and takes into account almost all the possible parameters that influences stress strain behaviour of CFRP confined reinforced concrete columns such as the lateral stress and strain, section geometry, corner radius, aspect ratio of plan area, the area and modulus of elasticity of the CFRP material, internal transverse confining steel, etc.

The stress strain curve is divided in to two main stages, namely stage 1 and stage 2 and is defined by two main parameters $f_{co}$and ε_{co} stress and the strain at the intersection of point between the 1st and 2nd stage of the stress strain curve. A typical example for the proposed curve is shown in Figure6.

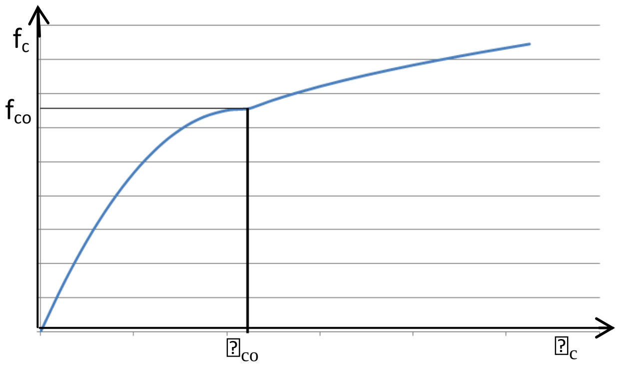

Figure 6:Typical stress strain model

The values of f_{co} and □$_{co}$ can be found using equation 1 and 2.

$$f_{co} = k_1 \epsilon_{l0} \left(E_{lf} + E_{ls} \left(\frac{A_{cc}}{A_g} \right) \right) \quad (1)$$

$$\varepsilon_{co} = \varepsilon_0 \left[1 + (310.57\varepsilon_{l0} + 1.9) \left(\frac{f_{co}}{f_c^{|}} - 1 \right) \right] \quad (2)$$

$$E_{lf} = k_{ef} \rho_f E_f / 2 \quad (3)$$

$$E_{ls} = k_{es} k_v \rho_{st} E_s / 2 \quad (4)$$

Where $f_{co}$is the stress at intersection point between the 1st and 2nd stage of the stress strain curve and $\varepsilon_{co}$is the corresponding strain. $k_1$is an experimental coefficient that is used to convert effect of lateral confinement pressure in to axial stress stain behaviour. Harajli[1] has used a value of 4.1 for *k1*and similar study has done by Campion and Miraglia[6] and have used a value of 2 to obtain a better correlation between experimental and analytical model. However in the present study a value of 4.1has used as it gives more acceptable correlation for predicted ultimate strength and strain capacity. $\epsilon_{l0}$is the strain of lateral steel at yield point if transvers hoops are provided, otherwise it is used as concrete strain at failure. Value of 0.002 is used for ϵ_{l0} assuming the effect of ties for lateral confinement is comparatively less than providing hoops. The term $E_{lf,}$ defined in equation 4 is to calculate the lateral confinement effect due to CFRP and$E_{ls,}$ defined in equation 5 is for the lateral confinement effect of steel.

$k_e(k_{es},k_{ef})$ = $A_e/A_{cc}$and A_e is defined as effective confined concrete area, that influences the effectiveness of lateral confinement in confining the concrete in the horizontal plane. $A_{cc}$is the area of concrete core. ρ_f,ρ_s,ρ_{st} are volumetric ratios of CFRP material, longitudinal reinforcement and transverse hoop reinforcement. k_v is a coefficient that defines the effectiveness of lateral confinement in longitudinal direction between transverse hoops or ties. Equations that are used to calculate $k_{ef,}k_{es}$ and k_v for a square section are shown in Figure7 and equations 5, 6 and 7

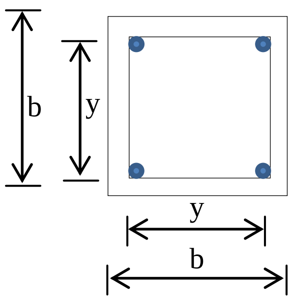

Figure 7:Dimension definition for Kv calculation for a square section

$$k_{ef} = \frac{1}{3(1-\rho_s)} \quad (5)$$

$$k_{es} = \frac{1}{3(1-\rho_{cc})} \quad (6)$$

$$k_v = \frac{(1-s'/2y)^2}{(1-\rho_{cc})} \quad (7)$$

Where $s^{|}$ is the clear vertical distance between horizontal links and ρ_{cc}steel ratio relative to the concrete core section. Equation 2 is to calculate ε_{co},ε_0 is the strain at maximum stress for unconfined concrete, taken as 0.002 as assumed by Harajli [1]. $f_c^{|}$is the characteristic cylinder strength of concrete, taken as 25N/mm^2 corresponding to a cube strength of 30 N/mm^2.

Then 1st and 2nd stages of the curve are defined as shown in equations 8 and 9.

$$f_c = f_{co}\left[\frac{2\varepsilon_c}{\varepsilon_{co}} - \left(\frac{\varepsilon_c}{\varepsilon_{co}}\right)^2\right] \text{ for } \varepsilon_c \leq \varepsilon_{co} \quad (8)$$

$$f_c = \sqrt{(K_0^2 - K)} - K_0 \quad (9a)$$

$$K_0 = 0.0031k_1E_{lf} - f_c^{|} - \frac{1}{2}k_1E_{ls}\varepsilon_{l0}\frac{A_{cc}}{A_g} \quad (9b)$$

$$K = f_c^{|2} + k_1 f_c^{|} E_{ls}\varepsilon_{lo}\frac{A_{cc}}{A_g} - 0.0032k_1E_{ls}f_c^{|}\left(\frac{\varepsilon_c}{\varepsilon_o} + 0.9\right) \quad (9c)$$

The stress strain curve can be generated by substituting the values for ε_c for equation 9c and by calculating stress from 9a for stage 2 and for stage 1 by directly using the equation 8. The upper limit of the curve is defined using another point f_{cu} and ε_{cu} and can be obtained using equation 10 and 11.

$$f_{co} = k_1\epsilon_l\left(E_{lf} + E_{ls}\left(\frac{A_{cc}}{A_g}\right)\right) \quad (10)$$

$$\varepsilon_{co} = \varepsilon_0\left[1 + (310.57\varepsilon_l + 1.9)\left(\frac{f_{co}}{f_c^{|}} - 1\right)\right] \quad (11)$$

Here ε_l should be the maximum lateral strain of CFRP, for ultimate strength and strain prediction a value of 0.0075 (0.75 of ultimate strain of CFRP) used with a slight change to recommended maximum value of ACI guidelines [11] to obtain a good agreement of results.

6. Results and Validation

6.1Experimental Results

The control specimens failed due to the crushing of concrete at its middle.Crack initiation occurred at top of the column. When loading The CFRP bonded columns, cracking sounds was observed at range of 700 KN and showed a noise associated failure. Specimen C3 failed by crushing of concrete due to deboning of CFRP layer at bottom while specimens C4 and C5 failed due to rupture of CFRP layer at lower middle level.

Figure 8 – Failure mode of CFRP confined column specimens C4 and C5

The failure loads are shown in Table 3. It can observed that the ultimate strength of fully confined concrete columns has given a failure load about 150% compared to the unconfined control specimen

Table4. Experimental failure loads

Specimen	***Failure Load***
Control Specimen (C1)	*834KN (1063KN Analytical)*
Fully confined specimen 1 (C2)	*1256KN*
Fully confined specimen 2 (C3)	*1275KN*
Fully confined specimen 3 (C4)	*1226KN*

6.2 Comparison of analytical and experimental results

The analytical stress strain curve and ultimate strength and strain capacity for CFRP confined concrete was generated using method proposed byHarjli[1].

The ultimate strength capacity and strain capacity predicted was 38.59 N/mm^2 at an ultimate strain of 0.0066. This shows ananalytical strength increase of 52.6%. When compared with experimental strength increase of 50.2% (derived from values of table 4) it can be noted that the strength increase prediction is with an acceptable accuracy. The stress strain curves for analytical and experimental studies are shown in Figure 9.

The obtained results were considered as lies within an acceptable deviation as some amount of deviation was expected for non-circular sectioned columns. The variation of experimental curves may occur due to variations in concrete compressive strength and due to casting variations. The specimen failed due to deboning specimen C3 shows the largest variation fromanalytical model where C4 shows the best agreement.

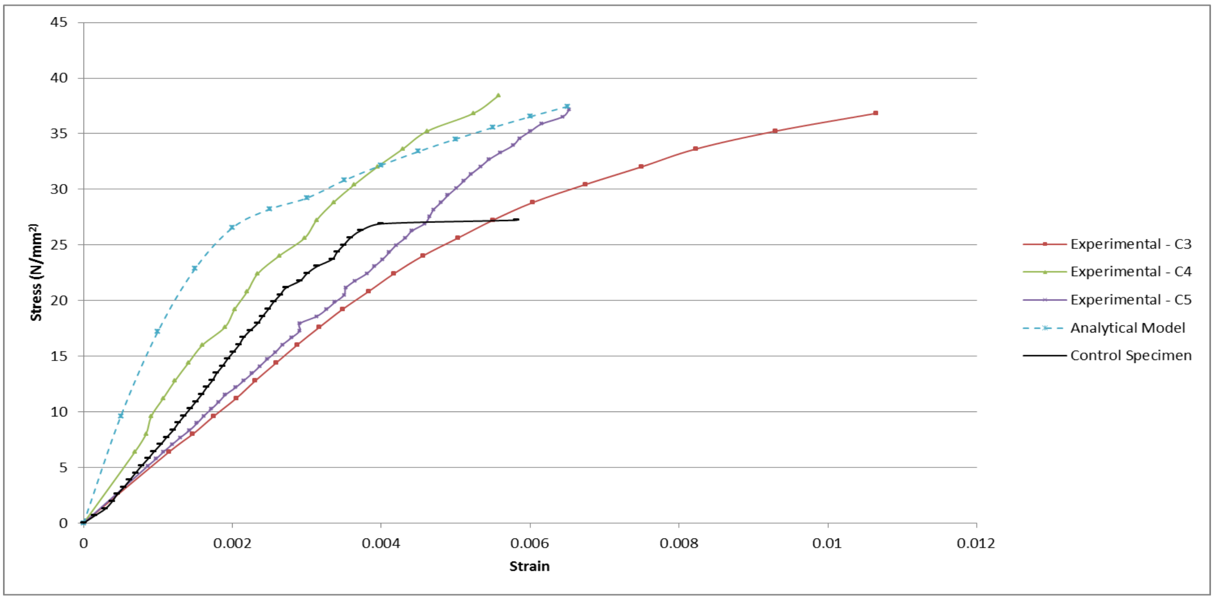

Figure 9: Analytical and Experimental Stress Strain Curves

7. Conclusion

An experimental and analytical study was carried out about the strength enhancement of short compression elements with square cross section due to external CFRP confinement. The experimental results showed a strength increase up to about 150% compared to unconfined control specimen. Using ananalytical model for the ultimate strength capacity, ultimate strain capacity and total stress strain behaviour of CFRP confined column specimen was predicted. It was observed that the predicted ultimate strength gain percentage and experimental strength gain percentage values had anacceptable agreement. It was considered that the obtained analytical and experimental stress strain curves have an acceptable agreement as a slight variation is expected for long, square cross sectioned columns. It is intended to carry out more testing to further verify or adjust the analytical model to obtain a more accurate prediction. This study will have a significant application in retrofitting of reinforced concrete structures.

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