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Evaluating the Efficiency of Carbon Fiber Reinforced Polymer (CFRP) in Increasing the Compressive Strength of Circular Concrete Column

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Abstract

Structural elements that have deteriorated or have become operationally ineffective during their lifetime can be retrofitted by using Fiber Reinforced Polymer (FRP). Instead of demolishing existing structures improving them by using FRP is a relatively new technique and its gaining popularity. Various experimental and analytical studies are being undertaken to evaluate the performance of FRP on enhancing the performance of structural elements. In this study axial compression tests are performed on Carbon Fiber Reinforce Polymer (CFRP) wrapped circular column specimen and the efficiency of CFRP to increase the ultimate compressive strengths of the columns specimen compared to the unwrapped specimen are investigated. Concrete composed of stone and brick aggregate and two different dimension variations are introduced and the effects of these parameters on the confining pressure provided by CFRP is also evaluated in this study.

Keywords: *Carbon fiber reinforce polymer, circular column, compressive strength, stone and brick aggregate*

INTRODUCTION

Improving the operating conditions of deficient or deteriorating structures is becoming a growing concern. Many environmental effects are responsible for the deterioration of structures mainly, corrosion, thermal cracking, freeze-thaw cycles, contact with harmful chemicals and saline water and prolonged exposure to UV- radiations, etc. [1]. Other factors such as gradual loss of strength with ageing, imperfect structural design increase of applied load and damages due to seismic load are also liable for need of improvement of structural elements. Also changes in structural design and safety guidelines may compel the use of structural retrofit technologies. The structural retrofitting process has two methods, i.e., (i) repair and retrofit or (ii) demolition and reconstruction [2]. Due to change in economic and social perspective the former option is gaining more acceptances. Repairing/ retrofitting is a more sustainable solution compared to demolishing and reconstructing due to conservation of resources and less carbon footprint [3]. These circumstances impel the need to prepare suitable retrofit systems to strengthen structures without putting more strain on depleting natural resources and the environment.

Historically, the retrofitting of reinforced concrete structural elements was done by removing affected or damaged concrete or steel part and replacing it with new and stronger material. Currently with advancement in construction technology this practice is substituted with using high strength and cheap FRP composite material. FRP composites are externally applied on structures to retrofit or enhance its capacity. FRP composites have become favorable retrofitting material due to their good engineering properties. Some useful intrinsic properties of advanced FRP composites are high specific strength to density ratio, high stiffness, greater resistance to fatigue stress, high damping and low thermal coefficient (in fiber direction) [4]. Also, installation of FRP composites can be completed easily and rapidly with minimal change in the geometry of the structure. In addition, manufacturing of FRP provides the scope for production in the required shape.

Extensive researches have occurred in the recent years on retrofitting of beams and columns with externally bonded FRP material to study the effect of confinement in enhancement of strength and ductility to provide suitable design guidelines of these members. These studies show significant improvement in factors such as strength, stiffness, ductility and durability. The most commonly used fibers in CFRP composites are carbon, glass or aramid. In some cases, paper, wood and asbestos have also been used as fiber reinforcement in FRP composites [5]. Carbon, aramid and glass FRP's have been effectively used in seismic rehabilitation of bridge piers in USA and Japan [6].

The axial capacity of a concrete column under compression can be significantly improved by providing an efficient confinement using FRP. Under axial loading initially the core concrete begins to crack and laterally expands, which is resisted by the FRP confinement [7]. The volumetric dilation of concrete under compressive loading is resisted by FRP wrap, which provides a confining pressure around the boundary of the concrete member. The confinement provided by the FRP jacket is developed only after the concrete core has undergone hoop elongation. At the beginning of loading axial stress and corresponding axial strain are very low, so the concrete behaves elastically and the transverse strain relates proportionally to the longitudinal strain due to Poisson's effect. With increasing axial stress micro-cracks begin to propagate causing volumetric dilation of the plain concrete [8]. When the load increases more cracks start to form due to dilation of concrete resulting in a large increase of the transverse strain. So, the mechanics of confinement is controlled by dilation ratio of the concrete and the radial stiffness of FRP wrap [9]. Sudden failure occurs when the FRP jacket ruptures.

In a circular concrete column, the confining pressure conveyed by the FRP is uniform around the circumference as illustrated in Fig. 1. When the concrete expands it imparts tensile stress on FRP jacket along the hoop direction. The lateral confining pressure provided by the FRP jacket depends on the amount and strength of FRP and the diameter of the confined concrete. Failure of the column occurs when the tensile strength of the FRP in the hoop direction reaches its ultimate value.

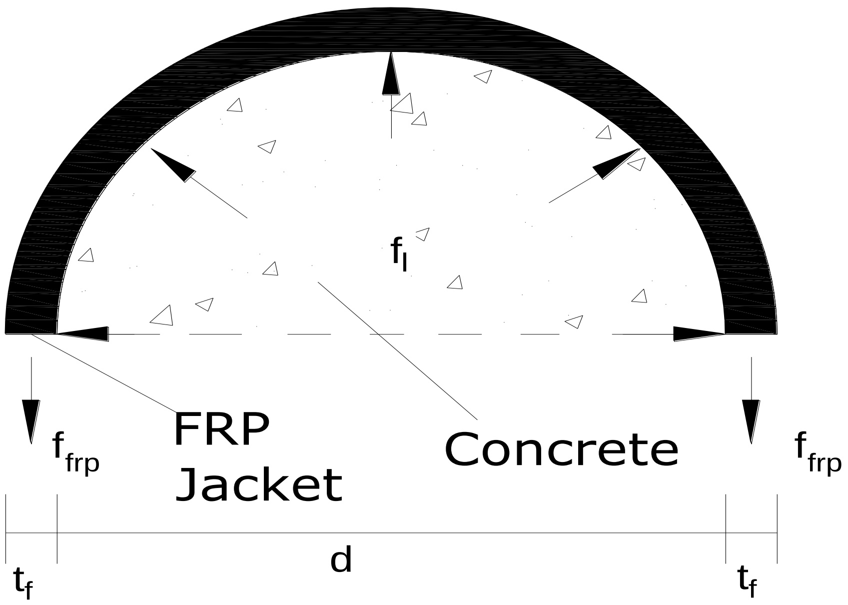


***Figure 1:** Free-body diagram of FRP jacket.*

Note: Here, f_l is lateral confining pressure, f_{frp} is the tensile strength of FRP in the hoop direction and t_f is the thickness of the FRP and d is the diameter of the concrete column.

This work is devoted to investigating the behavior of standard CFRP-confined circular plain concrete columns, under compressive loading. Unconfined concrete columns were primarily tested as control specimen. Single-ply CFRP wraps were used on circular columns of varying aggregates (Stone and Brick) and dimensions. The effectiveness of CFRP confinement in enhancing axial capacity under the prevailing experimental conditions were observed.

LITERATURE REVIEW

FRP composites have been used on a limited basis in structural engineering from the mid-1950s for both new construction and for repair and rehabilitation of existing structures [10, 11]. More attention is paid to the applications from the 1990s. Use of FRP material in aerospace, marine and automobile industries is increasing because of their good engineering properties. Although use of FRP composites as a retrofitting technique is a relatively new branch of study, but relative advantages and ease of use of FRP composites is attracting the interest of research and construction industries rapidly [12−14].

Benzaid and Mesbah investigated the monotonic axial compressive strength of concrete columns wrapped with unidirectional carbon fiber reinforced polymer (CFRP) sheets [15]. To study the behavior of FRP confinement, circular and square specimen were prepared using plain and reinforced concrete. It was determined that in all cases the presence of external CFRP jackets increased the mechanical properties of PC and RC specimens. It was observed that confinement efficiency was greater for circular specimen compared to the square specimen. Results also indicated that rupture of the FRP confinement occurred before the ultimate tensile strength or strain capacities of FRP composites was reached.

Çopur et al., examined the compressive behavior of Ultra-High Performance

Concrete (UHPC) columns wrapped with CFRP sheets and compared the gain in axial strength and axial strain, and their failure modes with unconfined columns [16]. It was found that the unconfined UHPC specimens would undergo brittle failure with a rapid load decrease after the peak load was reached but the failure of CFRP wrapped UHPC columns were more gradual accompanied by an explosive noise at the end. Axial and lateral strain capacity of the unconfined UHPC columns were increased by confining the UHPC columns with CFRP materials.

Hadi studied the behavior of columns under eccentric loads [17]. In this study, vertical FRP straps were used as column reinforcement and then the columns were wrapped with FRP. Two types of FRP material were used, CFRP and glass fiber reinforced polymer (GFRP). The columns were tested to failure by applying eccentric compressive loads and the behavior of the FRP wrapped columns was observed. The experiment showed that columns with CFRP straps and CFRP wrapping performed better than reference specimen without CFRP retrofitting. The results also showed that GFRP and steel reinforced column performed less efficiently compared to CFRP reinforced column under eccentric compressive load.

A.R. Rahai et al., investigated the behavior of CFRP wrapped concrete cylinders under compressive loading [18]. The tests were performed considering different wrap thickness and fiber orientation. The results showed that CFRP wrapped concrete cylinders demonstrated higher ultimate compressive strength, ductility, and stiffness. It was also determined that pure longitudinal orientations of the FRP composite did not significantly increase the compressive strength or ductility of the specimens and its effects could be neglected.

Neagoe investigated the response of retrofitted reinforced concrete beams with CFRP laminates under four-point loading test [19]. Two loading schemes were used, the only difference between them being the distance among the loading forces. Four of the five beams were preloaded until flexural cracks appeared and then retrofitted with CFRP. Two CFRP systems were used for strengthening, consisting of one or two laminates being applied at the bottom face of the beams. Finally, the retrofitted beams were loaded until failure. It was found from the experiment that the externally bonded CFRP increased the stiffness and maximum load carrying capacity of the beams but reduced ductility. The efficiency of strengthening depended on the number of CFRP laminates. Primarily failure mode was found to be de-bonding of CFRP plates.

EXPERIMENTAL PLAN

Materials

Concrete

Crushed stone and brick chips were used as aggregate to produce plain concrete. Total eight specimens were prepared, four of which were of stone and four of brick aggregate. Portland cement was used in the concrete mixture. Two different sizes were mixed to create the coarse aggregate sample. Fifty percent of the aggregate were 1 in. passing and 3/4 in. retained and other fifty percent consisted of 3/4 in. passing and 1/2 in. retained aggregate. The nominal compressive strength of stone concrete and brick concrete were 3000 psi (21 MPa) and 2600 psi (18 MPa) respectively.

FRP Material

Nitowrap 410 epoxy was used as FRP matrix. Nitowrap EP (CF200), uni-directional carbon fiber of weight 200 g/m^2 was used. Nitowrap 30 epoxy primer was used to coat the specimen before wrapping CFRP sheet about its circumference.

Specimen preparation

Dimensions of Column Specimens

Total eight column specimens were tested among which two different size variations were prepared. Four specimen of diameter of 4 in. and height of 8 in. (considered as size 1); four specimen of diameter of 6 in. and height of 12 in. (considered as size 2) were prepared.

Applying the CFRP Wrap

Four columns of each variant were selected as control specimen and the rest were wrapped with CFRP sheets. CRFP was wrapped around the specimens by a wet lay-up procedure. Initially, the columns were ground and cleared of dust and then CFRP was wrapped over primer coated column specimens. In the case of size 1 specimens wrapped with one layer of CFRP, the surface was coated first with a thin layer of epoxy primer then followed by the application of CRRP layer. For size 2 specimens wrapped with one layer of CFRP; 12 in. strips were used to wrap the 12 in. height specimen and two 2 in. strips were used to wrap the end portions of the column specimens as shown in Fig. 2. Also for every CFRP encased specimen there was an overlap of 25% maintained along the length of the CFRP sheets in each layers of application as indicated in Fig. 3. The specimen classifications and configurations are provided in Table 1.

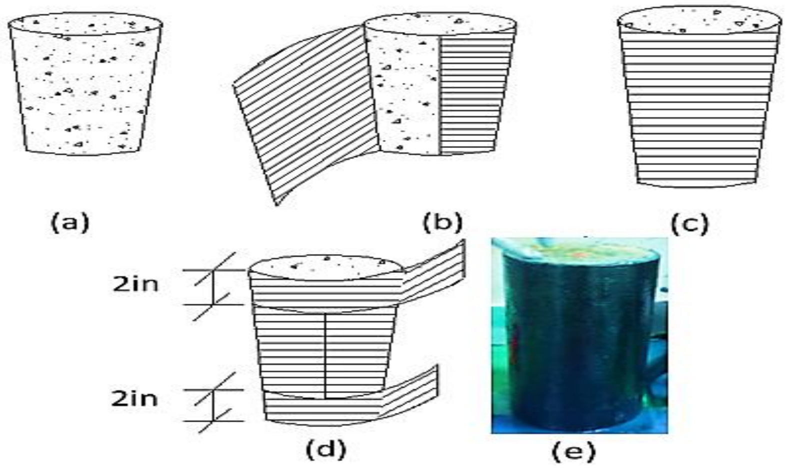


Figure 2: *(a), (b), (c), (d) Schematic diagram of the wrapping process of CFRP on size 2 specimen and (e) One layer of CFRP wrapped column.*

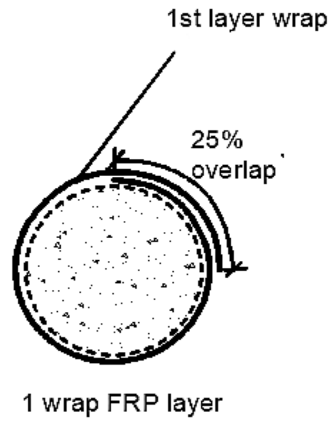


Figure 3: *Typical layout of FRP wrapped specimen.*

Table 1: *Summary of column specimen configuration after wrapping of FRP.*

Test Specimen Id	Size	Height of the column specimen(in)	Diameter (in)	Type of aggregate used	Type of FRP used to wrap	Number of FRP layers	Thickness of FRP layers (in)
BC1CON	1	8	4	Brick	-	-	-
SC1CON	1	8	4	Stone	-	-	-
BC2CON	2	12	6	Brick	-	-	-
SC2CON	2	12	6	Stone	-	-	-
BC1CFRP1W	1	8	4	Brick	CFRP	1	0.0468
SC1CFRP1W	1	8	4	Stone	CFRP	1	0.0468
BC2CFRP1W	2	12	6	Brick	CFRP	1	0.0468
SC2CFRP1W	2	12	6	Stone	CFRP	1	0.0468

Testing and Data Acquisition

Data Acquisition

A universal testing machine of 1000kN capacity was used to test the specimens. Vertical displacement and axial load are recorded from load cell. The stress-axial strain curves have also been plotted using these data. The lateral strain data were obtained using Digital Image Correlation Technique (DICT).

Tests Performed

The following tests were performed to evaluate the performance of FRP material:

- Tension test of CFRP specimen according to ASTM D3039/D3039M-00 [20].
- Compressive Strength Test of control and CFRP wrapped specimen according to ASTM C 39/C 39M-05 [21].

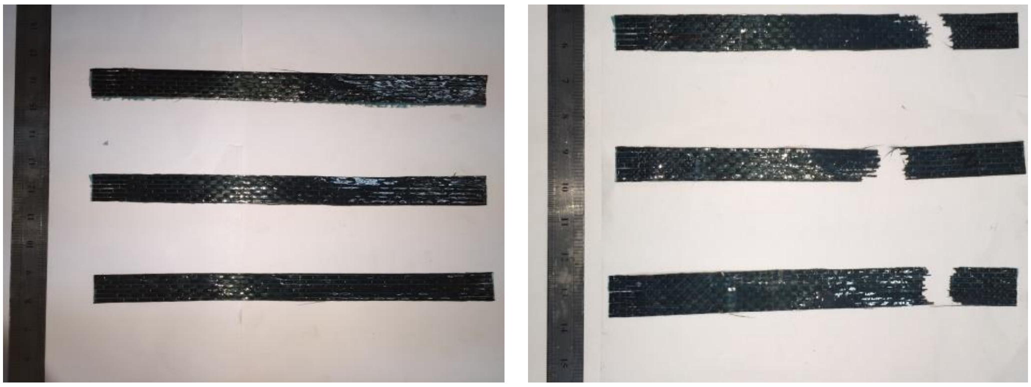
RESULTS AND DISCUSSION

Tension test of CFRP

Unidirectional carbon fiber was used to prepare three CFRP specimens for tension test. The specimens were tested until rupture according to ASTM tensile test standard. The test results are summarized in Table 2. Fig. 4 shows the before and after testing conditions of the tension test specimens.

Table 2: *Tension test results of CFRP coupon.*

Specimens	Ultimate tensile force (lb)	Average ultimate tension force (lb)	Ultimate strength (psi)	Average ultimate strength (psi)
1	1919	1876	42250	48351
2	1715		54640	
3	1995		48165	



(a) (b)

Figure 4: *CFRP tensile test specimen (a) before and (b) after the test.*

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Effects of CFRP Confinement on Circular Concrete Columns

The ultimate condition of failure of the concrete columns, which is basically comprised of the ultimate axial strength of both the CFRP confined and the unconfined columns were recorded at the failure of the specimen. In all cases, CFRP wrapped circular columns achieved greater values of ultimate compressive strength compared to their unwrapped counterpart. The results are represented in Table 3. The resulting stress-strain responses obtained from the compression test are presented in Fig. 5 to 12. The CFRP confinement system significantly increased the compressive strength of the column specimen. All concrete columns exhibited highly ductile behavior when sufficiently confined with CFRP wraps, since the efficiency of axial load carrying capacities are superior for wrapped columns. After reaching peak stress, none of the column specimens displayed any significant load carrying capability. The stress-strain behavior of test specimen under axial compressive load indicated that the CFRP confined specimen dilated significantly and generally lateral strain was greater for brick concretes. The CFRP confined column specimens were able to sustain higher stress and exhibited greater stiffness.

Table 3: *Summary of axial compressive test conducted on FRP wrapped concrete columns.*

CA type	Specimen designation	Confinement type	Size	No. of FRP layers	Max. axial stress psi (MPa)	Axial strain at failure	Lateral strain at failure	Parentage increase in axial load carrying capacity
Brick	BC1CON	-	1	-	2643 (18.23)	0.0013	0.0012	-
	BC1CFRP1W	CFRP	1	1	7900 (54.48)	0.0037	0.0052	198.94
	BC2CON	-	2	-	2075 (14.31)	0.0008	0.0105	-
	BC2CFRP1W	CFRP	2	1	6613 (45.61)	0.0025	0.0072	218.66
Stone	SC1CON	-	1	-	3088 (21.30)	0.0013	0.0009	-
	SC1CFRP1W	CFRP	1	1	8909 (61.44)	0.0039	0.0058	188.55
	SC2CON	-	2	-	3311 (22.83)	0.0007	0.0008	-
	SC2CFRP1W	CFRP	2	1	7225 (49.83)	0.0027	0.0060	118.26

Greater confinement efficiency was observed for smaller size 1 samples. For brick concrete, axial capacity of BC1CFRP1W column was approximately 1.195 times greater than the axial capacity of BC2CFRP1W column. For stone concrete, axial capacity of SC1CFRP1W column was approximately 1.233 times greater than the axial capacity of SC2CFRP1W column. It was also observed that for both confined and unconfined sample, circular stone concrete columns with aggregates of higher strength and stiffness provided greater ultimate compressive strength. For size 1 column specimen, axial capacity of SC1CFRP1W column was approximately 1.127 times greater than the axial capacity of BC1CFRP1W column. For size 2 column, axial capacity of SC2CFRP1W column was approximately 1.093 times greater than the axial capacity of BC2CFRP1W column.

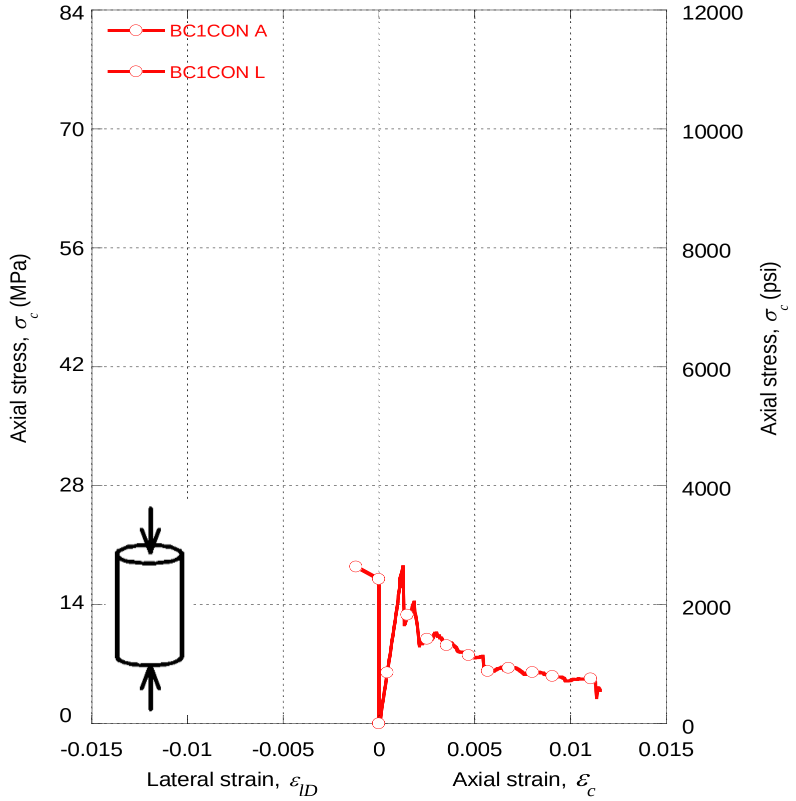

Figure 5: *Evaluation of axial stress v/s axial strain and axial stress v/s lateral strain behavior of unconfined circular plain brick concrete column of size 1.*

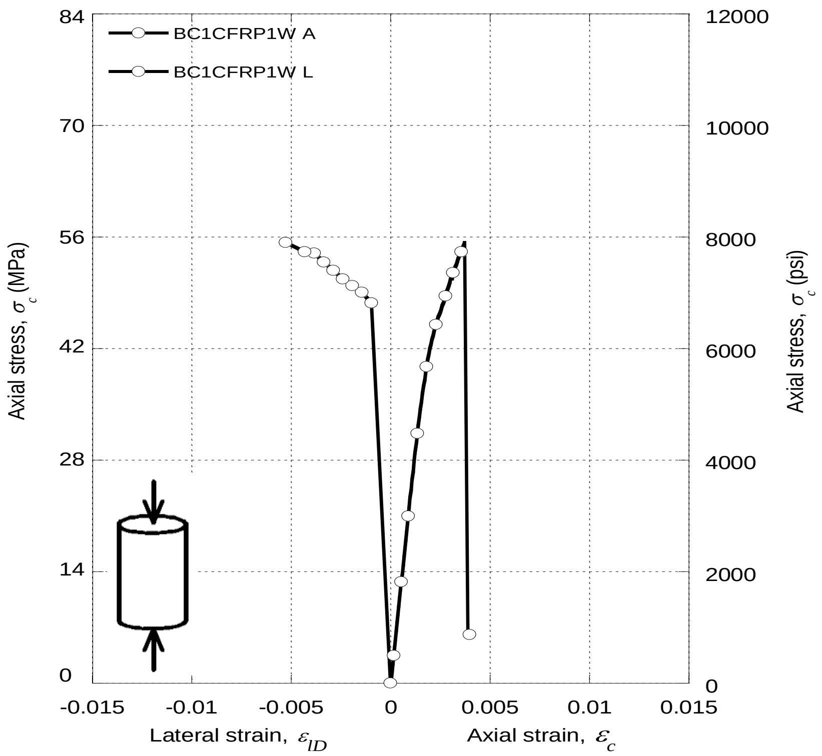

Figure 6: *Evaluation of axial stress v/s axial strain and axial stress v/s lateral strain behavior of CFRP confined plain brick concrete column of size 1.*

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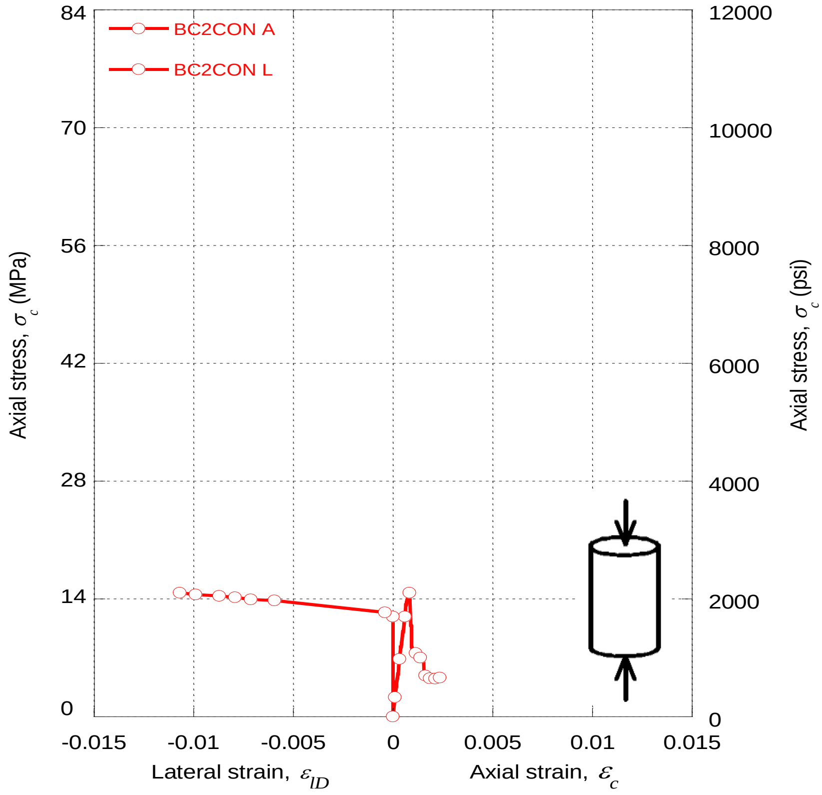

Figure 7: *Evaluation of axial stress v/s axial strain and axial stress v/s lateral strain behavior of unconfined circular plain brick concrete column of size 2.*

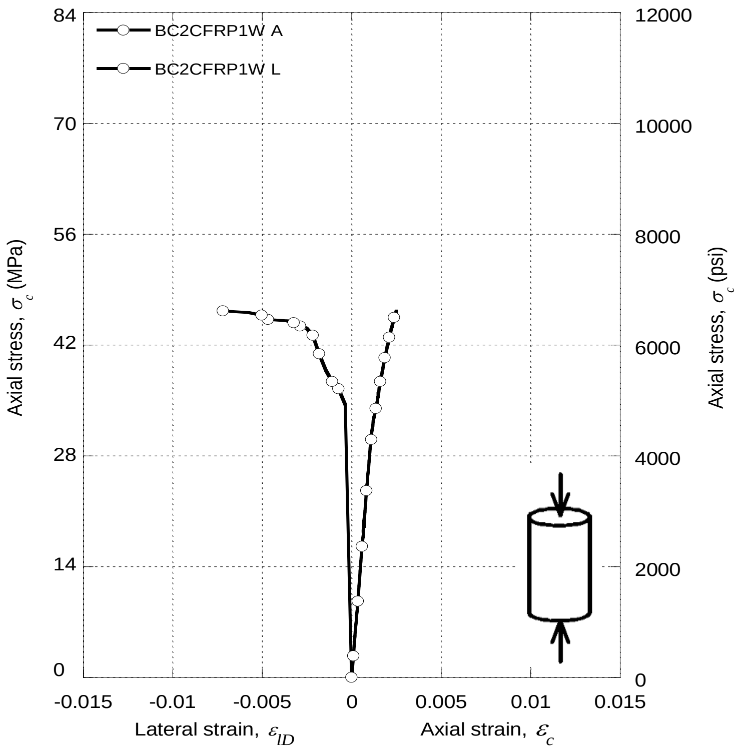

Figure 8: *Evaluation of axial stress v/s axial strain and axial stress v/s lateral strain behavior of CFRP confined plain brick concrete column of size 2.*

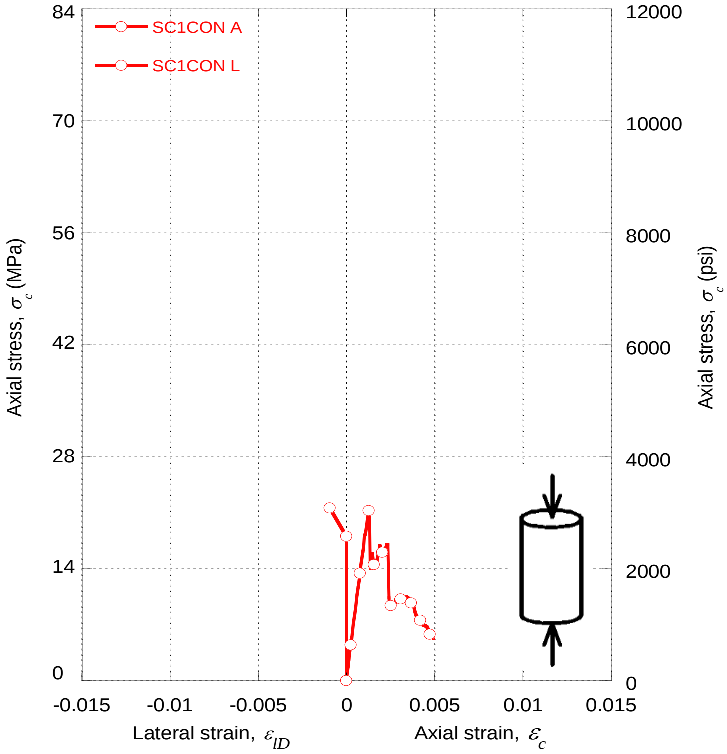

Figure 9: *Evaluation of axial stress v/s axial strain and axial stress v/s lateral strain behavior of unconfined circular plain stone concrete column of size 1.*

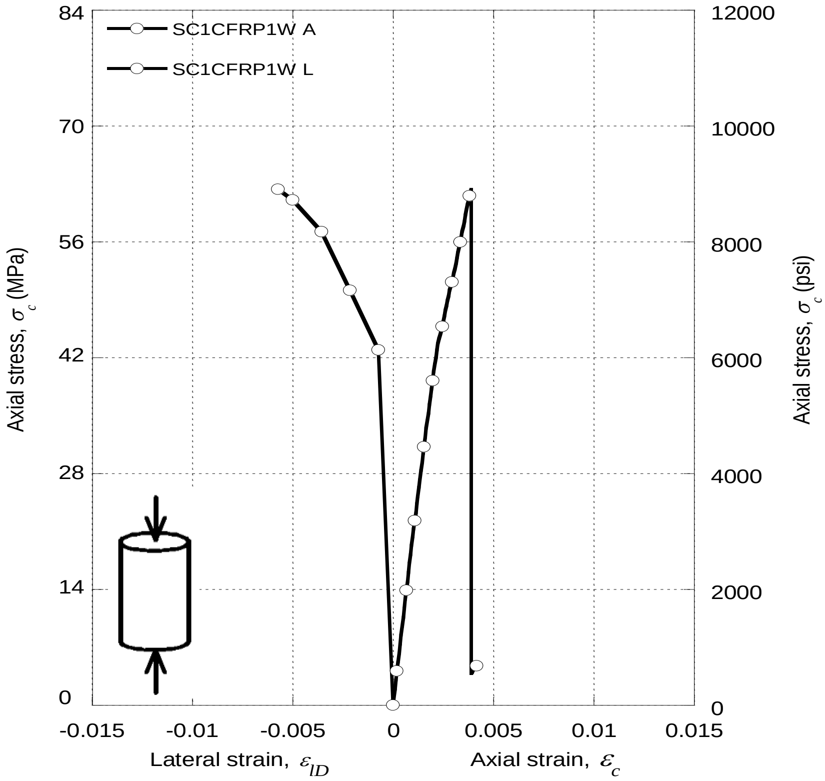

Figure 10: *Evaluation of axial stress v/s axial strain and axial stress v/s lateral strain behavior of CFRP confined plain stone concrete column of size 1.*

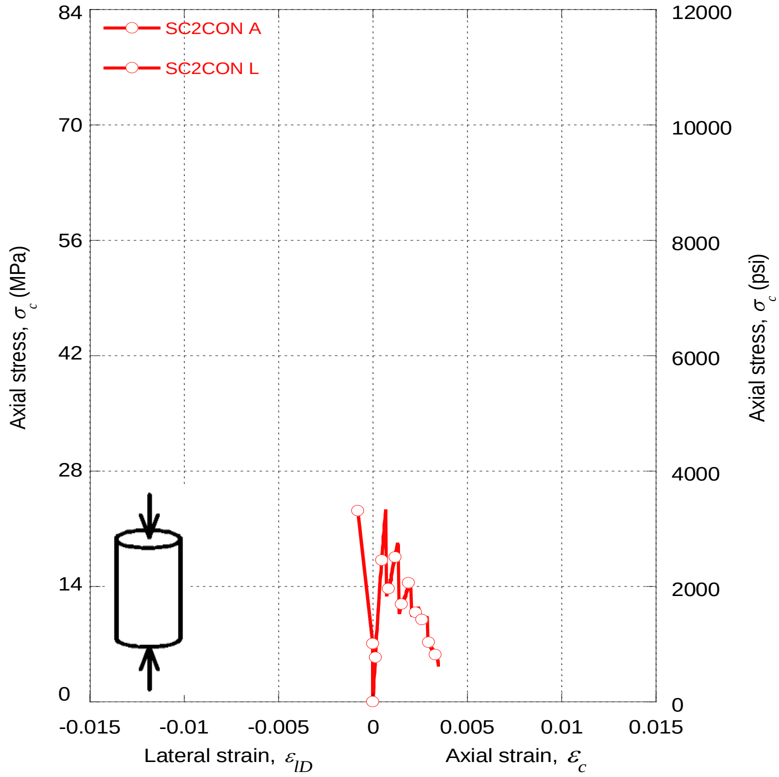

Figure 11: *Evaluation of axial stress v/s axial strain and axial stress v/s lateral strain behavior of unconfined circular plain stone concrete column of size 2.*

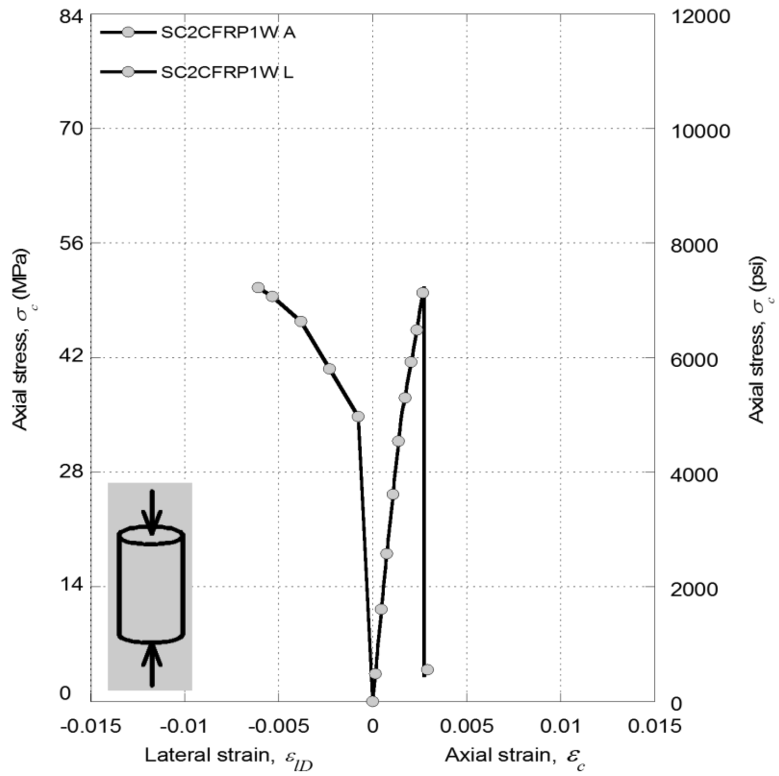

Figure 12: *Evaluation of axial stress v/s axial strain and axial stress v/s lateral strain behavior of CFRP confined plain stone concrete column of size 2.*

Failure Pattern
In case of CFRP, the performance of the columns under axial load was consistent. During the application of the load, small noises were heard representing gradual increase of micro cracks. The samples failed suddenly with loud noise. This type of failure indicates that the confining pressure provided by the CFRP wrap was uniform. By examining the broken samples, it was observed that there was good adhesion between the CFRP warp and the exterior of the specimens, failure did not initiate at overlap zone and no de-bonding of the FRP was observed. The failure patterns of CFRP confined specimens are presented in Fig. 13.

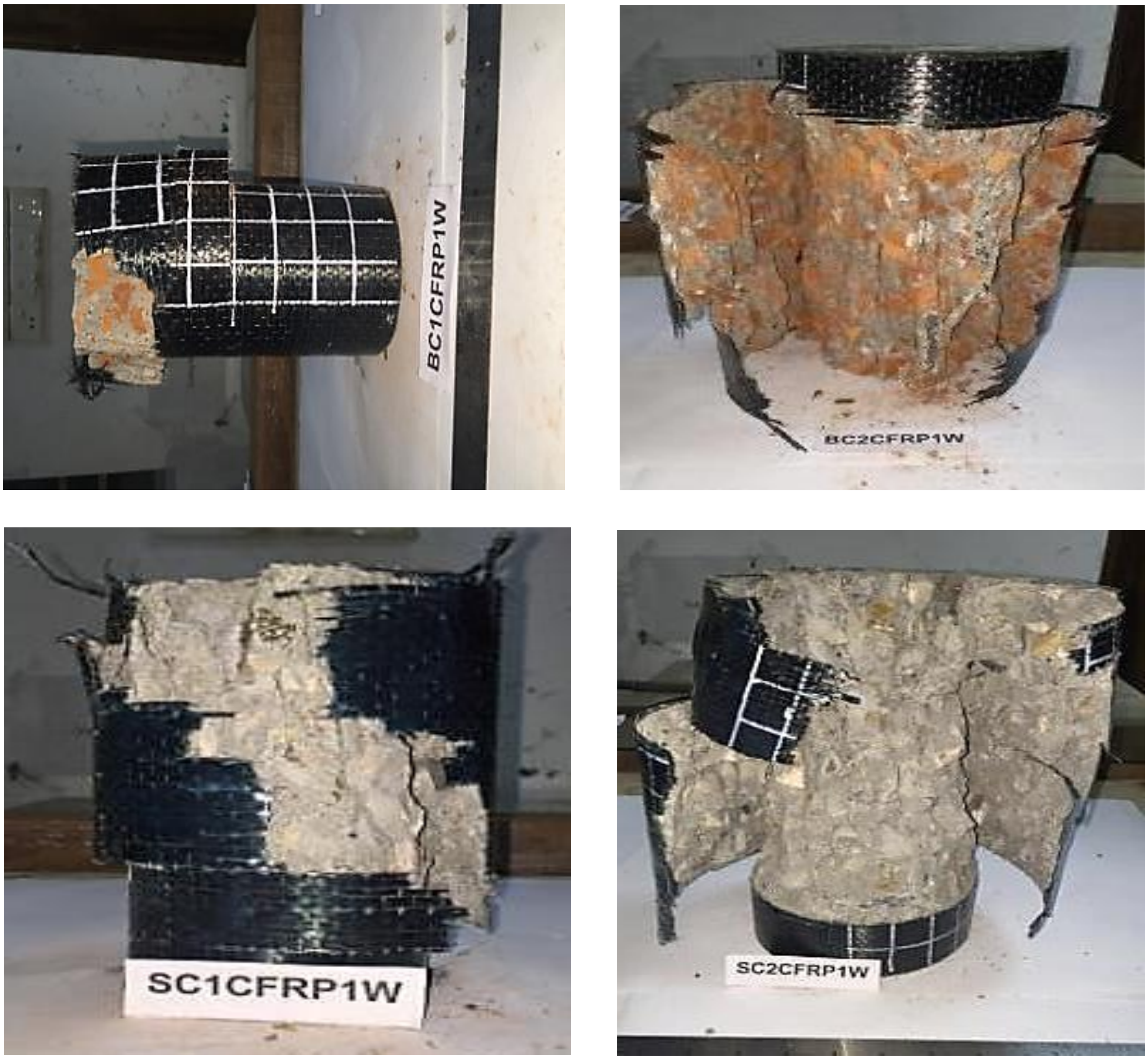

***Figure 13:** Failure patter of (a) BC1CFRP1W, (b) BC2CFRP1W, (c) SC1CFRP1W and (d) SC2CFRP1W sample.*

CONCLUSION
In this experiment four unconfined and four CFRP wrapped circular column specimen were tested under axial compression loading and the corresponding stress-strain responses were analyzed to see its effectiveness in enhancing the axial load carrying capacity of the columns. Variations in column dimension and constituent aggregate were

introduced to investigate their effects on CFRP confinement in increasing the axial compressive strength of the concrete columns. The results of the study showed that, the compressive strength of the column specimens were greatly enhanced by CFRP confinement. The CFRP confined column specimen withstood higher compressive stress, demonstrated greater stiffness and ductility. It was also prevalent that efficiency of CFRP confinement decreased with larger dimensioned samples. Effectiveness of CFRP confinement was also influenced by the aggregate type. CFRP reinforced stone aggregate concrete showed greater strengths than their brick aggregate counterparts.

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