# Behavior of Strengthened RC Columns with CFRP under Biaxial Bending

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## ABSTRACT:

In this work, the behavior of reinforced concrete columns under biaxial bending is studied. This work aims at studying the strengthening of columns by using carbon fiber reinforced polymer (CFRP). The experimental work includes investigation of eight reinforced concrete columns (150*150*500mm) tested under several load conditions. Variables considered in the test program include; effect of eccentricity and effect of longitudinal reinforcement (Ø12mm or Ø6mm). Test results are discussed based on load – lateral deflection behavior, load – longitudinal deflection behavior, ultimate load and failure modes. The CFRP reinforcement permits a complete change in the failure mode of the columns .The effect of longitudinal reinforcement in the case of biaxial bending is more pronounced for strengthened columns than for unconfined columns.

**Keywords: Strengthened، RC Columns، Biaxial Bending، CFRP، Experimental**

## سلوك الأعمدةِ الخرسانية المسلحة و المُقَوّاةِ بألياف الكربون البولمرية المسلحة تحت انحناء باتجاهين

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**الخلاصة:**

في هذا البحثِ تمت دراسة سلوك الأعمدةِ الخرسانية المسلحِة تحت انضغاط مع انحناء باتجاهين. هذا العملِ يَهدفُ لدِراسَة تَقْوِية الأعمدةِ باستعمال اللدائن الكربونية المسلحة. يتضمن الجانب العملي للبحث (8) نماذج من الأعمدة الخرسانية المسلحة (150*150*500ملم) فحصتَ تحت عِدّة حالات تحميلِ. تتضمن المتغيرات التي تم أخذها بنظر الاعتبار في برنامج الفحص ؛ تأثير اللا مركزيةِ وتأثيرِ حديد التسليح الطوليِ (Ø12 ملم أو6 Ø ملم). نوقشتْ نَتائِج الاختبار مستندة على سلوك الحملِ - الهطول الجانبي و سلوك الحملِ - الهطول الطوليِ و الحمل الأقصى وأنماط الفشلِ. التقوية باستخدام CFRPتغير كليا صيغة الفشل للأعمدة. إنّ تأثيرَ الحديدِ الطوليِ في حالة عزوم الانحناء باتجاهين أكثرُ وضوحاً للأعمدةِ المُقَوّاةِ مِنْها للأعمدةِ غير المحصورةِ .

**الكلمات الرئيسية: تقوية؛أعمدة خرسانية مسلحة؛انحناء باتجاهين؛ألياف الكربون البولمرية المسلحة؛اختباري**

## INTRODUCTION

Confinement of concrete is an efficient technique used to increase the load carrying capacity and/or ductility of a column. It is precisely the lateral pressure that induces in the concrete a tri-axial state of stresses and consequently an increment of compressive strength and ultimate axial strain. The disadvantages that come along with the advantages in FRP applications are namely: lower quality control, and environmental stability (long term performance of certain components of the FRP jacket might not be optimum under different effects like ultraviolet radiation, thermal cycles, and humidity). Rocca et al (2008)

## EXPERIMENTAL PROGRAM

### Specimen Characteristics

Tests have been performed on eight RC columns, 700 mm total length that were constructed for this study. All columns had a cross section of about (150x150 mm)as shown in Fig. 1

In order to apply the moments at the end of column without causing local failure at column ends , two steel caps are used for this goal. The details of manufacturing and using of these steel caps will be shown later.

## SPECIMEN NAMING SYSTEM

**General.** The test specimens have been given descriptive names. The specimen names, as shown in the second column of Table 1, are composed of groups of numbers and letters separated by hyphens. Each of these descriptive groups gives information about some aspect of the column in this order:

**Diameter of Longitudinal Reinforcement.** 12 and 6 refer to Ø12mm and Ø6mm longitudinal bars , respectively.

**Column Statue.** C denotes reference (unjacketed ) while S denotes strengthening .

**Eccentricities.** ex-ey denote biaxial moments

## LOADING CAPS.

A new loading cap was designed based on a loading cap designed by author and the technical staff of the General Company for Mechanical Industries The loading cap has four Ø20mm holes in the internally lower face that allows the thread part of the longitudinal reinforcement passing through them to give more development length in case of eccentric loading.

Each side of loading cap includes three M24 female threads with bolts that fasten the loading cap with the column through 5*100*148mm imbedded steel plates . The steel plates are intended to prevent the column from damage when the M24 bolts are tightened on the column. In addition to these steel plates, other imbedded steel plates (5x150x150) are added on the top and bottom of columns with four holes (Ø15mm for longitudinal reinforcement Ø12mm, while Ø12mm for longitudinal reinforcement Ø6mm) . The advantage of using this steel plate is to protect the column from damage during preparing to test. The final shape , the dimensions of loading cap and the steel plates are shown in Fig 2.

## SUPPORT SYSTEM

The main difficulty during testing columns under eccentric loading especially with high value of eccentricity or at stage of high curvature is the stability of the column ( column may be moved to the opposite side of eccentricity ) . In order to stabilize the column during testing, a support system is added to the testing machine . It consists of four opposite bolts at the top and the base of column in touch with the sides of loading caps with steel balls at their ends shown in Fig 3. These steel balls prevent the support system from contributing in loading capacity of column and constraining the horizontal movement but it allows the longitudinal motion.

Others advantages of the supporting system are moving the column easily inside testing machine until the column reached the intended eccentricity and keeping the column in the constant horizontal position when the column is moving vertically to apply fixation load before test.

## LOADING TECHNIQUE

In case of eccentric loading , a new loading system was developed. This loading system consists of three parts steel shaft with half sphere hole at its end , Ø45 steel ball and

(10x90x90mm ) square steel plate with sector sphere hole at its middle as shown in Fig 4.

The steel shaft can be moving vertically in fixed steel ring, see Fig. 5 . This ring is used for the purposes located the centers of upper and lower bases of the testing machine and prevent steel shaft from horizontal sliding during loading. This loading system ensures that the load still had a constant position during loading when the loading caps rotated on the steel shaft .The center of steel plate was located and the column was moved horizontally using supporting system until it had the intended eccentricity that the column should be tested, see Fig. 6.

## DIMENSIONS OF SPECIMENS

Each specimen had a middle test region 500 mm long and the remaining parts ( each part 100mm long ) are inside the steel caps as shown in Fig 7. This configuration forced general failure to occur in the test region and prevented premature failure at the ends. The imbedded ends also served to stabilize the column during testing and to simulate the general column-foundation or column-slab/beam interface. The test region of 500 mm was about 3.33 times greater than the dimension of the cross section to allow for a uniform strain and stress distribution in this region.

## REINFORCEMENT ARRANGEMENT

Columns were reinforced with four longitudinal rebars with threaded ends ( M11 for Ø12mm and M6 for Ø6mm ) , one located at each corner of the cross section. Each longitudinal bar had washer and nut at its ends imbedded in the column during casting fresh concrete. The nut and washer transmit part of the compression load directly to the longitudinal rebars . In the test region of the specimens, 15 mm of clear cover was provided for the transverse reinforcement in the columns. Transverse reinforcement consisted of 5.74mm deformed dowel. Transverse reinforcement was placed at 72mm to provide the necessary confinement according to ACI 318M-11 requirements. The ties were fabricated with 50-mm extensions on 135-degree hooks. Fig 8 shows reinforcement details.

## CORNER ROUNDING

Corner rounding is a well-accepted procedure that is commonly used when strengthening or retrofitting rectangular RC columns with FRP composites. The importance of the effect of the sharpness of the corners comes into play when one considers the tradeoff between the expense of grinding larger, smoother corners and the increase in jacket performance that comes from this activity. The corners of the square columns are rounded with the corner radius 10 mm.

The grinding machine was used for this task. To insure that the all column edges had approximately the same radius , one quarter of steel washer with internal diameter 20 mm are moving along the column's corner during the grinding .

## JACKETING

The steps of strengthening or retrofitting are followed :

1- The specimens were cleaned by washing with pressurized water and allowed to dry prior to composite application.
2- Just before composite application , the columns were wire brushed and vacuumed as well.
3- Apply the mixed resin Sikadur -330 to the prepared substrate using a trowel in a quantity of approximately ( 0.7 to 1.2 kg / $m^2$)
4- The SikaWrap Hex-230C fabric was cut by scissors to portions at (500*700mm)
5- Placed the SikaWrap Hex -230C fabric onto the resin with a towel until the resin is squeezed out between the roving.
6- In addition to jacket , three strips were added to the column (40*600mm) placed two at edges of column and one at the middle..
7- The CFRP sheets were overlapped 110 mm.
8- As a covering layer an additional resin of approximately (0.5kg/$m^2$) broadcast with the trowel can be added , which will serve as a bonding coat for following cementitiuos coating. details are shownin Fig 9.

## PROPERTIES OF CONSTRUCTION MATERIALS

**Steel Reinforcement**. Two sizes of steel reinforcing bars were used in the tested columns, deformed bars of size Ø12mm were used as longitudinal reinforcement, deformed bars of size Ø6mm were used as longitudinal reinforcement and as transverse ties. The yield stress and ultimate strength are summarized in Table.2.

## COMPRESSIVE STRENGTH ( $f'_c$)

For each batch, the strength of concrete ($f'_c$ ) was determined by testing three standard cylinders ( 100mm x 200mm ) at 28days of age. The properties of hardened concrete are summarized in Table.3.

## CFRP PROPERTIES

The mechanical properties of CFRP fibers are taken from manufacturing specifications and as shown in Table. 4.

## TEST MEASUREMENTS AND INSTRUMENTATION

For the biaxially loaded columns, lateral deflection measurements were taken with two perpendicular directions at the column midheight and 220mm above and below midheight using six dial gages. Axial deformations were recorded using four dial gages over a gage length of 500mm as shown in Fig.11.

## TESTING PROCEDURE.

The hydraulic testing machine shown in Fig.12. The load was applied gradually. At each load increment, readings were acquired manually.

Testing was performed as follows :

1. Putting the column inside the lower loading cap. Then the upper loading cap was placed on the column.
2. Moving the column horizontally using the supporting system until reaching the intended eccentricity.
3. The longitudinal bars that may undergo tension were tightened to the loading caps.
4. The load was applied slowly in increments of (10kN).

## TESTING REAULTS

General observations concerning the failure of the columns, the effects of the various test variables and the behavior of the CFRP jacket are discussed.

### Columns under Equal Moments ( Mx = My )

Four columns were tested under 45 – 45mm value eccentricities , 12C45-45 , 12S45-45 , , 6C45-45 and6S45-45. The results of these tests are shown in the Figs.13 to 17. Fig.4.13 shows that slightly difference in load carrying capacity between control and strengthened columns. Fig.4.16 shows a slightly higher load carrying of control column, compared with the strengthened one. This may be due to the slight drop in compression area of the CFRP column compared to the control one.

### Columns under Unequal Moments ( Mx = 2My )

Four columns were tested under 60 – 30mm value eccentricities , 12C60-30 , 12S60-30 , 6C60-30 and 6S60-30. The results of these tests are shown in the Figs.18 to 24. Fig.4.18 shows clearly a significant improvement in load carrying capacity of strengthened column compared to the control one. Figs.4.22 and 4.23. show that the behavior of the strengthened column is more ductile in the direction of major eccentricity ex compared to the control column. As far as the lateral displacement in the minor eccentricity ey, no such difference in behavior is indicated.

## STEEL REINFORCEMENT EFFECT.

The longitudinal reinforcement has a significant effect on the behavior of columns in their different states. Table 5 shows the percentage of steel reinforcement effect.

In the case of biaxial moments, the effect of the longitudinal steel reinforcement for strengthened columns is very significant. With Ø12mm longitudinal steel, the compression zone is greater than with Ø6mm longitudinal steel. Thus in the former, the influence of CFRP is much more significant_ between 47.7% to 55.6%

increase versus 28.5% to 30.1% for the case of the Ø6mm longitudinal , see Fig.28.

## EFFECT OF STRENGTHENING

Table 6 shows the influence of strengthening with CFRP on the ultimate load capacity. The effect of confinement increased when the percentage of longitudinal reinforcement is increased. For 6S45-45, the ultimate load was less than from 6C45-45 ultimate load. This unexpected result can be explained by noting that the compression zone of 6C45-45 was small as shown in the Fig.4.41. This essentially led to the disappearance of the positive effect of confinement . The drop in load carrying capacity by 7.8% may be due to the reduced column area because of edge rounding. If eccentricity was constant (e) where (e = ex + ey ) the maximum benefit of strengthening can be had when (ex = 2ey).For eccentric load, the strengthened. column failed when the CFRP was bulging at the compression zone.

## CONCLUSIONS

Based on the results obtained from the experimental work, the following conclusions are presented.

1. The FRP reinforcement permits a complete change in the failure mode of the columns. Thus, columns which may have brittle compression failure, will behave in a much more ductile fashion when FRP is used.
2. For eccentric loading, the effect of confinement increases when the amount of longitudinal reinforcement is increased.
3. The effect of longitudinal reinforcement in the case of biaxial bending is more pronounced for strengthened columns than for unconfined columns. The percentages of increase in ultimate load for (C45-45, C60-30, S45-45 and S60-30 ) were (30.1% ,28.5%, 55.6% and 47.7%,), respectively.
4. The effect of strengthening decreased when the eccentricity are increased. Thus , with increasing eccentricity , there will be a need for longitudinally directed fibers.
5. For both 12mm and 6mm bar columns, it was found that at the same total eccentricity (e) where (e = ex + ey ), the maximum benefit from CFRP strengthening occur when ( ex = 2ey ).

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## FIGURES

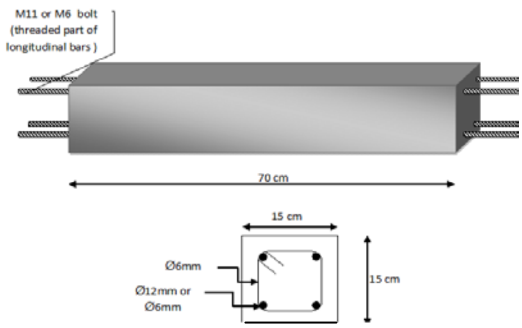
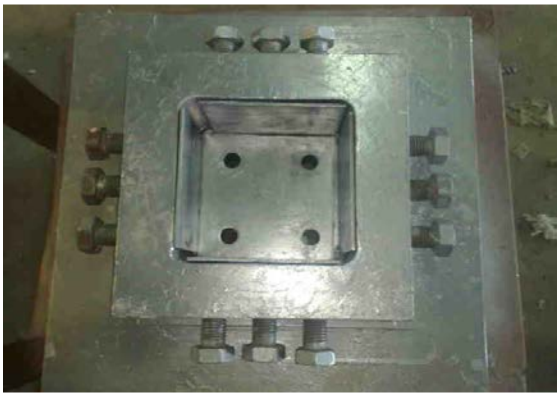
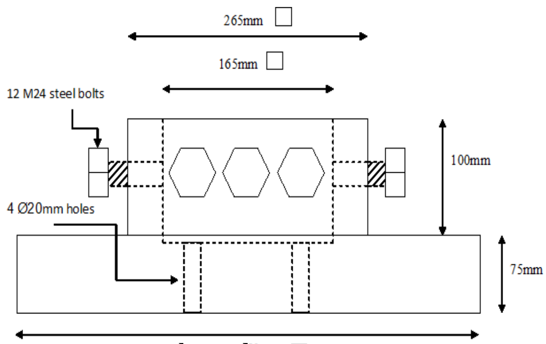



**Fig.1 Column Specimen with Dimensions**



a- Top View




b- Side View

**Fig. 2 Loading Cap**

**Fig. 3 Supporting System**

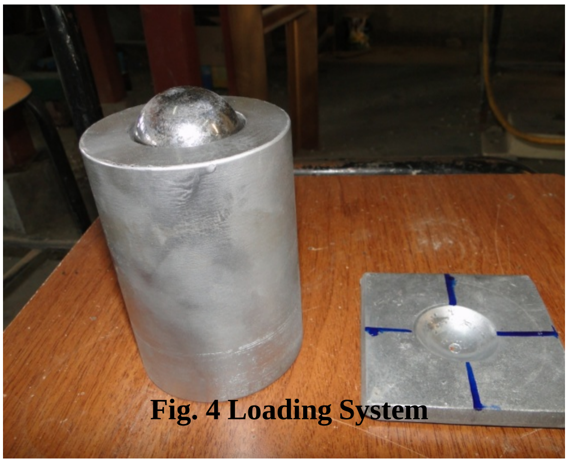


Fig. 4 Loading System

Fig. 5 Steel Shaft Inside Steel Ring

Fig. 6 Loading System During Loading

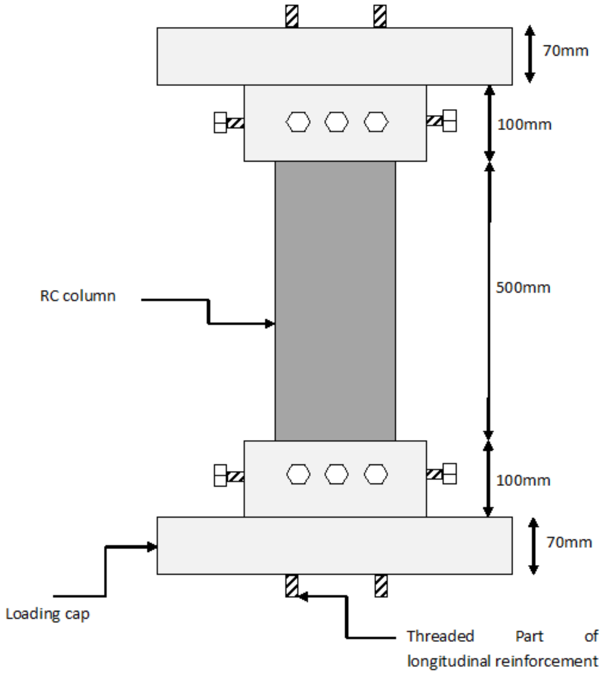



Fig 7. The Specimen Details and Dimensions

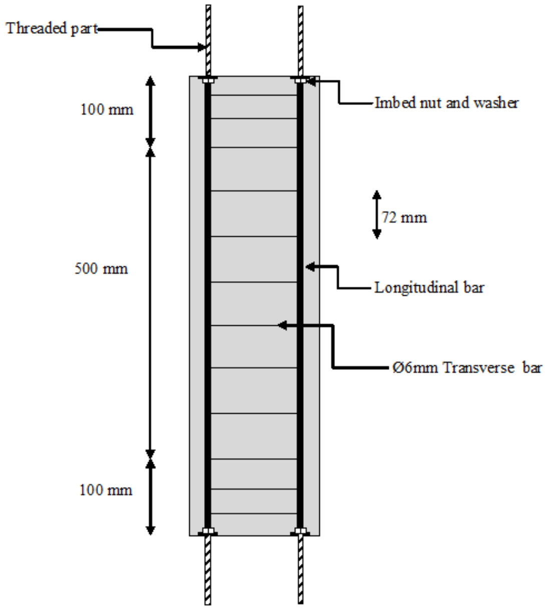
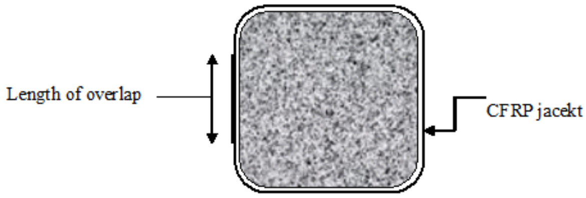
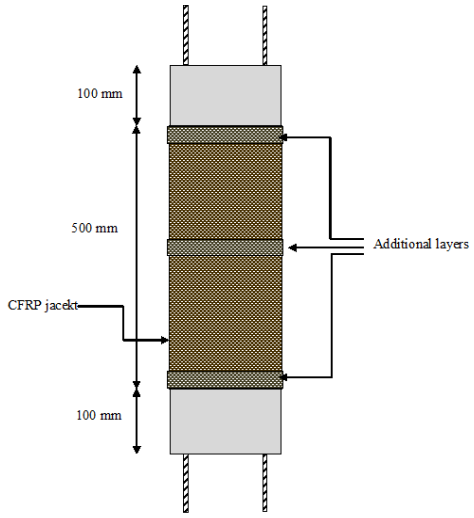



Fig. 8.Reinforcement Details




a-View of the Cross Section of a Jacketed Column




**b-Elevation View of a Jacketed Column**

**Fig 9. CFRP Details**

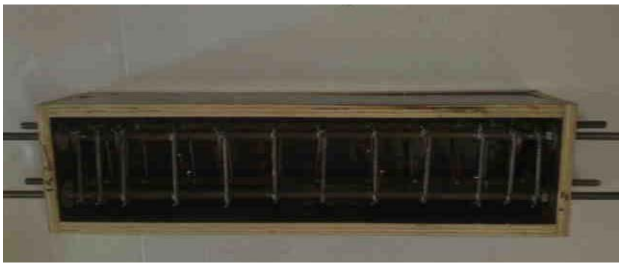


**Fig.10. Plywood Mold with Reinforcement Cage**

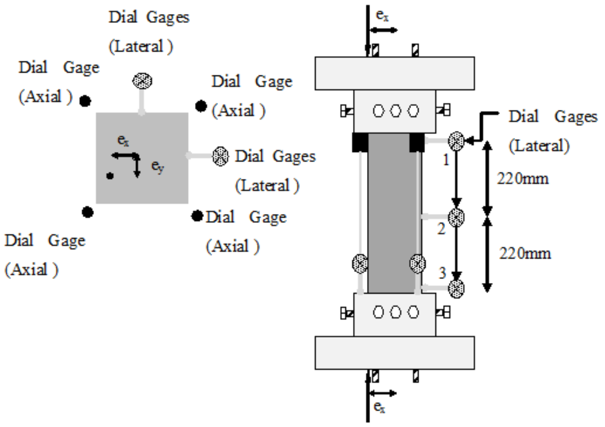



**Fig.11. Instrumentation of Biaxial Loaded Columns.**


**Fig.12. Test Machine and Instrumentation.**

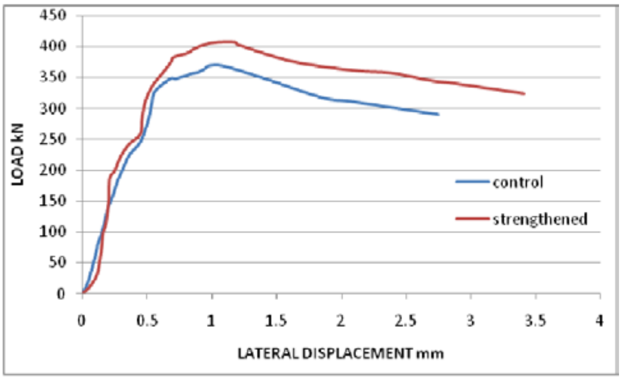



**Fig.13. Load - Lateral Displacement at Mid Height for Tested columns. 12C45-45 and12S45-45**

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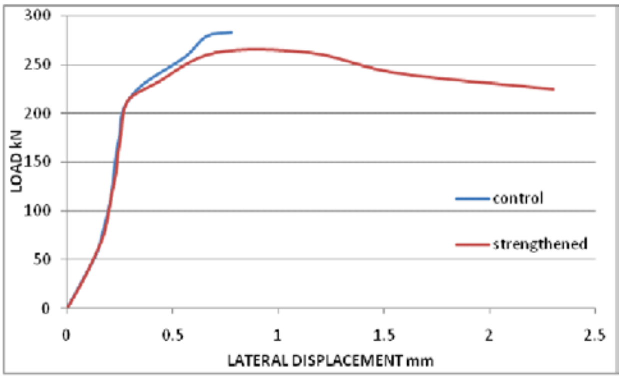


**Fig.16. Load - Lateral Displacement at Mid Height for Tested columns. 6C45-45 and 6S45-45.**

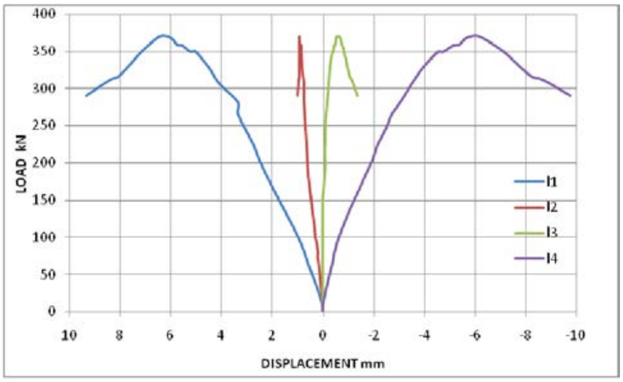


**Fig.14. Load - Displacement for Tested Column 12C45-45.**

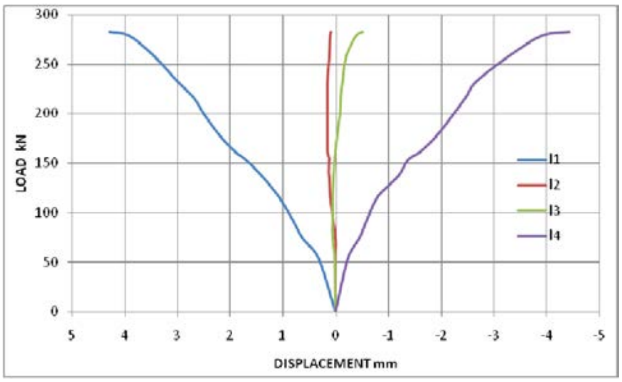


**Fig.17. Load - Displacement for Tested Column 6C45-45.**

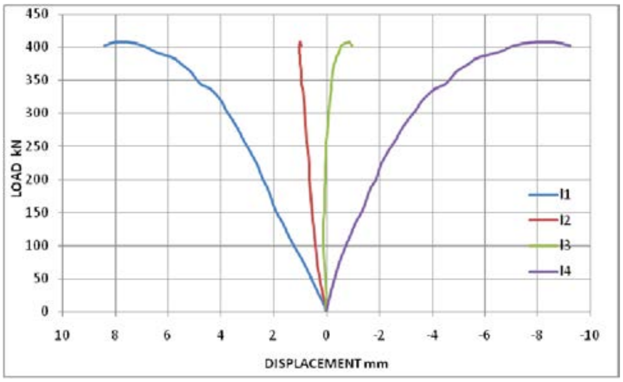


**Fig.15. Load - Displacement for Tested Column 12S45-45.**

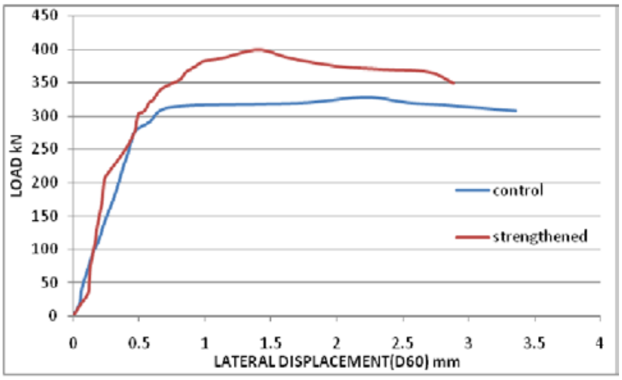


**Fig.18. Load - Lateral Displacement at Mid Height for Tested columns. 12C60-30 and 12S60-30 (with ex direction)**

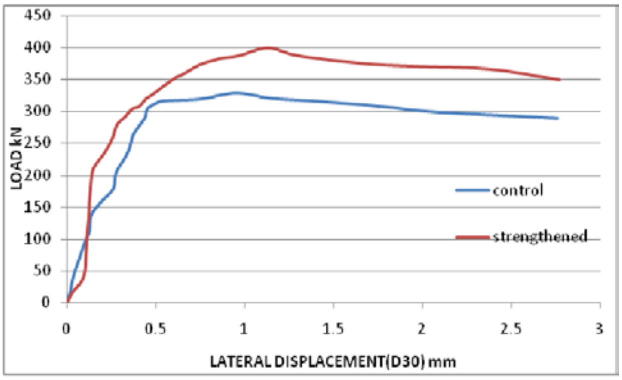


Fig. 19. Load - Lateral Displacement at Mid Height for Tested columns. 12C60-30 and 12S60-30 ( with ey direction)

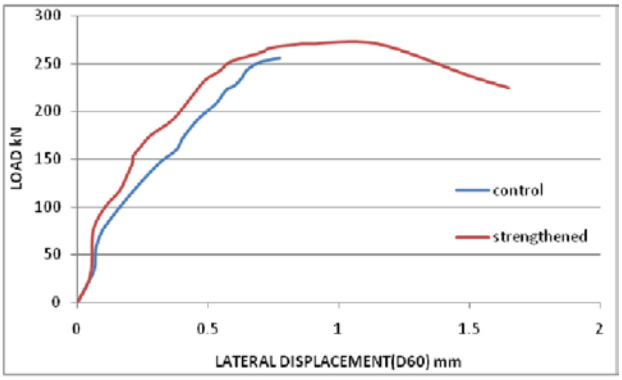


Fig.22. Load - Lateral Displacement at Mid Height for Tested columns. 6C60-30 and 6S60-30 (with ex direction)

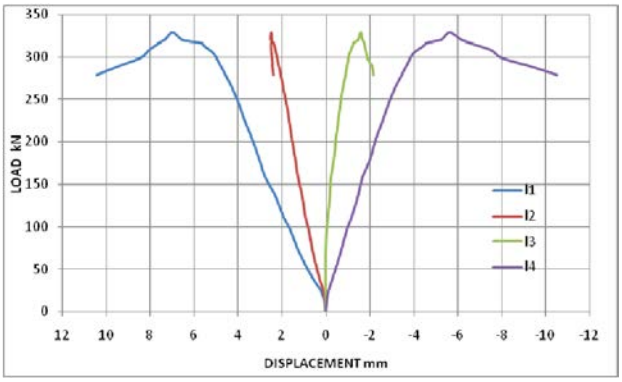


Fig.20. Load - Displacement for Tested Column 12C60-30.

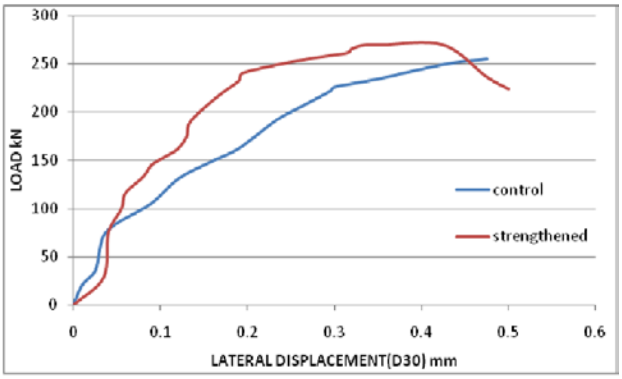


Fig.23. Load - Lateral Displacement at Mid Height for Tested columns. 6C60-30 and 6S60-30 (with ey direction)

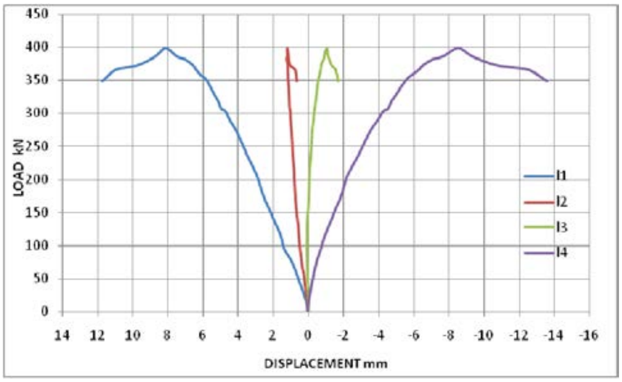


Fig.21. Load - Displacement for Tested Column 12S60-30.

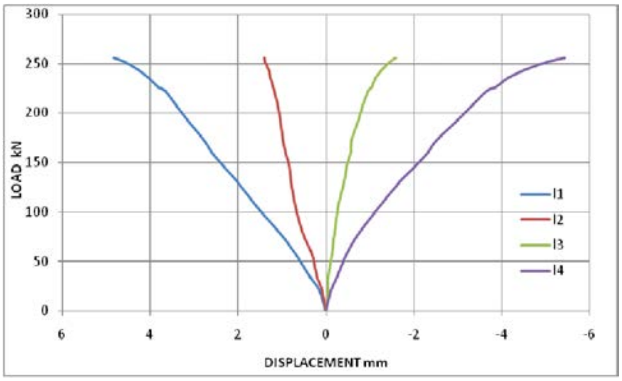


Fig.24. Load - Displacement for Tested Column 6C60-30.


**Fig.25. Compression Zone of Two Tested Columns**

## TABLES

**Table 1 Columns Codes**

| Ø12mm | | Ø6mm | |
|---|---|---|---|
| Column No. | Column Name | Column No. | Column Name |
| 1 | 12 C 45-45 | 5 | 6 C 45-45 |
| 2 | 12 S 45-45 | 6 | 6 S 45-45 |
| 3 | 12 C 60-30 | 7 | 6 C 60-30 |
| 4 | 12 S 60-30 | 8 | 6 S 60-30 |

**Table.2. Specification and Test Results of Steel Reinforcing Bars Values**

| Nominal diameter (mm) | Measured diameter (mm) | Yield stress (MPa) | Ultimate strength (MPa) | Modulus of elasticity (GPa) |
|---|---|---|---|---|
| 6 | 5.74 | 566 | 587 | 195.9 |
| 12 | 11.88 | 652 | 725 | 208.3 |

**Table.3. The Properties of Hardened Concrete**

| Test (MPa) | Experim-ental | Standard Specifica-tion | Note |
|---|---|---|---|
| ( $f'_c$ ) | 33.23 @28 day<br>34.38 @testing | ---- | ---- |
| Splitting Tensile Strength ( $f_{ct}$ ) | 3.35 | 3.23 | $0.56(f'c)^{0.5}$ |
| Modulus of Elasticity ($E_c$) | 26580 @28 day<br>26961 @testing | 27093<br>27558 | $47000(f'c)^{0.5}$ |

**Table.4. Mechanical Properties of CFRP Laminates. Sika report 2003**

| Sika Fiber | Tensile Strength, (MPa) | Tensile Modulus, (GPa) | Elongation at Failure, (%) | Major Poisson's Ratio |
|---|---|---|---|---|
| SikaWrap - 230C | 4300 | 234 | 1.8 | 0.22 |

**Table 5. Percent of Steel Reinforcement Effect**

| Column Code | Ultimate Load kN | | % of Increase in Ultimate Load |
|---|---|---|---|
| | Ø12mm Long. Reinf. | Ø6mm Long. Reinf. | |
| C45-45 | 369.77 | 282.52 | 30.1 |
| C60-30 | 328.23 | 255.52 | 28.5 |
| S45-45 | 407.17 | 261.75 | 55.6 |
| S60-30 | 398.86 | 270.06 | 47.7 |

**Table 6 Effect of Strengthening on Load Capacity**

| Column Code | Ultimate Load kN | | % of Increased in Ultimate Load |
|---|---|---|---|
| | Unconfined | Confined | |
| 12 – 45-45 | 369.77 | 407.17 | 10.1 |
| 6 – 45-45 | 282.52 | 261.75 | -7.8 |
| 12 – 60-30 | 328.23 | 398.86 | 21.4 |
| 6 – 60-30 | 255.52 | 270.06 | 5.7 |