

Experimental Study of Reinforced concrete Columns Strengthened with CFRP under Eccentric Loading

Asst. Prof.

Dr. Waleed A. Waryosh

Asst. Prof.

Dr. Mohammed M. Rasheed

Emil:mohammed_rasheed72@yahoo.com

Researcher

Alaa Haider AL-musawi

Emil:alaa_h_almusawi@yahoo.com

Abstract:

This paper presents the results of experimental studies on reinforced concrete columns strengthened with carbon fiber reinforced polymer (CFRP) under the combination of axial load and bending moment. A total of twelve specimens with square cross section (120 mm×120mm) were prepared and tested under eccentric compressive loading up to failure. The overall length of specimens with two haunched heads was 1230 mm. Test parameters were the type of concrete material(Normal and Self-compacting), thickness of layer (CFRP)and the load eccentricity, (eccentricity/ column depth ratio of 0.5 and 1). All specimens are Prepared and tested under eccentric compressive loading up to failure. The effects of these parameters on load-displacement and moment-curvature behaviors of the columns as well as the variation of longitudinal strain on different faces of the columns were studied. The results of the study demonstrated a significant enhancement on the performance of strengthened columns compared to unstrengthened columns.

Key words: RC columns; fibre reinforced polymeric composites (FRP); strengthening systems; Type of material.

دراسة عملية عن أعمدة الخرسانة المسلحة المقواة بألياف الكربون المعرضة للأحمال
اللامركزية

الخلاصة

في هذه البحث تم دراسة تصرف الأعمدة الخرسانية المسلحة والمقواة بألياف الكربون تحت تأثير حمل انضغاط محوري مع عزم احادي المحور. تم اعداد اثني عشر نموذج مربعة المقطع بأبعاد (120ملم×120ملم) وطول صافي 1230ملم، إن المتغيرات الأساسية التي اعتمدت في الفحص المختبري كانت نوع الخرسانة (خرسانة عادية المقاومة، خرسانة ذاتية

الرص) وسمك طبقة اليف الكاربون(طبقة واحدة بشكل عرضي او طبقة عرضي مع طبقة بشكل طولي طبقت على الوجه المعرض للشد فقط) وكذلك الامركزية للحمل(نسبة اللامركزية للحمل الى عمق المقطع 0.5 و1). اعدت النماذج بطول كلي مقدارة 1230 ملم وكانت النهايات مفصلية. التقوية كانت اما باستخدام طبقة او طبقتين من الالياف الكاربونية توضع اما بزاوية 0° او بزاوية 90° مع زاوية 90° , كان مقدار اللامركزية الذي تم دراسته هو 60 ملم و 120 ملم من مركز العمود. تم دراسة تأثير هذه المتغيرات على تصرف (الحمل-الازحة الجانبية و العزم-الانحناء) لهذه الاعمدة بالاضافة الى تغير الانفعالات الطولي والجانبى لكلا الوجهين(الشد و الانضغاط). اظهرت النتائج التجريبية زيادة في مقاومة الاعمدة والمطيلية بالنسبة للاعمدة المقواة مقارنة مع الاعمدة الغير مقواة.

1. Introduction

Strengthening of reinforced concrete columns is one of the most important tasks in civil engineering. Reasons of strengthening may be a change in structural use or removal of some adjacent load bearing structural members or when the column is sought to be used in a different manner from previously planned or because it is damaged by external factors during its service. The common strengthening methods, for reinforced concrete column, to increase the carrying capacity against axial loads and bending moments are given in the following:

1. Enlargement of column section with reinforced concrete jackets. This method is comparatively cheap and does not require special construction techniques, but the increase in the column size obtained after the jacket is constructed and the length of construction period make this method unattractive.
2. Using steel plate jacketing. This method has proved to be an effective measure for retrofitting and has been widely used in practice, but steel corrosion in corrosive environment and the need to heavy equipment's for construction make this method uneconomical, also Poisson' ratio of steel is higher than that of concrete at early stage of loading, this differential expansion results in partial separation of the two materials which results in delaying the activation of confinement mechanism. Furthermore, high modulus of elasticity of steel exerts large portion of axial load to steel jacket resulting in premature buckling [1].

All these disadvantages of reinforced concrete and steel jackets made the researchers look for alternative materials.

Recently fiber reinforced polymer FRP has emerged as a new material to be used in structural engineering due to its attractive mechanical properties such as: high tensile strength, light weight, high resistance for corrosion, high fatigue endurance, low thermal coefficient, short period of installation, easy application and low cost for maintenance [2].

One of the most important applications of FRP composites is strengthening of reinforced concrete columns by jacketing with wraps of FRP composites. Some research has been conducted on FRP-confined columns under eccentric loading. In a study performed by Parvin and Wang [3, 4]

conducted a study which involved numerical and experimental analysis of CFRP jacketed concrete columns, where the effect of CFRP jacket thickness and various eccentricities were investigated. The test program consisted of nine small-scale square concrete columns (108×108×305mm) wrapped with zero, one, two plies of unidirectional CFRP fabric under axial loading with various eccentricities that its magnitude was small enough not to generate any tension in the longitudinal direction. The results showed that CFRP jackets can significantly enhance the strength of concrete columns. Under eccentric loading for one layer, the increasing percentages in compressive strength are (53.8, 44.4, and 47.8%) for eccentricities (0, 7.6 and 15.2mm) respectively, and for two layers are (100, 79 and 80%) respectively. There was radical enhancement in ductility. The results of nonlinear finite element models were verified against the experimental results which correlated well. Finite element models can be used as templates to further study.

In [2003], **Li and Hadi** ^[5], and in [2004], **Hadi and Li** ^[6], tested several FRP-wrapped concrete columns with a circular section under eccentric loading at different conditions. The specimens were haunched at either one end or both ends. The effects of the concrete strength, internal steel reinforcement, wrap type, fiber orientation, and eccentricity were studied. The eccentric load was applied through a circular plate at each haunched end of the specimens. The experimental results clearly demonstrated that the FRP wrapping can enhance the strength, ductility, and energy absorption of circular concrete columns under eccentric loading.

In [2010], **Fitzwilliam and Bisby**^[7], tested a small-scale, contained columns wrapped with CFRP in a hoop and also in a longitudinal direction. For slender columns, wrapping in a hoop direction resulted in only a modest increase in capacity. Longitudinal CFRP wraps improve the behavior of slender concrete columns and allow for the achievement of higher strengths and capacities.

2. Research Objectives

In the presented study, an experimental program will be to used study the behavior of square rectangular columns strengthened by CFRP under eccentric loading.

Many specimens of self-compacting and normal reinforced concrete columns under different eccentric loading with different layers of strengthening can be give a good indicator on the efficiency of concrete type and the method of strengthened .

The parameter of this study will be of interest to those engineers involved in retrofit and strengthening of structures with FRP materials.

3. Experimental Program

3.1. Specimen Layout

A total of twelve RC specimens were designed with a square section (120 mm×120 mm), and a total length of (1230 mm). The length between corbels is (750 mm) and each corbel head had a height of 240 mm. Since large applied loads are expected to be required for failure of several specimens, large corbels or "feet" were designed in which a single load source could be used and applied eccentrically on the corbel thus simulating the combined stress effects in columns. All specimens were tested under compression eccentric loading up to failure. Figure (1) shows the geometry of the specimens. The main experimental parameters were the type of concrete, FRP thickness, fiber orientation, and eccentricity. Two different FRP thicknesses of 0.13 and 0.26 mm (one and two layers); two fiber orientations of 0°, 90° with respect to an axis perpendicular to the column axis; and two eccentricities of , 60 and 120 mm were investigated. The test program and specimen properties are summarized in Table (1), where L refers to a fiber layer whose axis is parallel to the column axis (90°) in tension face only; T refers to a fiber layer whose axis is perpendicular to the column axis and is used for lateral confinement of the

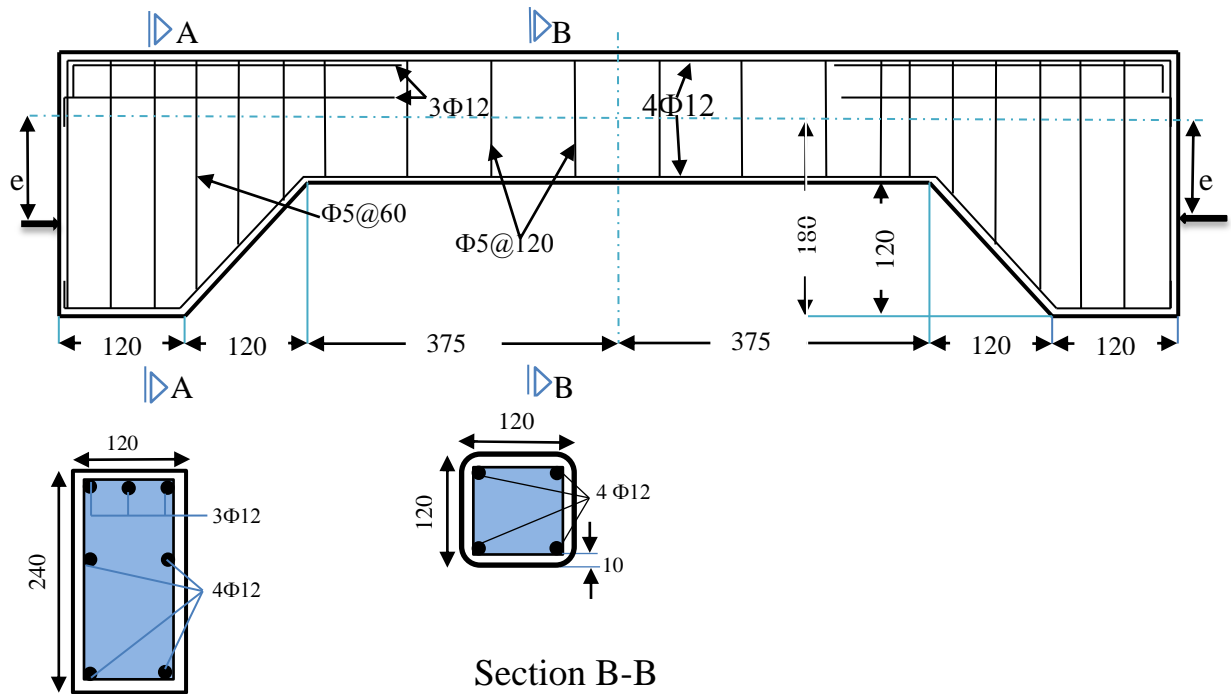
Two different FRP thicknesses of 0.13 and 0.26 mm (one and two layers); two fiber orientations of 0°, 90° with respect to an axis perpendicular to the column axis; and two eccentricities of , 60 and 120 mm were investigated. The test program and specimen properties are summarized in Table (1), where L refers to a fiber layer whose axis is parallel to the column axis (90°) in tension face only; T refers to a fiber layer whose axis is perpendicular to the column axis and is used for lateral confinement of the column (0°); the layers were applied as a longitudinal external (flexural) strengthening with continuous strips along the columns axis.as shown in figure (1)

All layers (i.e. longitudinal and transverse), were applied as uniaxial strips to cover all faces of the specimens consistently.

The specimens were divided into two groups. The first group labeled "S" consisted of strengthened specimens, and the second group labeled "U" were unstrengthened and served as control specimens. Five columns were unstrengthened and eight columns were strengthened; four fully with one transverse layer and four with two layers (transverse and longitudinal) of CFRP.

Table (1) Specimen design details.

Specimen	Strengthening	Type of concrete	Fiber orientation	Eccentricity (mm)
UN60	Unstrengthened	NSC	—	60
UN120	Unstrengthened	NSC	—	120
USC60	Unstrengthened	SCC	—	60
USC120	Unstrengthened	SCC	—	120
SN60-T	Strengthened	NSC	90°	60
SN60-TL	Strengthened	NSC	90°/0°	60
SN120-T	Strengthened	NSC	90°	120
SN120-TL	Strengthened	NSC	90°/0°	120
SSC60-T	Strengthened	SCC	90°	60
SSC60-TL	Strengthened	SCC	90°/0°	60
SSC120-T	Strengthened	SCC	90°	120
SSC120-TL	Strengthened	SCC	90°/0°	120



Section A-A

Section B-B

Figure (1) Specimen's details.

3.2. Material Properties

3.2.1. Normal Strength Concrete (NSC)

One normal strength concrete mix is designed in accordance with ACI-211^[8], the value of mix design for nominal 28-day cylindrical compressive strength of (28MPa). Mixture details are given in Table (2). It is found that, the used mixture produces give good workability and uniform mixing of concrete without segregation.

3.2.2 Self-compacting concrete (SCC)

Self-Compacting Concrete (SCC), which flows under its own weight and does not require any external vibration for compaction, SCC was first introduced in the late 1980's by Japanese researchers ^[9, 10], is highly workable concrete that can flow under its own weight through restricted sections without segregation and bleeding. Such concrete should have a relatively low yield value to ensure high flow ability, a moderate viscosity to resist segregation and bleeding, and must maintain its homogeneity during transportation, placing and curing to ensure adequate structural performance and long term durability. The successful development of SCC must ensure a good balance between deformability and stability. For SCC, it is generally necessary to use superplasticizers in order to obtain high mobility. Adding a large volume of powdered material or viscosity modifying admixture can eliminate segregation. The powdered materials that can be added are fly ash, silica fume, lime stone powder, glass filler and quartzite filler. Since, self-compatibility is largely affected by the characteristics of materials and the mix proportions, it becomes necessary to evolve a procedure for mix design of SCC. Okamura and Ozawa have proposed a mix proportioning system for SCC ^[10]. In this system, the coarse aggregate and fine aggregate contents are fixed and self-compatibility is to be achieved by adjusting the water /powder ratio and super plasticizer dosage. The coarse aggregate content in concrete is generally fixed at 50 percent of the total solid volume, the fine aggregate content is fixed at 40 percent of the mortar volume and the water /powder ratio is assumed to be 0.9-1.0 by volume depending on the properties of the powder and the superplasticizer dosage. The required water /powder ratio is determined by conducting a number of trials. One of the limitations of SCC is that there is no established mix design procedure yet. Mixture details are given in Table (2).

Table (2) concrete Mixture details

material	Unite	NSC	SCC
Cement	kg/m ³	450	450
Sand	kg/m ³	640	758
Gravel	kg/m ³	1133	890
Silica fume	kg/m ³	-	30
Limestone	kg/m ³	-	130
Superplsticezer(G51)	l/m ³	-	10
Water	l/m ³	200	200
w/p	%	44.4	32.8

3.2.3. Properties of fresh self-compacting concrete(SCC)

Self- Compacting Concrete is characterized by filling ability, passing ability and resistance to segregation. Many different methods have been developed to characterize the properties of SCC. No single method has been found until date, which characterizes all the relevant workability aspects, and hence, each mix has been tested by more than one test method for the different workability parameters. The slump flow test is used to assess the horizontal free flow of SCC in the absence of obstructions. On lifting the slump cone, filled with concrete, the concrete flows. The average diameter of the concrete circle is a measure for the filling ability of the concrete. The time T50cm is a secondary indication of flow. It measures the time taken in seconds from the instant the cone is lifted to the instant when horizontal flow reaches diameter of 500mm.figure (2) shows the slump flue test shape.



Figure (2) slump flue test.

The flowability of the fresh concrete can be tested with the V-funnel test, whereby the flow time is measured, figure (3). The funnel is filled with about 12 liters of concrete and the time taken for it to flow through the apparatus is measured. Further, T 5min is also measured with V-funnel, which indicates the tendency for segregation, wherein the funnel can be refilled with concrete and left for 5 minutes to settle. If the concrete shows segregation, the flow time will increase significantly. According to **Khayat** and **Manai**, a funnel test flow time less than 6s is recommended for a concrete to qualify for an SCC ^[11].

The passing ability is determined using the L- box test ^[12] as shown in Figure (4). The vertical section of the L-Box is filled with concrete, and then the gate lifted to let the concrete flow into the horizontal section. The height of the concrete at the end of the horizontal section is expressed as a proportion of that remaining in the vertical section (H_2/H_1). This is an indication of passing ability. The specified requisite is the ratio between the heights of the concrete at each end or blocking ratio to be ≥ 0.8 .

In the present study the table (3) gives the results of fresh concrete test the recommended values for different tests given by different researchers for mix to be characterized as SCC mix.



Figure (3). V-funnel test.



Figure (4). L-Box test.

Table (3) Recommended limits for different properties^[13]

Sr. No.	Property	unit	Result	Range*
1.	Slump Flow Diameter	mm	800	650-800
2.	T _{50cm} slump flow	sec	3	2-5
3.	V-funnel	sec	10	6-12
4.	V-funnel at T _{5minutes}	sec	0.4	0 ±3
5.	L-Box	H2/H1	0.98	0.8-1

3.3 casting and curing

A total of six batches of concrete are used to cast the columns. Each batch is used to cast two columns (with two prisms $100 \times 100 \times 500$ mm to calculate the modulus of rupture of concrete) and nine cylinders 150×300 mm (three cylinders to calculate the modulus of elasticity, three cylinders to calculate splitting tensile strength and three cylinders to calculate the compressive strength of concrete at age of 28 days).and three cubes $150 \times 150 \times 150$ (to calculate the compressive strength of concrete at age of 28 days for compare with cylinder compressive strength). All columns are cast vertically to simulate typical construction practice of columns. Concrete is discharged in the columns directly from 0.1 m³ capacity horizontal pan mixer in approximately 2 or 3 lifts. A total mixing time of about 5-8 minutes is used during all the batches in this study. The dry constituents are well mixed for about 2 minutes to ensure proper distribution of the ingredients and to disperse any agglomeration of the fine materials in the pan. For SCC batches with superplasticizers, the added water is premixed with superplasticizer and mixed for 3 minutes. For NSC an electric table vibrator is used to consolidate the concrete and to remove air bubbles at each of the lifts.

3.4. CFRP Installation

Carbon fiber tape was obtained from a local supplier and was used for the external confinement of the specimens. The rolls of carbon fiber were 100 m in length and 60 mm in width. For rectangular columns, the corners are usually rounded prior to the application of the FRP wrap to

enhance the effectiveness of the FRP confinement and to avoid stress concentration on the FRP wrap from sharp corners [13]. The surface of the specimens was cleaned of all rough surfaces and canvas that remained attached to the specimens after curing. A wet lay-up system was used to apply the carbon fiber. An epoxy resin, (one part hardener to four parts resin) was used to cure the carbon fiber. The epoxy resin was generously brushed onto the specimens, then the carbon fiber was applied, making sure the carbon fiber was pulled into tension. Once the relevant layer was wrapped, another coat of the epoxy resin was applied. FRP in the laterally wrapped specimens (CF) was applied horizontally with a 20mm overlap. For the vertically orientated carbon fiber specimens (VCF), the carbon fiber was restrained at the top face (tension face) of the specimen by placing a flap under the base of the specimen. The carbon fiber was pulled up the specimens and placed under a weight on top of the specimen to ensure that the carbon fiber was in tension. The carbon fiber was then coated with another layer of epoxy resin. Figure (5) shows the procedure of instillation.

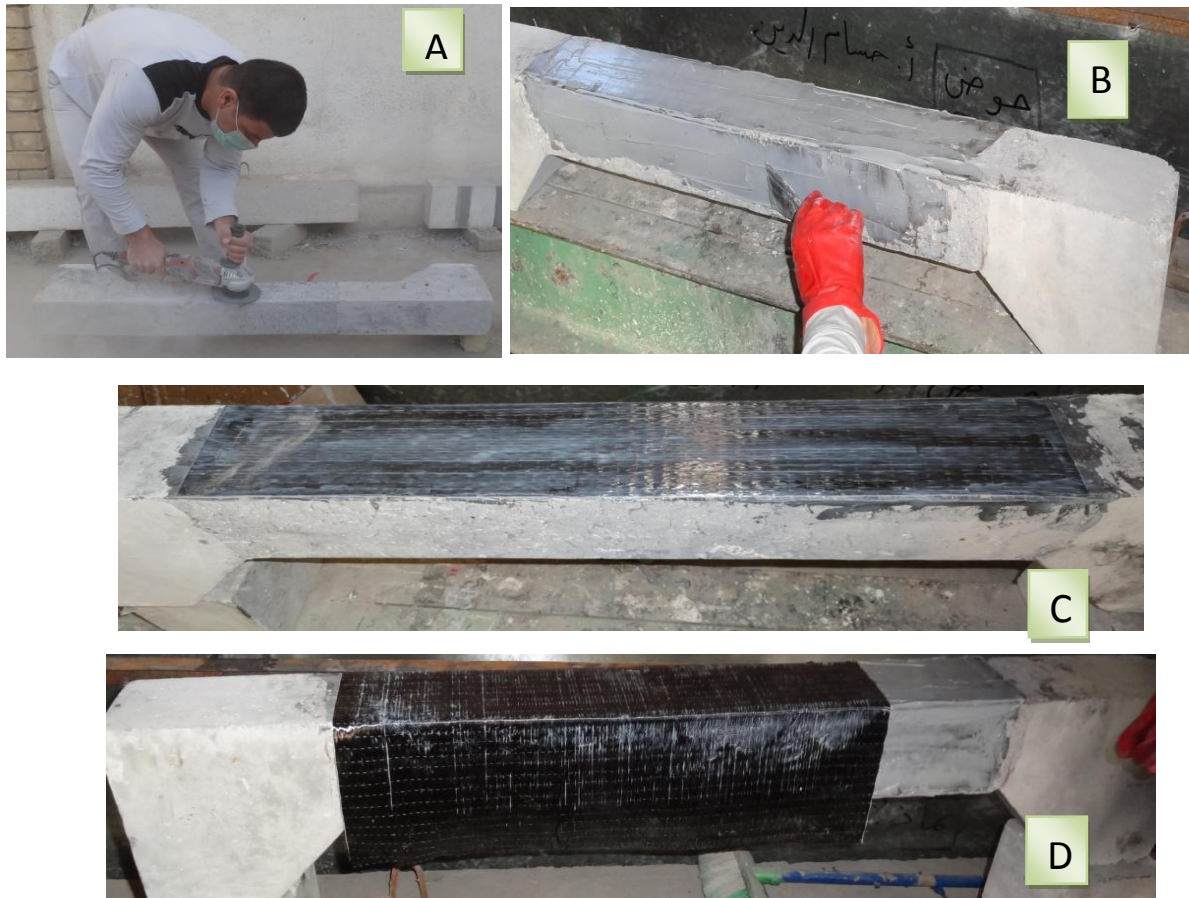


Figure (5), application of CFRP.

3.5 Testing of Concrete Column

3.12.1 Loading Cap

A new loading cap was designed based on a loading cap designed by Hadi (2006) [14]. The loading cap has rectangular section (120×240mm) thickness 20mm and can be provided to values of eccentric loading. The eccentric load was exerted on the loading cap via a wedge plate that was positioned into the 60 mm or 120mm grooves, respectively. The loading caps were manufactured in the Engineering Laboratory at the University of AL-mustansiriya and were made of high strength steel. Figure (6). (a) Shows Eccentricity of 60mm, and (b) shows Eccentricity of 120mm.

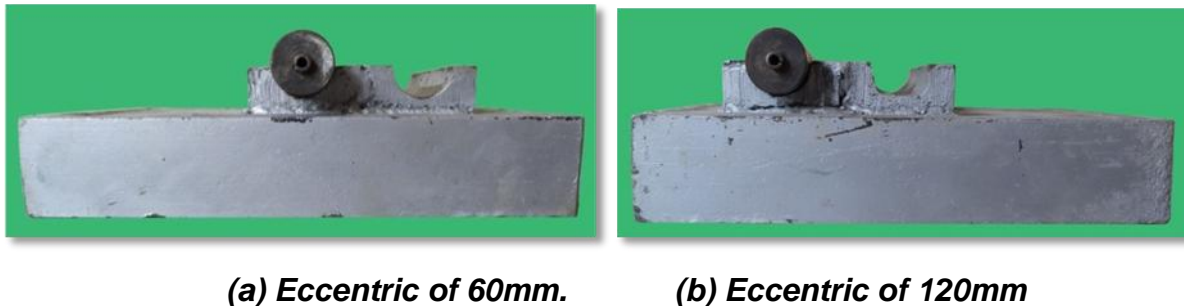


Figure (6) Loading cap used in the experimental.

3.6. Test Setup and loading

A hydraulic actuator was used to apply the axial load to the column specimens as shown in Figure (7). The lower ends of the specimens were attached to the actuator, while the upper ends were supported on the steel reaction cap, both end supports were designed as hinged connections with predefined eccentricity by using loading caps.

A total of four linear variable displacement (dial gauges) and 8 demec points;4 in each face were used for every specimen columns. Figure (7) shows the arrangement of dial gauges. The specimens were tested using a 3000 kN capacity compression actuator.

The tests were performed up to failure of the specimens. The test was stopped when the FRP failed on the tension face (i.e., for the strengthened specimens) or the concrete crushed on the compression face (i.e., for the unstrengthened Specimens), because the test setup and actuator situation were very sensitive and were not able to measure large postpeak deformations.

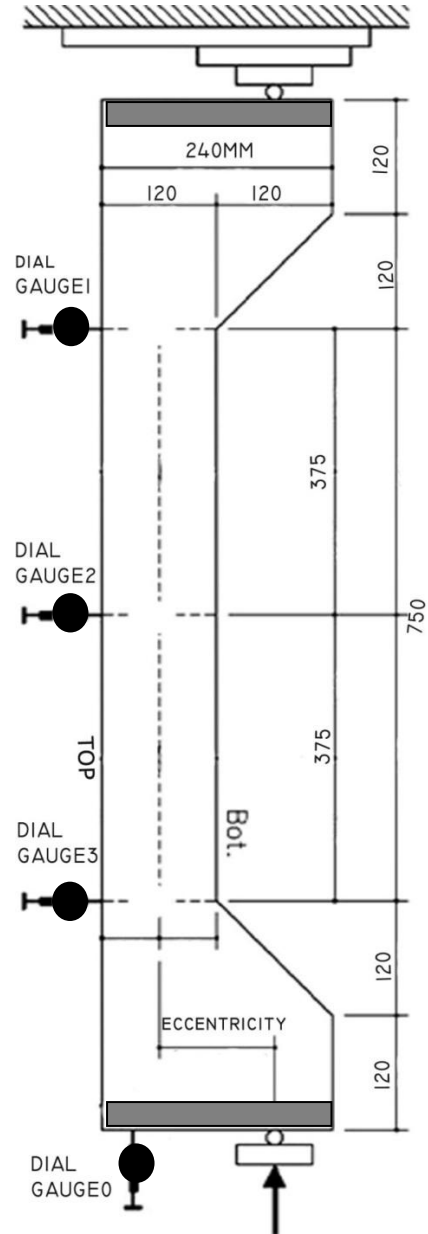


Figure (7) test setup.

4. Experimental Results and Discussions

4.1. Load-Displacement Behavior

The experimental load-displacement curves obtained for the tested columns are shown in Figs. (8) to (11). Figure (8) shows the effect of FRP on normal concrete columns of $e=60\text{mm}$ it can be

see the improvement on behavior of strengthened specimens respect to unstrengthened. Also, it can be seen there is little difference between specimens strengthened by TL and strengthened by T only.

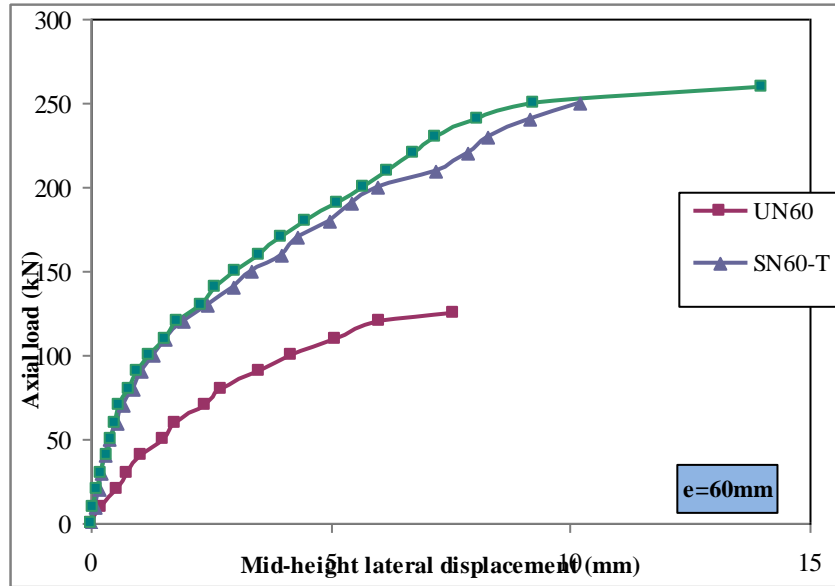


Figure (8) Load-displacement behavior of normal specimens e=60.

Figure (9) shows, the effect of FRP on self-compacting concrete columns of e=60mm it can be seen the important of strengthened by FRP strengthened by TL gives good response in compression with strengthened by T only.

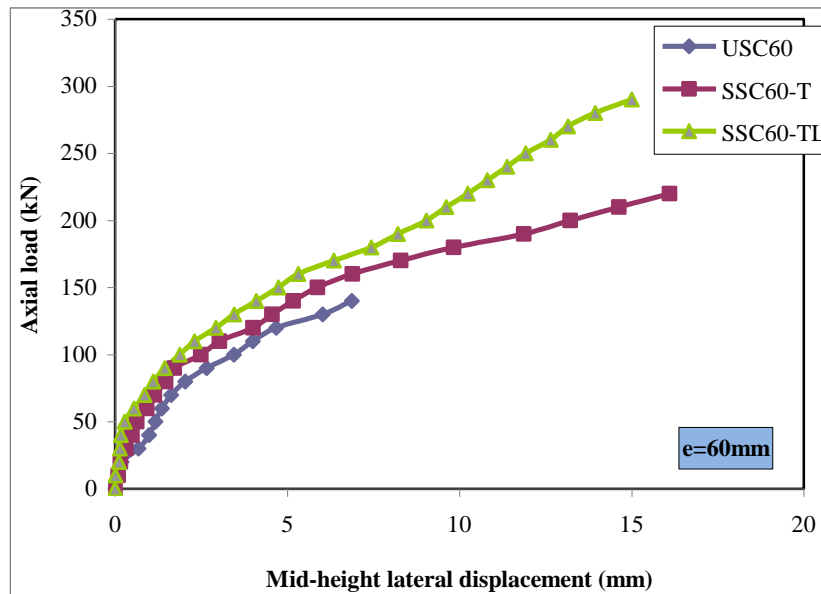


Figure (9) Load-displacement behavior of self-compacting specimens SSC e=60.

Figure (10) shows, the effect of FRP on normal concrete of $e=120\text{mm}$ it can be seen the improvement on behavior of strengthened specimens respect to unstrengthened. But little than normal concrete with $e=60\text{mm}$, because the increase in eccentricity from 60mm to 120mm . Figure (11) shows, the effect of FRP on self-compacting concrete columns of $e=120\text{mm}$ it can be seen the improvement on behavior of strengthened specimens respect to unstrengthened. But little than self-compacting concrete and normal concrete with $e=60\text{mm}$, because the increase of f_c from 28mpa to 47mpa and because increase in eccentricity from 60mm to 120mm .

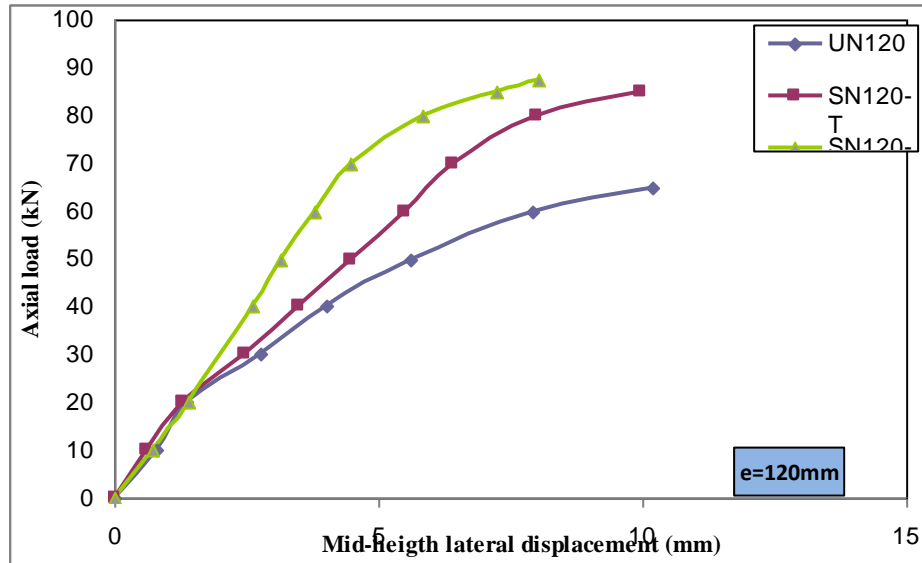


Figure (10) Load-displacement behavior of normal specimens $e=120$.

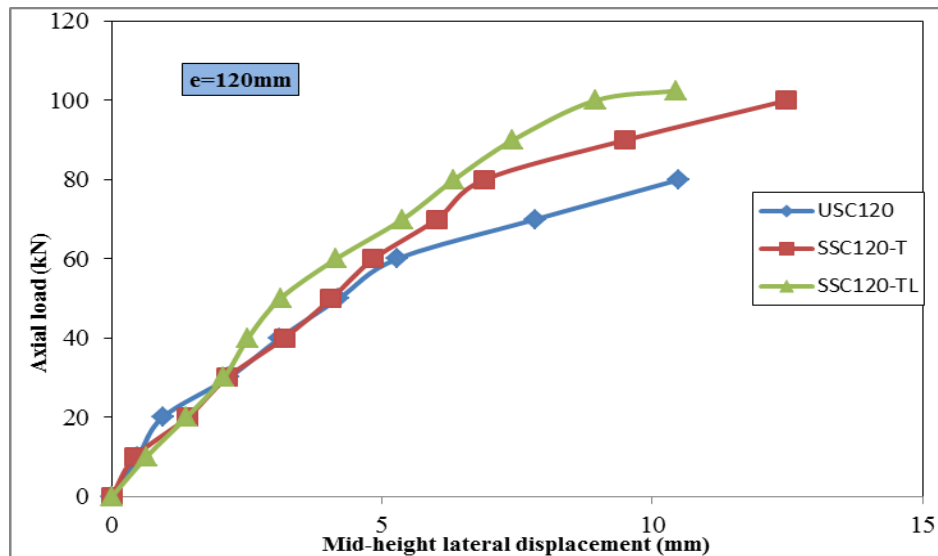


Figure (11) Load-displacement behavior of self-compacting specimens $e=120$.

4.2 Failure modes of test specimen

The crack patterns of all columns are shown in Figure (12). For test specimens, crushing of concrete was observed on the compression face of the column cross section at the lower middle zone of the specimens. All cracks were vertically initiated at the tension face of the columns. Those cracks generally commenced at the tension face of the specimens along the columns length. It may be observed that the number of cracks depends on type of failure mode which depends on the value of the load eccentricity. Specimens' (unstrengthen and strengthen) were subjected to load eccentricity of 120 mm which is deemed to cause a tensile failure mode, while specimens of (unstrengthen and strengthen) were subjected to load eccentricity of 60 mm which is deemed to cause a compressive failure mode. For columns of load eccentricity of 120 mm, the ratio ($e/h=1$) provides a large number of distributed cracks in the tension face along the column height as shown in crack pattern of columns UN120 and USC120. While, the ($e/h=0.5$) ratio of columns provides a less number of cracks compared with columns of ($e/h=1$) as shown for crack pattern of columns UN60 and USC60. Also crack patterns of test columns show that the crack widths of columns ($e/h=1$) are more than that of columns of ($e/h=0.5$). This is because of the tensile failure mode of columns of ($e/h=1$) as compared with the compression failure mode of columns ($e/h=0.5$).



Figure (12) Crack pattern for column.

4.3 Effect of the eccentricity

In order to explore the effect of the eccentricity on the behavior of the columns, load deflection curves were plotted for the all columns. Figure (13) shows the effect of the eccentricity on the

axial load capacity of the tested column specimens. It can be shown the effect of increasing eccentricity on the ultimate load, the ultimate load decreases with increase of the eccentricity, irrespective of the column is strengthened or unstrengthened, as well as can be shows to decrease the proportion of normal strength concrete is similar to the self-compacting concrete.

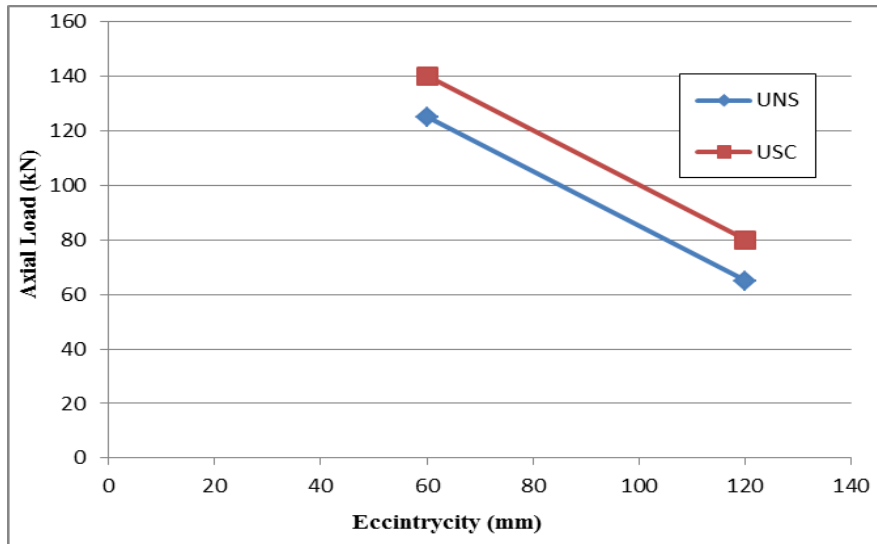


Figure (13) Effect of eccentricity on columns unstrengthen .

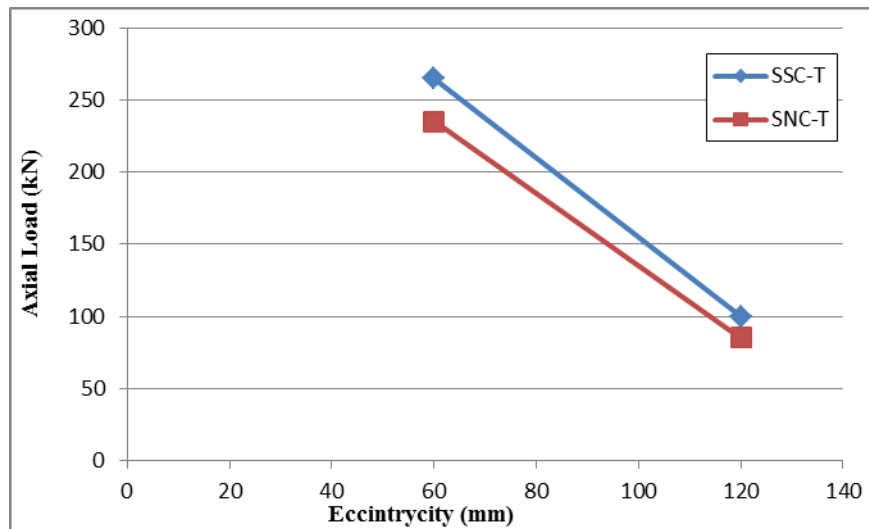


Figure (14) Effect of eccentricity on columns strengthened by T.

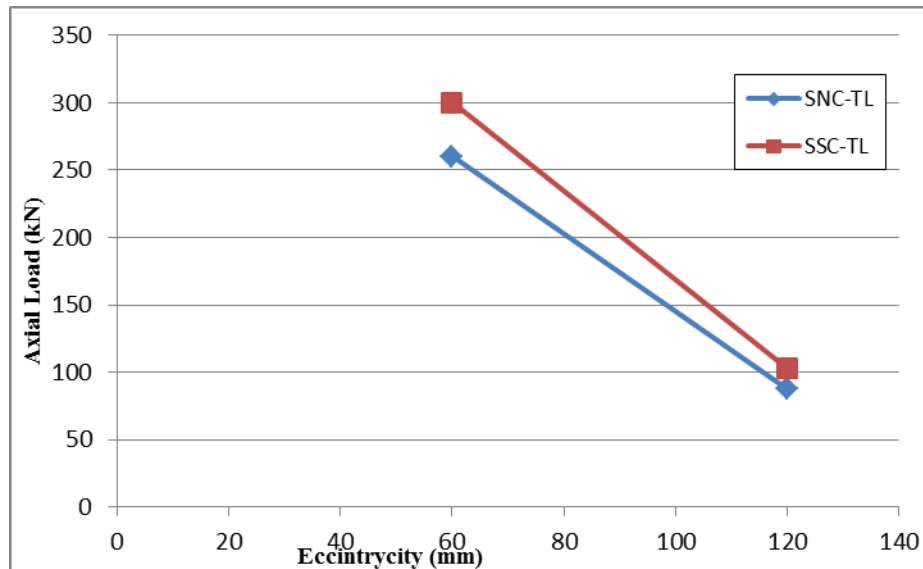


Figure (15) Effect of eccentricity on columns strengthened by T. &L.

5. Conclusions

Based on evidence from the experimental results reported in this work, the following conclusions can be drawn.

5.1. Effect of Type of concrete material on the columns

Effect of type of concrete material on the columns under eccentricity can be drawn.

- 1- The efficiency of self-compaction concrete more than of the conventional concrete because the difficulty of full compaction of the concrete, leading to the production of concrete is an integrated compaction and usually leads to no segregation.
- 2- Using vibrator machines, whether external or internal lead sometimes to the deviation of the modified column, leading to eccentricity load
- 3- When the strengthened columns fail in tension-controlled failure, the transverse layers could not make any improvement on the confinement of the compression side of the section. In this region the concrete behavior is similar to the unconfined concrete.

5.2. Strengthening with CFRP

The use of CFRP materials can improve significantly the behavior of the RC columns as following:

1. The strengthening efficiency of the column is made of self-compacting concrete more than column made normal strength concrete, because of high compressive strength and homogeneity of concrete.
2. Lateral strengthen method of the column incidentally more efficient than longitudinal strengthen method by using strips on the faces of the column
3. The strengthened specimens had similar bilinear load-displacement curves as the unstrengthened specimens. The first part of all curves was approximately linear up to the yield point, when the tension steel bars yielded.
4. The efficiency of the RC columns confined with CFRP membranes is reduced if the load eccentricity is increased.
5. Failure of the CFRP confined RC elements depends on the failure of the CFRP composite membrane.
6. During the experimental program it was noticed that the failure of the eccentrically loaded elements occurred at the compressed side.

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