STRENGTHENING OF REINFORCED CONCRETE COLUMNS WITH CFRP SHEETS AND PRECAST PANELS

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ABSTRACT

Researches undertaken in the past years concentrated on studying FRP-confined circular columns subjected to concentrated loads. Only few of these studies addressed the engineering behavior of square members when subjected to eccentric loading. The purpose of this research was to investigate the performance of short square reinforced concrete columns strengthened with CFRP sheets or strengthened with precast concrete panels then subjected to loading at different eccentricities (٠, ٧٥, and ١٥٠)mm from center line of the column. This study use precast concrete panels as strengthening materials that have same coefficient of thermal expansion of the concrete column. This is not exist in other types of strengthening materials. The experimental program consist of casting twelve reinforced concrete square section (١٥٠ x ١٥٠)mm columns and strengthened with CFRP sheets or precast concrete panels. All the columns have an overall length of ١٦٠٠mm and reinforced with same amount of steel ratio.

The columns were divided in to four main groups. The first group consists of three reinforced concrete columns considered as reference columns. The second group consist of three columns strengthened by fully wrapped CFRP sheets. The third group consist of three columns strengthened by precast concrete panels fixed by epoxy. The strengthening of the three columns of the forth group was the same as group three, but the panels were fixed by epoxy and anchor bolts. The specimens wrapped with CFRP sheet and loaded at (٠, ٧٥, and ١٥٠)mm eccentricity, led to increase of ultimate carrying capacity of (١٠.٢, ٢٥.٧ and ١١.٥)%, respectively, compared to reference columns. The specimen confined by precast concrete panels and epoxy show increasing of failure load of (١١.٩, ٥٤.٧, and ١٧.٣)%, respectively, relative to reference columns. For the fourth group the strength enhancements for the different eccentricities are (١٢.٣, ٥٢, and ٢٠.٩)%, respectively, compared to reference columns. The load-deflection curves show that of group four column possessed, were more stiffness than other group of strengthening.

In general, columns strengthened by precast panels are more effective in resisting external loads relative to columns strengthened by CFRP sheets, similar behaviours were observed at different eccentricity ratio. Two analytical methods are proposed and compared with ACI-٤٤٠ method to calculate strength of confined cylinders (f'_{cc}) based on compressive strength of the concrete cylinders (f'_c). Then from these f'_{cc}, the nominal axial load capacity is determined for the columns at different eccentricities. The suggested equations, show that a good results, when applied on the limited data available from literatures.

Keywords: CFRP sheets, Reinforced concrete columns, Strengthening, Concrete panels, Confinement, Experimental test, Theoretical analysis.

١. INTRODUCTION

Columns are defined as members that carry loads chiefly in compression, usually columns carry bending moments as well, about one or both axes of the cross section, and the bending action may produce tensile forces over a part of the cross section. Even in such cases, columns are generally referred to as compression members, because the compression forces dominate their behavior. In addition to the most common type of compression member (vertical elements in structures), compression members include; compression elements in trusses, shells,......[١]. The ratio of longitudinal steel area A_{st} to gross concrete section A_g is in the range from ٠.٠١ to ٠.٠٨, according to ACI-٣١٨ Code ١٠.٩.١.[٢]. In the last twenty to twenty five years, FRP Fiber Reinforced Polymer (FRP) materials have emerged as promising alternative repair materials for reinforced concrete structures, and they are rapidly becoming materials of choice for strengthening and rehabilitation of concrete infrastructure. FRP plates or sheets can be bonded to the exterior of concrete structures using high-strength adhesives to provide tensile or confining reinforcement which supplements that provided by internal reinforcing steel.[٣] As the cost of FRP materials continues to decrease and the need for aggressive infrastructure renewal becomes increasingly evident in the developed world, pressure has mounted for the use of these new materials to meet higher public expectations in terms of infrastructure functionality. Aided by the growth in research and demonstration projects funded by industries and governments around the world during the late ١٩٨٠s and throughout the ١٩٩٠s FRP materials are now finding wider acceptance in the characteristically conservative infrastructure construction industry.[٤] FRP materials are non-corrosive and non-magnetic, and can thus be used to eliminate the corrosion problems in variably encountered with conventional repair materials such as externally-bonded steel plates. In addition, FRPs are externally light, strong, highly versatile, and comparatively easy to install, making them ideal materials for the repair and strengthening of concretes.[٣]

Carbon Fiber Reinforced polymers (CFRP) a composite materials compression a polymer matrix reinforced with carbon fiber cloth, mat, or strands. There are currently three main applications for the use of FRPs as external reinforcement of reinforced concrete structures: [٣] flexural strengthening, shear strengthening, and compression member strengthening. A potent advantage of using FRP as an alternate external confinement to steel is the high strength to weight ratio comparisons. In order to achieve an equivalent confinement, FRP plates are up to ٢٠% less dense than steel plates and are at least twice as strong, if not more. Manufacture of modern composites is, then, possible in reduced sections and allows composite plates to be shaped on-site. The lower density allows easier placement of confinement in application. Design of external confinement to structure should be made with conservative adjustments to the primary structure's dead weight load. Changes of the stiffness of members should be considered when redesigning the structure. [٥] It is well known that concrete expands laterally before failure. If the lateral expansion is prevented, a substantial concrete strength and deformation enhancements may be gained. Therefore, when a column is wrapped with FRP sheets, its axial load capacity is expected to be enhanced due to the confinement effect of the externally bonded transverse fibers.[٦] In the last few decades, several attempts have been made all over the world to study these problem and to increase the life of the structures by suitable retrofitting and strengthening techniques. For the past few years, FRP materials has been investigated to provide such confinement. **Hadi, ٢٠٠٥[٧]:** Nine circular reinforced concrete columns, confined with three layers CFRP or E-glass fibers, were presented, the columns were loaded at eccentricity of (٠, ٢٥, ٥٠ and ٧٥mm) compared each result with reinforced concrete specimen for eccentricity zero the carbon increased by ٦% and the glass decreased by ٤%. for eccentricity ٢٥mm the carbon and the glass increased by ٥٤% and ٢%, while for eccentricity ٥٠mm increased by ٢٩% and ٢٩%, respectively. CFRP-confined columns displayed a higher load capacity and ductility, both when tested concentrically and eccentrically. **Lignola et al, ٢٠٠٧[٨]:** To study the behavior of rectangular hollow cross sections subjected to combined axial load and bending, a total of seven ١:٥ scale specimens has been tested. Tested specimens have external dimension of the section ٣٦٠mm, wall thickness of ٦٠mm, and height of ١.٣m representing, in reduced scale, typical square hollow bridge piers, subjected to axial and eccentric loading (e=٥٠, ٢٠٠ and ٣٠٠mm). Accordingly, three unstrengthened specimens and three other specimens strengthened with two plies CFRP laminates. The strength increase was approximately ٧% in the case of larger eccentricity, where as a gradual, more ductile behavior was observed when increasing the eccentricity. **Le et al, ٢٠١٣[٩]:**The researcher studied twelve hollow square reinforced concrete specimens wrapped with CFRP. The effect of ply configuration on the behavior of the specimens is investigated. All specimens were ٨٠٠mm high and had the dimensions of (٢٠٠x٢٠٠) mm in cross-section and a hollow core of (٨٠x٨٠) mm. A number of the specimens were externally wrapped with CFRP in three different ply configurations of hoop, vertical and 45° angle with reference to the circumferential direction, respectively. The columns were loaded as columns under three eccentricities (٠, ٢٥, and ٥٠) mm. The result show that; for axial and eccentricity ٥٠mm the specimens strengthened by one vertical and two hoop configuration of CFRP were the best, that increased failure load by ١٣.٧% and ١٧.٨% compared to unstrengthened column, respectively. For eccentricity ٢٥mm, the specimen strengthened by three horizontal layers of CFRP was the best, which increased the load by ٢٤.٧%. The columns wrapped exclusively with hoop configuration proved to show the greatest ductility properties.

٢. Strengthening by Concrete Enlargement

In the past, other types of strengthening were used, when the concrete material properties deteriorate (decrease of strength and stiffness) especially when subjected to high temperature (fire). The section of column or beam were reinforced externally with a new steel bars surrounded by a form, after that, the concrete cast inside the form. This method was called enlargement or jacketing of column section or beam section [١٠, ١١]. This method was tedious to work, fixing of new reinforcement, and covering with form work in site. Also, the casting process is not easy to be done.

٣. EXPERIMENTAL PROGRAM

In order to test the behavior of CFRP wrapped and enlargement section specimen, an experimental program was designed and conducted. The program consisted of casting twelve reinforced concrete columns. The design of the reinforced concrete column was done according to ACI-Code ٣١٨-١١[٢]. All the columns have a total height of ١٦٠٠mm with length of the tested part at ١٠٠٠mm with cross section of (١٥٠x١٥٠)mm. The haunched parts at each end is (١٥٠ x ٣٠٠)mm. The line load was applied to the haunched area at ٠, ٧٥, and ١٥٠mm (e/h=٠, ٠.٥, and ١) eccentricity from center line of column cross section.

All the column were reinforced with same amount of reinforcements ٤-φ١٢mm (٢% of steel ratio) with ties φ٦mm at ١٥٠mm c/c at test length. The reinforcement at haunched parts were increased to avoid bearing failure near supports, see Fig (١). The columns were divided in to four groups. The specimens of the first group, CR were made of reinforced concrete without any modification, as reference columns. The specimens of the second group CF were made of reinforced concrete column, after ٢٨ days from casting of concrete, that were wrapped with three layers of carbon fiber reinforced polymer (CFRP) sheets, see Fig.(٢).

While third group CE were made of reinforced concrete column with enlargement of section, increasing size of column, by four precast panels fixed to the column by epoxy see Fig. (٣).

The columns of the last group, CEA were made of reinforced concrete columns with enlargement of section using precast reinforced concrete panels. The difference between the columns of this group and third group is that, the panels in this group were fixed to the column by epoxy and anchor bolts, intended to increase the bond between the panels and the column. see Fig.(٤).

an axial loading at ٧٥mm eccentricity are denoted by ٧٥. Those tested at ١٥٠mm axial eccentric load are denoted ١٥٠. The longitudinal reinforced bar of the columns is deformed steel bars ١٢mm diameter was used, and ٦mm diameter bars are used as ties. The strength properties of the reinforcement were determined from three specimens of each type. as shown in Table (١). Carbon fiber reinforced polymer (CFRP) (SikaWrap-٣٠٠C) imported by Sika Company branch Erbil were used for strengthening of columns. Sika Wrap-٣٠٠C is a unidirectional woven carbon fiber fabric for the dry or wet application process, one roll of carbon box is ١٠٠m length with ٥٠٠mm width, ٠.١٦٦mm thickness and fabric density ١.٧٩g/cm٣. the manufacturing company are shown in Table (٢). Sikadur-٣٣٠ epoxy impregnation resin is a two part (resin and hardener), solvent free, thixotropic epoxy based impregnation resin/ adhesive. This epoxy is used for CFRP

The specimens in each group were tested at ٠, ٧٥, and ١٥٠mm eccentricity from center line of the column cross-section. The specimens tested under an axial concentric loading are denoted by ٠٠, specimens tested by applying

type Sikawrap-٣٠٠C fabric reinforcement for the dry application method. Also, Sikadur-٣٢ Epoxy resin is applied for bonding a new concrete to existing concrete. It is suitable for bonding concrete panel with the existing column. The concrete mix proportion is designed according to ACI-Code to achieve the strength of ٣٠MPa. The mix proportion was (١:٢.٨٥:٣.٣٤) by weight. The designed water cement ratio was ٠.٥٣. Concrete cylinder specimens were cast for each batching and tested, to determine the compressive strength of concrete.

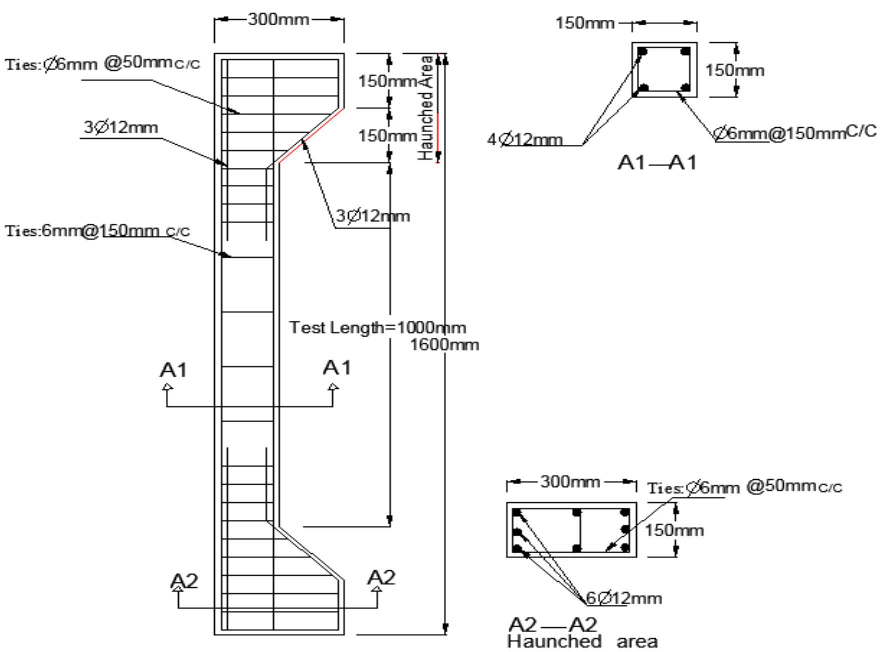


Fig. (١) Reinforcement details for all columns

Table (١) Strength properties of reinforcement

Size (mm)	Area (mm٢)	Yield strength f_y (MPa)	Ultimate strength f_u (MPa)	Elongation %
٦	٢٨.٢٧	٥٥٨	٦٢٠.٨	٣.٩
١٢	١١٣	٥٦٨	٦٥٩	١٨

Table (٢) Properties of Sika wrap-٣٠٠C

Tensile strength (MPa)	٣,٩٠٠
Tensile E-Modules (MPa)	٢٣٠,٠٠٠
Elongation at Failure %	١.٥
Fabric width (mm)	٥٠٠
Fabric thickness (mm)	٠.١٦٦

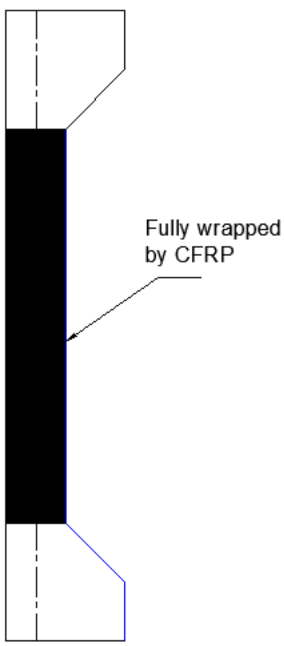


Fig.(٢) Reinforced concrete columns wrapped by CFRP sheets (CF)

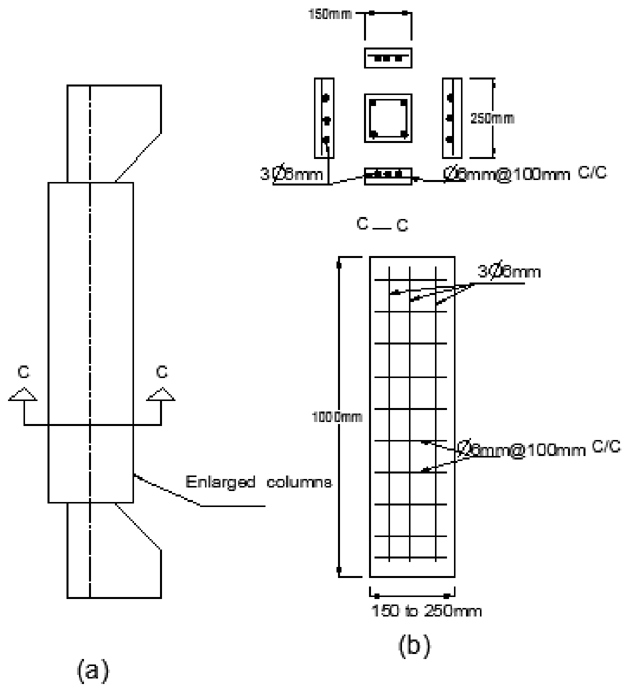


Fig. (٣) a. Enlargement of reinforced concrete column with panels (CE) using just epoxy

b. Details of panels

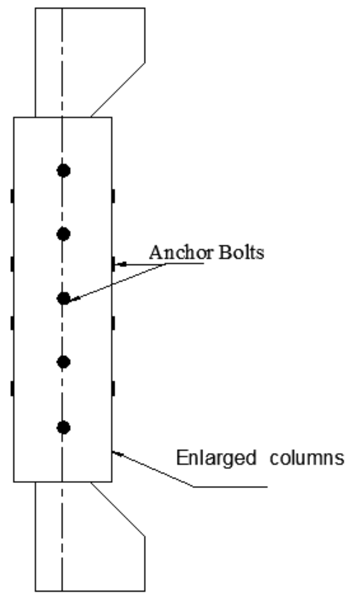


Fig. (٤) Enlargement of reinforced concrete column (CEA) using epoxy and anchored bolt.

٤. Process of Strengthening

Three different method of strengthening were used in the research, The first method of strengthening for column is wrapped with three layers of CFRP, The concrete surface was roughened by the steel brush, then the surface of the concrete was washed and cleaned till it was free from loose, dust, oil coating from mould, and unsound materials. The column surface was coated with Sikadur٣٣٠ epoxy type, epoxy resin was spread on the wanted area of the specimen then the first layer of CFRP was attached. The surface of the fiber sheet was pressed with hand and roller to remove the warping or buckling of the sheets on the column surface, see Fig.(٥). According to manufacture manual after ١٠ hours epoxy resin was spread again on the surface of the first layer of CFRP then the second layer was attached. The same procedure was followed until three layers of CFRP were bonded, at least ١٠٠mm overlap was maintained. The specimens were then left to dry for ١٠ days as specified by the manual. The second method, of strengthening is done by precast panels, enlargement process was done after ٢٨ days. The strengthening consists of ٤-panel for each column and with the same properties of the column material. Before bonding of concrete panel, the surface of the column was cleaned from any dust. Then the column surfaces were coated with epoxy types Sikadur٣٢, slow hardener the adhesive was evenly spread on the surfaces of the column and panel surface. Four concrete panels were attached to the surface of the column, then the column and surrounding panels were pressed together from two perpendicular sides of the column, and left to dry for one week. For the third method of strengthening, same as second method except anchored bolts were used. The columns were drilled by ١٠mm diameter at specified locations, then the column were cleaned and coated by Sikadur-٣٢ as mentioned above, after that the anchor bolts were used. See Fig.(٤).

Fig. (٥) Installation of CFRP sheets.

٥. Loading Cap

The loading Cap consists of a set fixed at haunched end of the column. The set consist of two plates (١٧٠ X

٣٦٠)mm and ٥٠mm thickness, each plate was grooved with a semi-circular shape along ١٧٠mm, the two plates were connected by a roller with a φ٥٠mm diameter put inside the grooves of the two plates. The eccentric load was created for the column by grooving three semi-circular shape, the center of each groove far from the column center line by (٠, ٧٥, and ١٥٠)mm. A ٦mm thick plate with height of about ١٠٠mm were welded to base plate, that to be attached to the column. The side plates have ٦-φ١٢mm bolts, to fix the column with the loading cap. See Fig.(٦).

Also, a ٨mm rubber plastic was used to avoid local failure between plate and specimen.

Fig. (٦) loading cap

٦. Testing Procedure

The twelve columns were tested at age of around ١٢٠ days. Nine columns were painted white in order to observe failure type.

The apparatus used to apply the load was a computerized universal testing machine (steel frame) with max. capacity of ٢٥٠٠kN located in the Engineering Laboratory of the university of sallahaden-Erbil. Firstly, in order to level the column haunched end attached to loading machine, high strength plaster was mixed, then poured and leveled in to the top of specimens. The loading cap was fixed to the haunched ends of the column by ٦-φ١٢mm bolts. Then, the column was turned around and lifted up to be position inside the testing machine. A small load was applied on the column in order to make it straight. After ensuring that the column was vertical in its location inside the steel frame, LVDT were put at mid height of column. The LVDT wires and the wire of electrical strain gauge were connected to the data logger to measure the lateral deflections and strain at specified location of the column.

All the columns were loaded at same rate of loading high quality digital camera was used during the final stage of the loading to record the behavior and type of failure.

٧. EXPERIMENTAL RESULTS

Experimental results of twelve reinforced concrete columns, subjected to concentric and eccentric loading are presented and discussed. With cast of each specimen, three cylinder ١٠٠mm diameter with ٢٠٠mm height were cast to determine compressive strength of the concrete. While just samples of three cylinders of (١٠٠ x ٢٠٠) mm were cast for all groups to find splitting tensile strength, and just three cylinders (١٥٠ x ٣٠٠)mm were cast for testing modulus of elasticity for all specimens, as shown in Table (٣).

٧.١ Crack Pattern and Mode of Failure

٧.١.١ Concentric Loading Columns (e=٠)

During testing of concentric column CR٠٠ a big problem were encountered, that the specimen fail due to bearing failure between the base plate of steel cap and the concrete of the haunched end of the column, and flight far away from steel frame at a load not reached maximum carry capacity. The reason may be, the surface of concrete that contact with base plate of loading cap may not be perfect straight and leveling, leads to concentric stress in a limited area, so reached maximum bearing capacity of concrete, then leads to local failure in the concrete of the haunched end due to bearing. In the first trial we fail to reach maximum carry capacity of the column CR٠٠. Therefore, we developed the cap, the base plate of the cap that contact with concrete welded with ٦mm side plates along perimeters of base plate, added six bolts inside the ٦mm side plate to fix the base plate of loading cap to the haunched end of the column. Also, three layers of ١٠٠mm of CFRP sheets were used to confine haunched end of the column (near support) to be in sure that avoided bearing failure of the column. Also, ٨mm thick plastic rubber were put between the base plate and the haunched end, to avoid concentration of stress at a point on the contact surface between the base plate and concrete of the column, at the ends.

In the second trial we were successes to reach max carry capacity of the concentric loaded column, and the failure region transfer to column test length (between the haunched end).

During loading stages of column CR٠٠ prior to failure no significant cracks were observed, except a few vertical hair cracks which disappeared after failure. The final failure was occurred, with a sudden and explosive noise. The specimen CR٠٠ failed in a brittle manner, without acoustical or visual clear warnings. The concrete crushed at mid height of the column and the steel bars buckled out words. See Fig. (٧).

The specimen CF٠٠ which is confined with three layers of CFRP sheets, no cracks during loading stages could be observed since the column is surrounded by CFRP sheets. The column failed by noticeable swelling under CFRP sheets at mid height of the column, Also a few cracks were observed at the haunched ends, as shown in Fig.(٨).

The specimen CE٠٠ consist of a column enlarged by precast panel fixed with epoxy. no cracks were noticed before failure, then sudden failure was occurred without any warning and the panels dropped out due to de-bonding with a big sound and explosive noise the longitudinal steel came out. The column shows the same behavior as column CR٠٠ unstrengthened column, at failure, as shown in Fig.(٩).

The specimen CEA٠٠, strengthened by precast panel using epoxy and anchored bolt to fix them to the column. During the loading process was noticed (close to failure) horizontal hair cracks occurred at mid height of panels, cracks occurred at joint of column haunched ends, also vertical cracks occurred between the panel it's self (de-bonding between panels), any sudden failure or explosive not occur, since anchored bolts restrict the panels and the column together, this is mean that anchored bolt leads to be more flexible during failure. as shown in Fig.(١٠). In specimens CF٠٠ and CEA٠٠ when the load reached max capacity, we can stop the loading and not to get explosive, while columns CR٠٠ and CE٠٠ reached ultimate capacity and explosive very suddenly without any warning, the explosive is very dangerous to the surrounding persons.

In specimens CF٠٠, CE٠٠, and CEA٠٠ the cracks appears clearly on side face of haunched parts, and the cracks almost vertical, this is mean that the CFRP and the panels confined increased the column carry capacity, so transfer the cracks to these parts.

During the loading stages and near ultimate no buckling along the height of the column was noticed for all the specimens, this is mean that lateral deflection is very small.

٧.١.٢ Eccentric Loading Columns (e=٧٥mm)

The first crack for reference column CR٧٥ was produced vertically at the compression side of the column, and they propagated in the longitudinal direction of the column. While, the cracks at the tension side expanded in transverse direction (horizontally). The specimen gave warning before failure. Furthermore, close to failure the horizontal cracks opened clearly at mid height of the column, and the final failure occurred by crushing of concrete at compression side. During removal of column from the steel loading frame the buckling of the longitudinal steel bars was observed. As shown in Fig. (١١). The failure of specimen CF٧٥ occurred at compression side by concrete crushing under the CFRP sheets (near haunched area). Also, visible small horizontal cracks occurred at back of the haunched area. as shown in Fig. (١٢).

The specimen CE٧٥ was strengthened by panels and epoxy. The panel at the tension side exhibited horizontal cracks and spread along test area of the column, finally at failure the tension panels far a good distance from the column at one face. During the loading process we noticed, the failure at compression side occurred due to de-bonded between panel from the column face, the panel at compression side of column completely separated from the column. Also, the splitting of concrete at compression side close to haunched end was observed at failure. See Fig. (١٣). The specimen CEA٧٥ enlarged by precast panels, fixed with epoxy and anchored bolt horizontal cracks were observed at tension side on face of panel and near joint between haunched area and column test area. Vertical cracks were observed between the panels and the column at both compression and tension sides these cracks were very small relative to the vertical cracks of specimen CE٧٥ for the same load at different loading stages, the panels also did not separate from the column. This show that, the anchor bolts are very effective for panels role in strengthening of column to control the cracks. see Fig. (١٤).

٧.١.٣ Eccentric Loading Columns (e=١٥٠mm)

The first cracks and cracks propagation at compression and tension side of the column are similar to CR٧٥, but the width of cracks are wider especially on tension side. These cracks happened at lower loads relative to CR٧٥. This means that the moment increases the number and width of cracks especially at tension zone. Most of the cracks are horizontal, these horizontal cracks spread uniformly (approximately) along column testing area, See Fig.(١٥). The buckling (i.e. curvature) of all columns at eccentricity ١٥٠mm are very clear during loading stages . The specimen CF١٥٠ showed horizontal cracks at 45̊ occur at sides of haunched area. Also, visible small horizontal cracks occurred at back of haunched area. as shown in Fig. (١٦).

The loading process of CE ١٥٠ (the enlarged section by panel and epoxy) led to horizontal cracks , at tension side near mid height of panel. Also, crack propagation happened at the haunched sides at 45̊ degree. The final failure occurred at compression side by de-bonding of the panel, see in Fig.(١٧). In the column CEA١٥٠ horizontal cracks occurred at tension panel and crack propagation occurred at joint between panels and the column near the haunched part, as shown in Fig.(١٨).

At maximum load small vertical cracks occurred between panels, also, a number of cracks at 45̊ observed on side faces of haunched ends, crack number is more than CEA٧٥. The panels with anchor bolts restraint the cracks width during all the loading stages. There is no dangerous to push and separate the panels out of the column. This is mean that the role of anchor bolts is very important in stress transfer among the column and the surrounding panels.

٧.٢ Ultimate load carrying Capacity of the Columns

Test results in terms of the maximum axial load of reference columns over the strengthened columns at different eccentricities are given in Table (٤).

٧.٢.١ Concentric Loading Columns (e= ٠)

The failure load of specimen wrapped with CFRP (CF٠٠) is ٩٣٢kN, that means an increase of failure load by ١٠.٢% compared to unstrengthened specimen CR٠٠ of ٨٤٦kN. For the specimen CE٠٠, the failure load was ٩٤٧kN, i.e. the strengthening with precast panels for concentric load was increased by ١١.٩% compared to unstrengthened specimen CR٠٠. Also, for the specimen strengthened with panels and another bolts CEA٠٠ the failure load was ٩٥٠kN, so there was gain an enhance of the maximum load with ١٢.٣% compared to the unstrengthened specimen CR٠٠. Also we are noted that: Anchor bolt did not affect significantly the max capacity, since the drilling process of the column and the panels may leads to decrease effective area of concrete cross section of the column and disturb the area around the hole.

٧.٢.٢ Eccentric Loading Columns at ٧٥mm

The maximum load carrying capacities of CF, CE, and CEA were ٣٣٨kN, ٤١٦kN, and ٤٠٩kN indicates that, the columns have increased in ultimate loads: ٢٥.٧%, ٥٤.٧%, and ٥٢% for columns strengthened with carbon fiber, panels with epoxy, and panels with epoxy and anchors, respectively. The results show that the columns strengthened with panels with and without anchor bolts have increased about twice the columns strengthened by carbon fibers, for eccentricity at ٧٥mm.

٧.٢.٣ Eccentric Loading Columns at ١٥٠mm

The specimen CF١٥٠ failed at the maximum experimental load of ١٥٥kN, resulting in an increase of ١١.٥% compared to the unconfined specimen CR١٥٠. Also, the max load obtained for the column CE١٥٠ was ١٦٣kN, showing an increase of ١٧.٣% compared to CR١٥٠. In case of the specimen CEA١٥٠, the failure load was of ١٦٨kN, an increase of ٢٠.٩% compared to the reference column. Also, the results indicated that, panels with and without anchors bolts are more efficient in strengthening the columns than carbon fiber at eccentricity of ١٥٠mm. The strengthening of each specimen by different methods (CFRP, concrete panel by epoxy and concrete panel by epoxy and anchor bolts) show that by using concrete panels and anchor bolts are more strengthened and stiffness than that other for different eccentricity, i,e. more economic than using CFRP sheets. Furthermore the difference between in maximum carry capacity CE and CEA were not more, but according to mode of failure, the specimens of CEA have more ductile than CE during failure mode.

Table (٣) Control specimen

Specimens	**Compressive strength (*f'c*) MPa**	**Modulus of Elasticity MPa**	**Splitting tensile strength MPa**
CR٠٠	٢٨.٠	٢٣٨٠٠	٢.٥١
CR٧٥	٣٠.١		
CR١٥٠	٣٦.٢		
CF٠٠	٣١.٣		
CF٧٥	٣٥.٠		
CF١٥٠	٣٣.٩		
CE٠٠	٣٣.٣		
CE٧٥	٣٣.٠		
CE١٥٠	٣٤.٣		
CEA٠٠	٣٢.٠		
CEA٧٥	٣٢.٧		
CEA١٥٠	٣٨.٠		
Mean	٣٣.١٥		
S.D	٢.٥٦		
C.O.V %	٧.٧٣		

Table (٤) Test results for all groups

No	**Specimens**	**Groups**	**Eccentricity (mm)**	**Load at Failure (kN)**	**% of increasing failure load**	**Moment at Failure (kN.m)**	**Mode of failure**
١	CR٠٠	G١	٠	٨٤٦		٠	Compression failure
٢	CR٧٥		٧٥	٢٦٩		٢٠.١٨	Crushing + Tension failure
٣	CR١٥٠		١٥٠	١٣٩		٢٠.٨٥	Tension failure
٤	CF٠٠	G٢	٠	٩٣٢	١٠.٢	٠	Compression failure + CFRP swelling
٥	CF٧٥		٧٥	٣٣٨	٢٥.٧	٢٥.٣٥	CFRP Swelling + tension failure
٦	CF١٥٠		١٥٠	١٥٥	١١.٥	٢٣.٢٥	CFRP de-bonding + Tension failure
٧	CE٠٠	G٣	٠	٩٤٧	١١.٩	٠	Compression failure + Panel debonding
٨	CE٧٥		٧٥	٤١٦	٥٤.٧	٣١.٢	compression failure +Panel de-bonding
٩	CE١٥٠		١٥٠	١٦٣	١٧.٣	٢٤.٤٥	Panel de-bonding + tension failure
١٠	CEA٠٠	G٤	٠	٩٥٠	١٢.٣	٠	Vertical cracks between panels
١١	CEA٧٥		٧٥	٤٠٩	٥٢	٣٠.٦٨	Vertical cracks between panels
١٢	CEA١٥٠		١٥٠	١٦٨	٢٠.٩	٢٥.٢٠	Vertical cracks between panels + tension failure

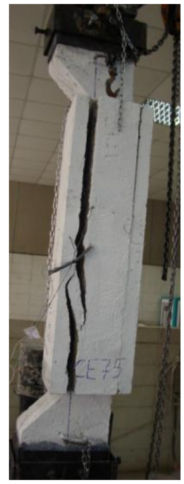
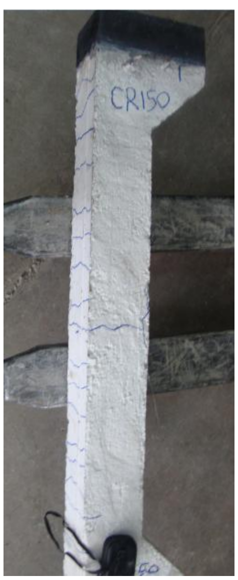



Fig. (٧) Failure in CR٠٠ Fig.(٨) Failure in CF٠٠ Fig.(٩) Failure in CE٠٠ Fig.(١٠) Failure in CEA٠٠




Fi R٧٥ n CF٧٥ in CE٧٥ Fig.(١٤) Failure in CEA٧٥

Fig.(١٥) Failure in CR١٥٠ Fig.(١٦) Failure in CF١٥٠ Fig.(١٧) Failure in CE١٥٠ Fig.(١٨) Failure in CEA١٥٠



٨. Load-

Curves

The lat

mid height of the column is another factor to compare among different types of strengthening and to show the efficiency of each type, since the load-deflection is a sign to stiffness of the column under the load. It is noticed that the slope of load -deflection curve of the reinforce column

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than the other columns strengthened by epoxy or unstrengthened column. This phenomena are evidence at higher stages of loading for columns loaded at eccentricity ٧٥mm and ١٥٠mm as shown in Fig.(٢٠) and Fig.(٢١), respectively.

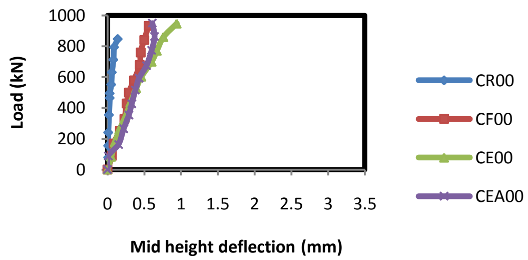


Fig.(١٩) Concentric- load: curves for different types of strengthening

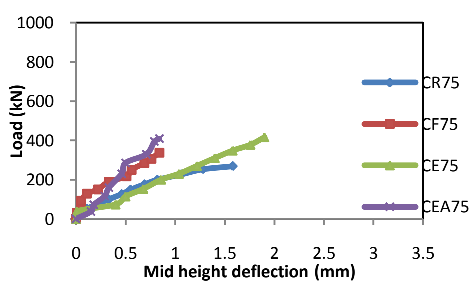


Fig.(٢٠) Eccentric- load: curves for different types of strengthening at e=٧٥mm

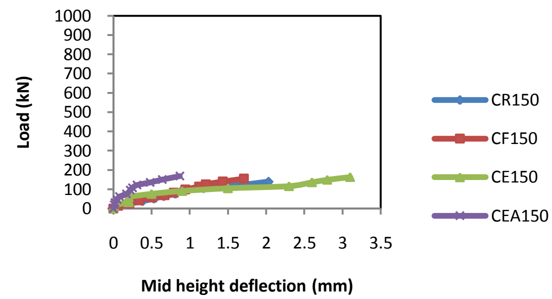


Fig.(٢١) Eccentric-load: curves for different types of strengthening at e=١٥٠mm

٩. THEORITICAL ANALYSIS

Various models for confinement of concrete with FRP have been developed, most of these models assume that the confinement action by the FRP increases as concrete expands. The magnitude of the lateral confinement is dependent on the stress-strain role of the confining device, as the FRP is subjected to tension in the hoop direction, eventual failure occurs when its hoop tensile strength is reached[١٢]. Most of analytical study of strengthening of column are mainly depend on preliminary concept that originally developed by Rechart, Brand tzaeg, and Brown[١٣], in which the strength at failure for concrete confined by a hydrostatic fluid pressure, and expressed in the form:

$f'_{cc} = f'_{co} + k_1 f_l$--------------------------(٥-١)

Where

f'_{cc}: Maximum strength of the confined concrete

f'_{co}: Maximum strength of the unconfined concrete

f_l: Lateral confining pressure

k_1: Confinement effectiveness coefficient.

٩.١ Analytical Results for Columns Strengthening

٩.١.١ ACI ٤٤٠.٢R-٠٨ Method

ACI ٤٤٠.٢R-٠٨ method was used to find the maximum confined concrete compressive strength f'_{cc} and the maximum confinement pressure f_l using Eq.(٥-٢) (Lam and Teng ٢٠٠٣) with the inclusion of an additional reduction factor $\psi_f = 0.95$. The value of this reduction factor is based on the committee's judgment. [٣٣]

$f'_{cc}=f'_{co}+\psi_f\ 3.3 k_a f_l$------------------(٥-٢)

where

$f_l = (2 E_f\, n\, t_f\, \varepsilon_{fe}) / D$--------------------(٥-٣)

For specimen wrapped by concrete panels it is proposed to use Eq.(٥-٤) instead of Eq.(٥-٣):

$f_l = (2 f_t\, n\, t_f) / D$--------------------(٥-٤)

f'_{co} : unconfined cylinder compressive strength of concrete

ε_{fe} : effective strain level in the FRP at failure $\varepsilon_{fe} = \kappa_\varepsilon \varepsilon_{fu}$

for combined axial and bending it must be $\varepsilon_{fe} = 0.004 \le \kappa_\varepsilon \varepsilon_{fu}$

k_ε : strain efficiency factor, by Lam and Teng k_ε = ٠.٥٨٦[١٤]

t_f : Thickness per ply

ε_{fu}: Rupture strain

E_f : Modulus of Elasticity of CFRP sheets

f_t :Tensile strength of concrete; f_t= ٠.٥$\sqrt{f'co}$

D: diagonal of the rectangular cross section as shown in Fig. (٢٢), $D = \sqrt{b^2 + h^2}$

k_a: shape efficiency factor depend on two parameters: The cross-sectional area of effectively confined concrete A_e, see Fig.(٢٢), and the side aspect ratio h/b as shown below:

$$\kappa_a = \frac{A_e}{A_c}\left(\frac{b}{h}\right)^2$$ ------------------------------------- (٥-٥)

and

$$\frac{A_e}{A_c} = \frac{1 - \dfrac{\left[\left(\frac{b}{h}\right)(h-2r_c)^2 + \left(\frac{h}{b}\right)(b-2r_c)^2\right]}{3A_g} - \rho_g}{1-\rho_g}$$ ----------------(٥-٦)

where r_c : radius of the corners

ρ_g : longitudinal steel reinforcement ratio

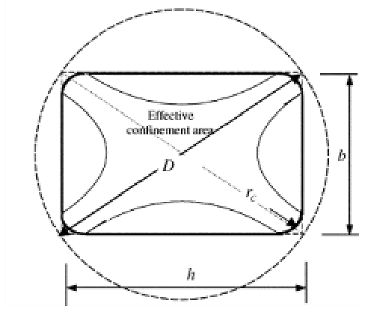


Fig.(٢٢) Equivalent circular cross section (Lam and Teng ٢٠٠٣)

The maximum compressive strain in the FRP sheets and panel confined concrete ε_{ccu} can be found by method of ACI ٤٤٠.٢R-٠٨using Eq.(٥-٧). This strain should be limited to the value given in Eq.(٥-٨) to prevent excessive cracking and the resulting loss of concrete integrity.[١٤]

This equation is also used for calculation of compressive strain in the confined materials.

$$\varepsilon_{ccu} = \varepsilon'_c\left(1.50 + 12\kappa_b \frac{f_l}{f'_c}\left(\frac{\varepsilon_{fe}}{\varepsilon'_c}\right)^{0.45}\right)$$ ---------(٥-٧)

---------(٥-٨)

where

k_b: Shape factor, $\kappa_b = \frac{A_e}{A_c}\left(\frac{h}{b}\right)^{0.5}$

ε'_c: compression strain in concrete, ε'_c = ٠.٠٠٢

ε_{fe} : effective strain level in the FRP at failure $\varepsilon_{fe} = \kappa_\varepsilon \varepsilon_{fu}$ for combined axial and bending must it be $\varepsilon_{fe} = 0.004 \le \kappa_\varepsilon \varepsilon_{fu}$

٩.١.٢ Saafi et al Method:

Saafi, Toutanji, and Li[١٥] have also used regression analysis based on their experimental results to device an expression to predict the ultimate strength of confined specimen. This method also used for calculations of column confined by precast panels. The confined strength expression recommended is given by:

$$f'_{cc} = f'_{co}\left[1 + 2.2\left(\frac{2tf_f}{Df'_{co}}\right)^{0.84}\right]$$ -----------------------(٥-٨)

t_f : Thickness per ply

f_f : Ultimate tensile strength of CFRP, or f_t = Tensile strength of concrete

D: diagonal of the rectangular cross section as shown in Fig. (٢٢), $D = \sqrt{b^2 + h^2}$

$\varepsilon_{ccu} \le 0.01$

٩.١.٣ Proposal Model-١

The proposal is based on observation that a linear relationship exists between the confined strength and the lateral confining pressure from the FRP as shown in Fig.(٢٣) . The proposed equation was Eq.(٥-٩) is given by:

f'_{cc}/f'_{co} = ١.٩٥٥ f_l/f'_{co} + ١.٣٦٨--------------------(٥-٩)

Where

f_l : Lateral confining pressure, refer to Eq.(٥-٣) and Eq.(٥-٤), ACI٤٤٠.٢R-٠٨ method

D: diagonal of the rectangular cross section as shown in Fig.(٢٢), $D = \sqrt{b^2 + h^2}$

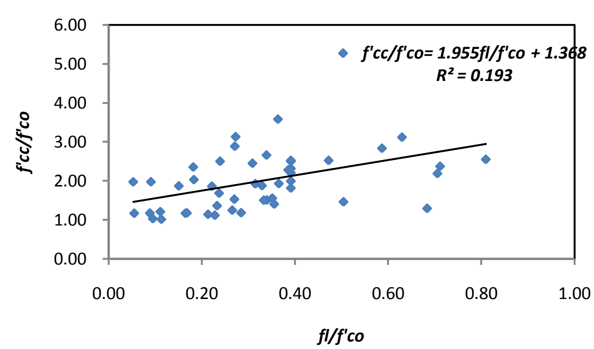


Fig.(٢٣) Normalize confinement compressive strength with FRP versus lateral confining pressure for proposal-١

٩.١.٤ Proposal Model-٢

The first comprehensive tests on confined concrete with lateral hydrostatic pressure and spiral reinforcement were reported by Richart et al[١٣], Eq.(٥-١). To calculate the lateral stress f_l applied to the square concrete column by confinement, a free-body diagram of a circular cross section is considered (i.e. effective area), as shown in Fig.(٢٤).

$f'cc/f'co = k * fl/f'co + 1$ -----------------(٥-١٠)

$f_l = ٢ f_t\, t / D$ -------------------------(٥-١١)

For square D = ٠.٨b

and $k = A\,(A_{confined} / A_{gross})$

or $k = (A_{confined} / A_{gross})^{B}$

*A and B:*Constant

Based on the experimental result on CE٠٠ and CEA٠٠ we found that:

$k = ٣.٥٦[(\pi D^{٢}) / (٤A_{gross})]$ or $k = [(\pi D^{٢}) / (٤A_{gross})]^{-٠.٨١٥}$ ------(٥-١٢)

Where

f_{cc}: Maximum strength of the confined concrete

f'_{co}: Maximum strength of the unconfined concrete,

f_l: lateral confining pressure

k: confinement effectiveness coefficient.

$A_{confined}$: Confined area

A_{gross}: gross area

*A and B:*Constant

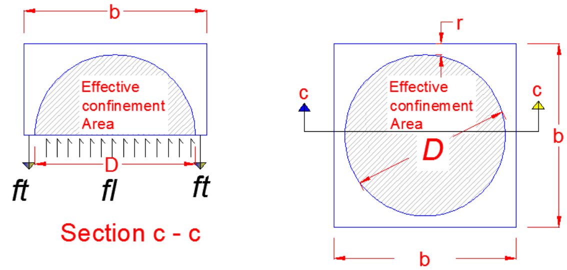


Fig.(٢٤) Confinement area of square section

٩.٢ Comparison between Experimental and Theoretical Results

Table (٥) shows the experimental and analytical load results of groups G١, G٢, G٣ and G٤. The results show that for each method and proposal except ACI ٤٤٠.٢R method the safety factor are greater than one (i.e., safety factor means $P_{Exp.}/P_{Theo.} \geq$ ١).

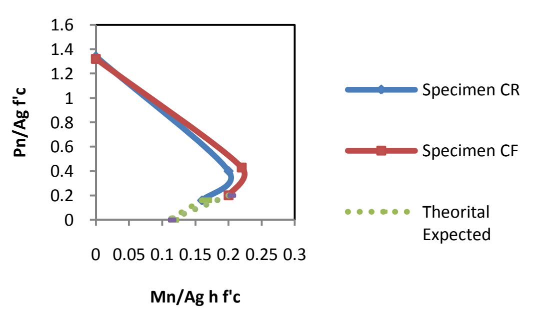
٩.٣ Interaction Diagram

A better approach providing the basis for practical design, is to construct a strength interaction diagram defining the failure load and failure moment for a given column for the full range of eccentricities from zero to infinity. as showing in Fig.(٢٥) to Fig.(٢٧) for columns strengthened with CFRP confined with precast concrete panels, with epoxy, and columns confined with epoxy and bolts, respectively. The results show that, specimens wrapped with CFRP have slight difference relative to un wrapped columns. While in specimen confined with precast panels have significant difference relative to unconfined. The interaction diagrams for each group for experimental and calculated results are plotted, and shown in Figs.(٢٨), to (٣٠). The results show that for columns confined with CFRP sheets, the ACI ٤٤٠.٢R method have great difference relative to experimental works, that means too un-conservative (i.e. theoretical >> experimental) compared to other methods as shown in Fig.(٢٨). While, for specimens column confined with panels by epoxy and the specimens columns confined with panels by epoxy and anchors bolts, the methods and proposals for analysis have values less than experimental results value, that means all methods are conservative, as shown in Fig.(٢٩) and Fig.(٣٠).

Table (٦) Comparison between experimental and analytical results

		ACI٤٤٠.٢R	Saafi Method	Proposal-١	Proposal-٢	

Specimen	Test Results kN									ε_{ccu}
		$P_{Theo.}$ kN	$\frac{P_{Exp}}{P_{Theo.}}$ kN	P_{Theo} kN	$\frac{P_{Exp}}{P_{Theo.}}$ kN	$P_{Theo.}$ kN	$\frac{P_{Exp}}{P_{Theo.}}$ kN	$P_{Theo.}$ kN	$\frac{P_{Exp}}{P_{Theo.}}$ kN	
CR٠٠	٨٤٦	٧٩٢	١.٠٦							
CR٧٥	٢٦٩	٢٤٥	١.٠٩							
CR١٥٠	١٣٩	١٣٢	١.٠٥							
CF٠٠	٩٣٢	١١٣٦	٠.٨٢	١١٨٧	٠.٧٩	١٣٩٣	٠.٦٧	١١٤٥	٠.٨١	٠.٠١
CF٧٥	٣٣٨	٣٨٨	٠.٨٧	٣٤٢.٦	٠.٩٩	٣٤٩.٥	٠.٩٧	٣٠٣.٥	١.١١	٠.٠٠٥
CF١٥٠	١٥٥	١٨٤	٠.٨٤	١٤١.٩	١.٠٩	١٤٥.٩	١.٠٦	١٣٨.٦	١.١٢	٠.٠٠٥
CE٠٠	٩٤٧	٩٢٦	١.٠٢	٩٧٤	٠.٩٧	١١٦٠	٠.٨٢	٩٢٥.٨	١.٠٢	٠.٠٠٣
CE٧٥	٤١٦	٣٥٦	١.١٧	٢٨٢.٢	١.٤٧	٣٢٣.٩	١.٢٨	٢٦٩.٢	١.٥٥	٠.٠٠٣
CE١٥٠	١٦٣	١٨١	٠.٩٠	١٣٢	١.٢٣	١٤٢.٣	١.١٥	١٣٣.٣	١.٢٢	٠.٠٠٣
CEA٠٠	٩٥٠	٩٠٠.٦	١.٠٦	٩٤٨	١.٠٠	١١٢٦	٠.٨٤	٨٩٩.٥	١.٠٦	٠.٠٠٣
CEA٧٥	٤٠٩	٣٥٤	١.١٦	٢٨٠.٦	١.٤٦	٣٢٢	١.٢٧	٢٦٧.٦	١.٥٣	٠.٠٠٣
CEA١٥٠	١٦٨	١٨٦.٨	٠.٩٠	١٣٨.٦	١.٢١	١٤٦	١.١٥	١٣٥.٧	١.٢٤	٠.٠٠٣
Mean			٠.٩٧		١.١٣		١.٠٢		١.١٨	
Standard deviation			٠.١٣		٠.٢٢		٠.٢٠		٠.٢٢	
Coefficient of variation %			١٣.٥		٢٢.٩		٢١		٢٣.٧	



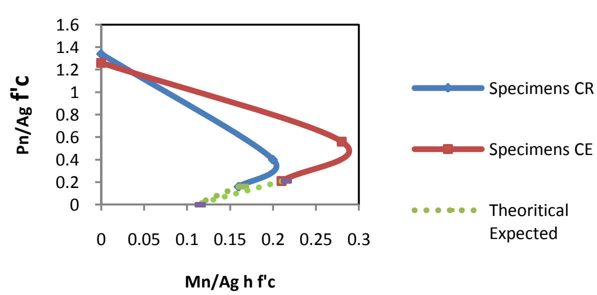
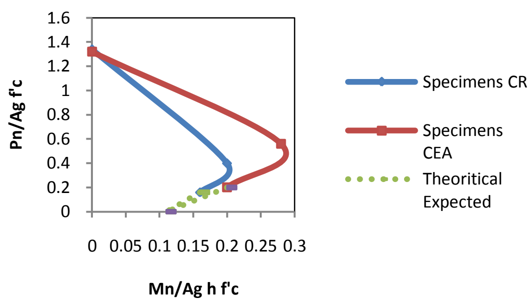


Fig.(٢٥) Interaction diagram for reference columns and columns confined with CFRP sheets

Fig. (٢٦) Interaction diagram for reference columns and columns confined with panels by epoxy



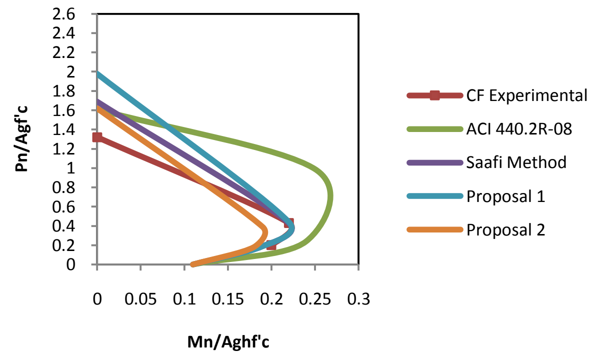
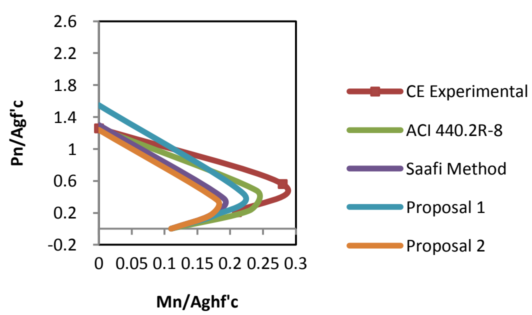


Fig.(٢٧) Interaction diagram for reference columns and columns confined with panels by epoxy and bolts

Fig.(٢٨) Interaction diagram for experimental and theoretical (methods and proposals) for CF



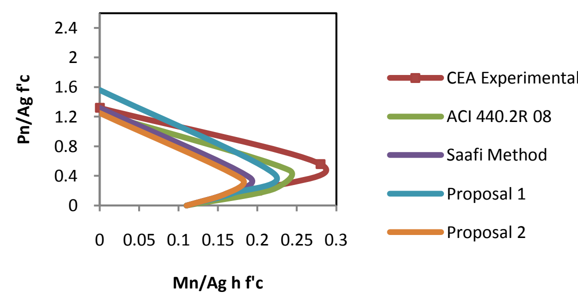


Fig.(٢٩) Interaction diagram for experimental and theoretical (methods and proposals) for CE

Fig.(٣٠) Interaction diagram for experimental and theoretical (methods and proposals)for CEA

١٠. Conclusions:

١. The increase in axial load carrying capacity of concentric columns strengthened with CFRP, precast panels by epoxy, and precast panels by epoxy and bolts were found be ١٠.٢%, ١١.٩%, and ١٢.٣%, respectively, in comparison with reference column (unstrengthened columns).

٢. For strengthened columns; with CFRP, precast panels, and precast panels by anchors bolts; the increased axial loads capacity for specimens loaded at eccentricity e=٧٥mm, were found to be ٢٥.٧%, ٥٤.٧% and ٥٢%, respectively, over control specimen, CR٧٥. Furthermore, the columns loaded at eccentricity ١٥٠mm the increase were ١١.٥%, ١٧.٣% and ٢٠.٩%, respectively, with respect to unstrengthened columns, CR١٥٠.

٣. In general, columns strengthened by precast panels are more effective in resisting external loads relative to columns strengthened by CFRP sheets, the same result is obtained for different eccentricity ratios.

Furthermore, specimens strengthened with panels that fixed by epoxy and bolts failed gradually, giving ample warning before final collapse, while in specimens confined by panels just with epoxy failure was explosive, without any warning before failure.

٤. The columns loaded at eccentricity ٧٥ mm have higher carry capacity than columns under eccentricity ٠.٠ mm or ١٥٠ mm. The same notes were observed for different types of strengthening used in this research.

٥. Confined reinforced concrete columns with CFRP sheets and panels show bilinear load deflection responses, with significant enhancement in strength and ductility.

٦. The load deflection curves for columns at different eccentricity show that the difference are more evidence between concentric loaded column and the other two eccentric loading columns.(i.e. relative to concentric load) for eccentric loads at ٧٥mm and ١٥٠mm are shows: for unstrengthened column (CR) increased by ٢١٤%, and ٥٠٨%, for columns strengthened by CFRP sheets increased by ١٧٦%, and ٥٠١%, for columns strengthened with panel by epoxy increased by ١٢٦%, and ٤٨١%, and for columns strengthened with panel by epoxy and anchors bolts increased by ١٣٢%, and ٤٦٥%, respectively, compared to concentric loads for each groups.

٧. The load deflection curves of columns Strengthened by precast panels fixed by epoxy and anchor bolts are more stiffness (i.e. slope of curve) than other ways of strengthening.

٨. The ultimate strain recorded for CFRP sheets never reached to its ultimate value that suggested by the manufactures due to reach to failure of ultimate loads before reached to ultimate strain.

٩. The measured concrete strain above precast concrete panel was less than the value of concrete strain of reference column due to the de-bonding of precast panels.

١٠. The proposed design formula (proposed-١) was suggested for computing the confinement compressive strength (***f'cc***) of column externally bonded with CFRP sheets gave reasonable results with average, standard deviation and coefficient of variable of ١.٠٢, ٠.٢, and ٢١%, respectively.

١١. The proposed equations for strengthening of columns by CFRP or precast panels for calculation of axial load and moment on the limited data from literature, show a good results for ACI ٤٤٠ and proposal-٢ relative to proposal-١or Saafi methods.

REFERENCES

١. Nilson, A. H., Darwing, D. and Dolan, Ch. W. **" Design of Concrete structures"**, Fourteenth Edition, Published by McGraw-Hill Book Company, ٢٠١٠, ٢٦٢pp.

٢. ACI ٣١٨M-١١ Code **"Building Code Requirements for structural concrete"**, American Concrete Institute, Farmington Hills, ٢٠١١, ١٤٤pp.

٣. Bisby, L. A. and Williams, B. K. **"An Introduction to FRP Strengthening of Concrete Structures"**, Prepared by ISIS Canada, February ,٢٠٠٤, pp١-٤.

٤. Bakis, C. E., Bank, L. C., Brown, V. L., Consenza, E., Davalos, J. F., Lesko, J. J., Machida, A., Rizkalla, S.H., Triantafillou, T. C. **"FRP Composites for Construction-State-of-the-Art Review"**, Journal of Composites for Construction, ASCE, May ٢٠٠٢, pp٧٣-٨٧.

٥. Hadi, M. N. S.,**" Behaviour of FRP Wrapped Normal Strength Concrete Columns under Eccentric Loading"**, Elsevier, Composite Structures ٧٢, February, ٢٠٠٥, pp٥٠٣-٥١١.

٦. Lei, X., Pham, T.M, and Hadi, M. N. **"Behaviour of CFRP Wrapped Square RC columns under eccentric loading"**, Australasian Structural Engineering Conference, ٢٠١٢, ٨pp.

٧. Hadi, M. N. S. **"Comparative of FRP Strengthened Concrete Columns under eccentric Compression Loading"**, Elsevier, Composite Structures ٧٤, April,٢٠٠٥, pp ١٢٧-١٣٥.

٨. Lignola, G. P., Prota A., Manfredi G. and Cosenza E. **"Deformability of Reinforced Concrete Hollow Columns Confined with CFRP"**, ACI Structural Journal, V.١٠٤, No.٥, September-October,٢٠٠٧, pp ٦٢٩-٦٣٧.

٩. Le, T., Lester, M. T. and Hadi, M. N. **"Effect of Ply Configuration on Hollow Square Reinforced Concrete Columns Confined with Carbon Fiber Reinforced Polymer"**, ٢٢nd Australasian Conference on the Mechanics of Structures and Materials, ٢٠١٣, pp١٠٧-١١٢.

١٠. Bouvier, A. C. **"Techniques of Seismic Retrofitting for Concrete Structures"**, Tufts University, grants MIT Permission, June ٢٠٠٣.

١١. Lixian, L., Reddy, D.V. and Sobhan, K. **"Strengthening of Fire-Damaged Columns by Cross-Sectional Enlargement"**, A Computational Evaluation Seventh LACCEI Latin American and Caribbean Conference for Engineering and Technology, ٢٠٠٩. ٣٢. Richart, F. E., Brandtzaeg, A. and Brown, R. L. **"The Failure of Plain and Spirally Reinforced Concrete in Compression"**, University of Illinois Bulletin, Building No.١٩٠, Engineering Experiment Station, Vol. XXVI, No.٣١, April ٢, ١٩٢٩.

١٢. Matthys, S. Toutanji, H. Audenaert, K., and Taerwe, L. **"Axial Load Behavior of Large-Scale Columns Confined with Fiber Reinforced Polymer Composites"**, ACI Structural Journal, Vol. ١٠٢, No.٢, March-April,٢٠٠٥, pp ٢٥٨-٢٦٧.

١٣. Richart, F. E., Brandtzaeg, A. and Brown, R. L. **"The Failure of Plain and Spirally Reinforced Concrete in Compression"**, University of Illinois Bulletin, Building No.١٩٠, Engineering Experiment Station, Vol. XXVI, No.٣١, April ٢, ١٩٢٩.

١٤. ACI Committee ٤٤٠, **"Guide for the Design and Constructions of Externally Bonded FRP Systems For Strengthening Concrete Structures"**, (ACI ٤٤٠.٢R-٠٨) American Concrete Institute, Farmington Hills, ٢٠٠٨, ٧٦pp.

١٥. Saafi M., Houssam A., Toutanji and Li Z. **"Behaviour of Concrete Columns Confined with Fiber-Reinforced Polymer Tubes"**, ACI Materials Journal, V.٩٦, No.٤, ١٩٩٩, pp ٥٠٠-٥٠٩.