Al-Nahrain Journal for Engineering Sciences (NJES) Vol.20 No.3, 2017 pp.625-635

Strengthening and Retrofitting of Reinforced Concrete Hollow Columns using High Strength Ferrocement Fibers Composites

Akram S. Mahmoud
Civil Engineering Department,
College of Engineering,
University of Anbar
dr.akramsh1@gmail.com

Sinan A. Yaseen
Civil Engineering Department,
College of Engineering,
University of SalahAldin

Samar S. Shafeeq
Civil Engineering Department,
College of Engineering,
University of Anbar

Abstract:

Eight RC circular hollow columns (external diameter = 220 mm, internal diameter = 100 mm, length = 1000 mm and the hollow part = 700mm) casted and strengthened with ferrocement fibers composites to illustrate the behavior of these columns under concentric and eccentric axial compression force. Two columns where used as reference columns, which were repaired after failure to be tested as retrofitted columns. Six specimens were strengthened with one and two WWM layers as required. The variables considered included number of the WWM layers (N), the loading configuration and the eccentricity value (e) of loading. The ferrocement thickness was constant at 20 mm in all retrofitted and strengthened specimens.

The test results revealed that the maximum increase in the ultimate concentric loads were 67% by strengthening the reference column with two layers of WWM, and the maximum increase in the ultimate eccentric load of columns was 78% by increasing of the WWM from one to two layers. For a constant number of WWM layers, the change from concentric to eccentric force caused a decrease in the ultimate load value attaining 73.5% for one- layer WWM strengthened columns. The failure of columns occurred by yielding of steel reinforcement followed by concrete crushing (i.e. tension failure).

Key Words: Hollow Columns, Ferrocement, High Strength Concrete, Strengthening, and Repair.

1. Introduction

Failure of the most authoritative structural elements such as columns may lead to total collapse of a building structural frame , as they represent the only structural elements that convey the total vertical loads of the building to the earth. They may lose their strength and stiffness due to damages occurred in their service life. Therefore, rehabilitation is necessary in case of noticeable crack for further carrying out loads and transmitting them to the ground [1]. There are many configurations of strengthening reinforced concrete structures. Jacketing is the most popularly used method for strengthening the building columns. The most common types of jackets are steel jacket, reinforced concrete jacket, fiber reinforced polymer composite jacket, jacket with high tension materials like carbon fiber wraps and glass fiber wraps. The main purposes of jacketing are (i) increasing concrete confinement especially for circular cross-sectional columns, (ii) increasing shear strength, and (iii) increasing flexural strength [2].

This study, illustrats the behavior of circular hollow columns confined by ferrocement composite. Ferrocement is a type of thin walled stiffener for reinforced concrete members, it is commonly constructed of hydraulic cement mortar reinforced with closely spaced layers of continuous and relatively small size wire mesh [3]. The choice of ferrocement as a strengthening material instead of steel plates or any type of fibers, in this study was because it was considered an alternative solution from conventional strengthening techniques, because FRP materials are effected by ultra violet and temperature changes: while steel strips have extreme corrosion state in wet and humid environment. Secondly, it is suggested to rail bridge in Hit city, where that site is exposed to highly extreme temperature changes that cause emanation of sulphurous gases and damaging other conventional materials.

Compared with conventional reinforced concrete, ferrocement is reinforced in two directions; therefore, it has homogenous isotropic properties in two directions. Benefiting from its usually high reinforcement ratio, ferrocement generally has a high modules of rupture and high tensile strength. In addition, because the specific surface of ferrocement reinforcement is higher than that of reinforced concrete, larger bond forces develop with matrix resulting in average crack spacing and crack width of magnitudes smaller than those of conventional reinforced concrete [4]. In (1989), Razvi and Saatcioglu [5] investigated the behavior of small-scale reinforced concrete columns specimens when Welded Wire Fabric (WWF) was used as lateral reinforcement to confine the concrete core of the column. Various combinations of WWF and tie reinforcement have been used as confinement steel. The experimental results showed that the use of WWF as confinement reinforcement improves concrete strength and ductility very significantly.

In (2003), *Takiguchi* [6] studied the behaviour and strength of reinforced concrete columns strengthened using ferrocement jackets. Six identical reference columns were prepared and tested after being strengthened with circular or square ferrocement jackets. The main parameters included the jacketing schemes and the number of layers of wire mesh. The results showed that the peak strength and ductility is enhanced tremendously.

In (2012), *Shahzada et al.* [7] studied the retrofitting of masonry columns using ferrocement. Two sizes of columns were used. The (228.6 x 228.6) mm retrofitted columns, gave strength 1.5 times more than the strength of un-retrofitted (228.6 x 228.6) mm columns, while (342.9 x 342.9) mm retrofitted columns gave strength 1.35 times more than the strength of un-retrofitted columns. The test results indicated that the ferrocement specimens having one layer of wire mesh wrapped around showed an increase in failure load up to (60-70)% as compared to control specimen of simple brick masonry columns. The cracking resistance and stable crack growth mechanism of bare masonry columns was improved due to the provision of ferrocement coating. The ferrocement columns were kept in one piece after failure unlike bare masonry columns.

In (2013), *AL-Sulyfani et al.* [8] examined the behavior of reinforced concrete short columns subjected to combined axial load with flexure strengthening by ferrocement. Seven columns were tested with dimensions (150 x 250 x 2350) mm, out of which, one is the control-unstrengthened column tested to failure to find out their load carrying capacities. Six columns strengthened with ferrocement. The main objective of this work was to investigate the effects of ferrocement thickness and number of wire meshes on the load capacity of those columns. The test results showed that, the increasing wire mesh layers from 2 to 5 caused an increase in the ultimate load of the strengthened column with ferrocement compared with the control column. When 20 mm ferrocement thickness was used with 5-wire mesh layers, the ultimate load increased by 36.8% when compared to the control column, whereas using 30 mm thick ferrocement within 5 wire mesh layers cased an increase of 48%.

In (2015), *Sirimontree et al.* [9] focused on the behavior of reinforced concrete columns encased by longitudinal steel and ferrocement under static axial loading. RC column specimens were encased by vertical steel reinforcements, wrapped by varying amount of wire mesh and then covered with cement mortar. The test results showed significant improvement of strength and ductility of strengthened column compared with reference specimen. Ductility is also significantly improved by the increase of the volume of wire mesh. Modified ACI equation can be applied to predict static strength of both RC column and RC column strengthened by additional steel and ferrocement.

2. Research Significance

Compression columns potentially support a variety of structures such as bridge decks and floor slabs. Columns vary in physical shape depending on their application, although typically they are either circular or rectangular, solid or hollow, for the simplicity of construction. The columns are the alone elements in structures which undergo the vertical loads from slabs, girders and beams and transmitted to foundation which in turn transmitted to the earth. These elements need to be strengthen because the deterioration of these elements cause the total failure of this structure. From this point, the importance of columns strengthening is required.

In addition, the attempts of investigation of strengthened reinforced concrete circular hollow columns are still few. Nevertheless, ferrocement has high potential as a retrofit or strengthening material, for example ferrocement jackets can be used on reinforced concrete columns. This work is an attempt to respect reinforced concrete circular hollow columns strengthened with ferrocement fibers composites.

3. Experimental Work

3.1 Column description and casting

Eight reinforced concrete hollow columns were tested under different loading systems. In all columns, the cross section was circular with external diameter of 220 mm and internal diameter of 100 mm, with overall length of 1000 mm. The hollow part inside the column was 700 mm in length; with 150 mm length of solid concrete up and down of the column was introduced at the top and bottom end of each column to represent the supports (base and head), and to prevent the failure at supports. Six bars of 10 mm diameter steel having yield strength of 478 MPa, and 575 MPa ultimate strength were used as longitudinal steel reinforcement. A 6 mm diameter bars having 578 MPa yield strength, and 641 MPa ultimate strength were used for ties spaced at 50 mm c/c at support region of column and 74 mm c/c at the hollow core of column, as shown in **Fig. (1)**.

The main variables that have been considered in this study included the number of welded steel wire meshes embedded in the strengthening or repairing layer, with the loading configurations system and the eccentricity of eccentric loading.

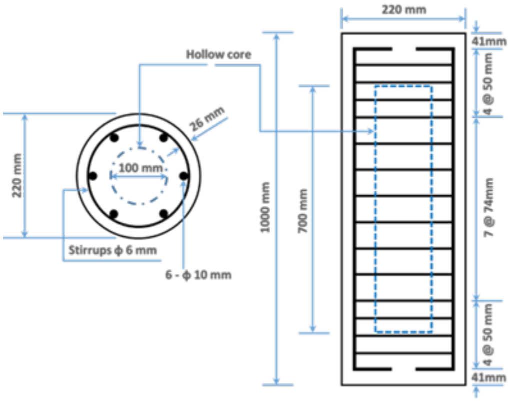


Figure (1): Reinforcement details in the specimen

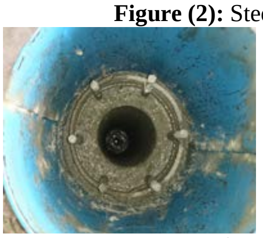
Cement, fine aggregates, coarse aggregates and reinforcing steel bars were used in casting the columns. The cement used in this study was Ordinary Portland Cement (OPC) type-I. The chemical composition and physical properties conformed to the [***ASTM C150-00***] [10]. The fine aggregates (sand) and coarse aggregates (gravel with maximum size of 10 mm) conformed to the [***ASTM C33-03***] [11]. The reinforcing steel bars were tested to comply the [***ASTM A 615/A 615M -03***] [12]. The mix proportion (by weight) of concrete materials was (1: 1.7: 2.64) (cement, sand, gravel) with water to cement ratio (w/c) equals 0.47 which gives slump about 100 mm, where test was done according to ***ASTM C143-00*** [13]. This mix gives compressive strength at (28) days equal to 38 MPa, where this test was done according to ***ASTM C39/C39-01*** [14].

Each column was casted in two steps to make the hollow core in the column. In the first step of casting the parts of mold (the base and two halves of cylinder, as shown in **Fig. (2)**) were oiled and bonds together by bolts, the steel shaft was put in the mold center after the steel reinforcement placing. After that, the first part was casted. The shaft pulls out after casting complete through (1 - 1.5) hrs. In the next cast day, the hollow part was filled with sand, then the second part was casted as shown in **Fig. (3)**.

4. Ferrocement fibers composites application

The ferrocement mortar used in this study is known as *Cempatch S*, the high strength cementitious repair mortar. *Cempatch S* is a one-component polymer modified and fiber reinforced repair mortar. *It* is a blend of dry powders, selected aggregates and fibers (high performance fibrillated polypropylene fibers "*PP Fibers*") which when mixed with water, it produces a thixotropic mortar which is suitable for vertical and overhead application. The specifications of *Cempatch S* and *PP Fibers* have been published by the manufacturer [15]. **Table (1)** shows some properties of Cempatch S and which used in this study. A 50 mm cube specimens of Cempatch S were tested in the laboratory, the average compressive strengths at (7 and 28) days were (59 and 67) MPa, respectively.

Figure (2): Steel Mold of column



a) First part casting of column

b) Hollow core filling with sand

c) Final casting of column

Figure (3): Stages of column specimen casting

Table (1): Technical Cempatch S properties [15]

Colour	**Grey and white**
Compressive strength (MPa)	**> 50 @ 7 days > 60 @ 28 days**
Minimum application temperature	**5°C**

All concrete surfaces attached to ferrocement mortar must be cleaned well to ensure a good bond between the mortar and the concrete surface before applying one coat of acrylic bonding agent *Cempatch AB* (Acrylic bonding and curing agent for cement mixes and concrete repair). *Cempatch AB* should be left to become tacky before applying the repair mortar. The specifications of Cempatch AB published by the manufacturer [15]. In addition, *Cempatch AB* complies to [***ASTM C1059–99, Type 1 & 2***] [16], when tested in accordance with test method

[***ASTM C1042***] [17]. *Cempatch AB* should be brushed vigorously into the presoaked surface making sure to fill all pores and voids. Ensure that the repair mortar is applied when the film is formed and is still tacky. **Table (2)** shows some properties of *Cempatch AB* used in this study.

Table (2): Technical Cempatch AB properties [15]

Colour	**White emulsion**
Tensile bond strength (MPa)	**2.5 @ 7 days**

The strengthened and retrofitted specimens were jacketed with ferrocement fiber composite mortar, and the thickness of mortar was 20 mm in all of the strengthened and retrofitted specimens. The layers of welded wire meshes fabricated from single strand filaments were used as reinforcement for ferrocement jacket. The wire is of 0.6 mm diameter forming 12 mm square mesh, It was created volume fraction as shown in **Table (3)**. Except the reference samples, some of samples strengthened with one layer of WWM and the others with two layers of WWM, see **Fig. (4)** and **Table (4)**.

Table (3): Volume fraction of wire mesh layers

No. of layers	**Thickness of jacketing (mm)**	**Volume fraction (Vf %)**
1	**20**	**0.117**
2	**20**	**0.235**

After completing the surfaces preparation, the welded wire meshes were wrapped around the column in one or two layers as required as shown in **Fig. (5)**, where the overlap, in layer, was at least 120 mm. Cempatch S can be applied by trowel or hand. The mixed mortar should be applied using firm pressure to fully compact the mortar to ensure good adhesion with the steel reinforcements and the substrate, as shown in **Fig. (6)**. Finishing and leveling should be carried out initially by wooden or plastic float. Final finishing should be carried out using steel float.

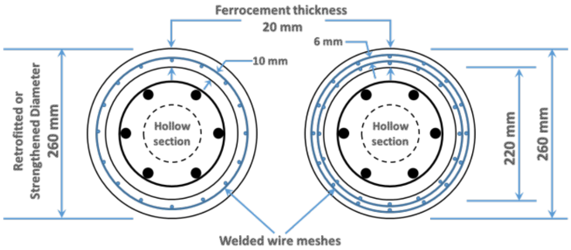


Figure (4): Cross section in the ferrocement jacketed column

Tests of the samples were achieved by applying line load in concentric and various eccentric locations to reach failure. The concentric loading system means that the loads applied in the centroid of the column specimen. The eccentric loading system means that the load is applied at a known distance from centroid of the column sample. In this study, the distances were 0.2 and 0.6 of radius of the column.

Table (4): Strengthening and retrofitting details of the column samples

Group Name	***Column Symbol***	***No. of WWM***	***Brief Description***
Reference Specimens	*SA 0*	*0*	*Axial loading*
	SE0.2r 0	*0*	*Eccentrical loading (Eccentricity = 0.2 radius of column)*
Strengthened Specimens	*SA 1*	*1*	*Axial loading w/one layer of WWM*
	SE0.2r 1	*1*	*Eccentrical loading w/one layer of WWM (Eccentricity = 0.2 radius of strengthened column)*
	SE0.6r 1	*1*	*Eccentrical loading w/one layer of WWM (Eccentricity = 0.6 radius of strengthened column)*
	SA 2	*2*	*Axial loading w/two layers of WWM*
	SE0.2r 2	*2*	*Eccentrical loading w/two layers of WWM (Eccentricity = 0.2 radius of strengthened column)*
	SE0.6r 2	*2*	*Eccentrical loading w/two layers of WWM (Eccentricity = 0.6 radius of strengthened column)*
Retrofitted Specimens	*RA 1*	*1*	*Axial loading w/one layer of WWM*
	RE0.2r 1	*1*	*Eccentrical loading w/one layer of WWM (Eccentricity = 0.2 radius of retrofitted column)*

where,

- **A** • Axial loading system
- **E** • Eccentrical loading system
- **R** • Retrofitted sample
- **r** • radius of sample
- **S** • Strengthened sample
- **0, 1, 2** • No. of welded wire meshes

Figure (5): Welded wire mesh wrapping around the column

Figure (6): Ferrocement application around the column

a) Test layout

b) Loading system shows sample under compression

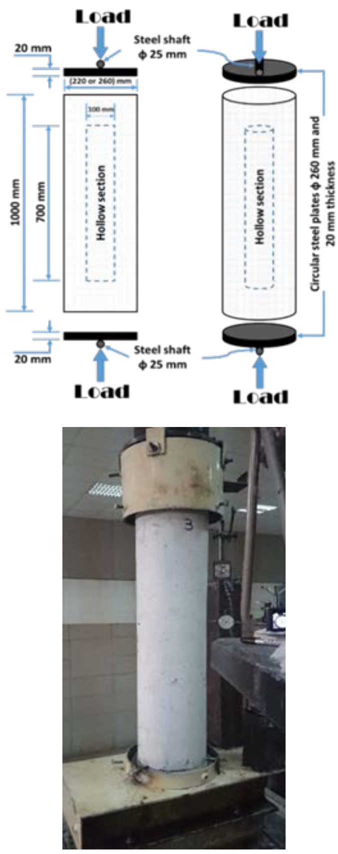


Figure (7): Testing of column specimen

5. Test setup and procedure

The universal testing machine which was used in the present study consisted of a self-supporting steel frame with a hydraulic jack of 250 Ton capacity as shown in **Fig. (7)**. To represent the line load, two steel shafts with (25) mm diameter were used. These shafts were attached to circular steel plates (20) mm thickness at top and bottom to transmit the load to the column surface uniformly and consequently the premature (local) failure which occurs because of stress concentration will be avoided.

The total load on the test column sample was equal to the applied load of the universal test machine. At each load stage, the vertical and horizontal displacements were recorded and the cracks were noticed where all the columns were painted white for better observation of crack propagation. The self-weight of the steel plates, and the column sample itself were ignored. As the failure was reached, the failure load was recorded, and the load was removed to allow taking photographs of the final cracked column sample.

6. Results and discussion

Table (5) provides a summary of the measured loads at first cracking and measured loads and horizontal displacements at first yielding of steel reinforcement and ultimate for all column specimens.

Table (5): Summary of test results for all column specimens

Column Symbol	*First crack load (kN)*	*Yield load (kN)*	*Yield horizontal displacement (mm)*	*Ultimate load (kN)*	*Ultimate horizontal displacement (mm)*
SA 0	*80.1*	*450*	*1.74*	*640*	*6.86*
SE0.2r 0	*70.9*	*450*	*2.59*	*640*	*4.98*
RA 1	*70.7**	*640*	*2.43*	*990*	*5.05*
RE0.2r 1	*55.3**	*640*	*3.51*	*750*	*4.56*
SA 1	*130.5*	*630*	*1.81*	*1020*	*4.91*
SE0.2r 1	*55.1*	*640*	*2.85*	*930*	*5.14*
SE0.6r 1	*50.6*	*235*	*2.59*	*270*	*3.21*
SA 2	*150.8*	*640*	*1.6*	*1070*	*4.37*
SE0.2r 2	*120.4*	*640*	*2.91*	*1049*	*4.76*
SE0.6r 2	*100.2*	*410*	*2.5*	*480*	*4.5*

** These values had taken after finishing of reference specimens retrofitting.*

7. Load – horizontal displacement curves

7.1 Effect of Welded Wire Mesh Layers on the Load (L)-Horizontal Displacement (HD) Curves

Fig. (8) shows the effect of WWM layers on the (L-HD) curves of columns with eccentricity equal to zero. The results showed that the (L-HD) curves of these columns were approximately identical until the load reached 400 kN with low difference in the mid height displacement. After that, the columns were in disunity till their ends. The columns (SA 1 and SA 2) remained close to each other with low differences in displacement to the ends, where the change of WWM layers from one to two layers resulted in decreases of 28.4% and 36.3% of the ultimate HD, respectively, with respect to reference column (SA 0). However, the (L-HD) curve of retrofitted column (RA1) was quit to the other columns after a load of (450) kN approximately linearly to the end of test, whereas the retrofitted of (SA 0) with one layer of WWM (RA 1) results in a decrease of (26.4%) of the ultimate HD with respect to reference column (SA 0). All these significant differences occurred due to the confinement of strengthening layer by ferrocement meshes.

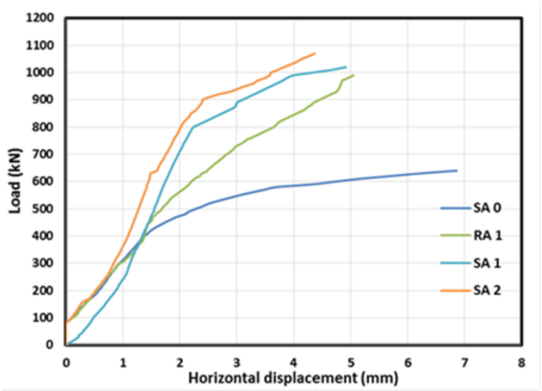


Figure (8): Effect of WWM layers on the (L-HD) curves with e = 0

Fig. (9) shows the effect of WWM layers on the (L-HD) curves of columns with eccentricity equal to (0.2r). The results show that the (L-HD) curves of these columns were approximately identical until the load reached 400 kN with low increase and decrease in the mid height displacement. After that, the columns were in disunity till their ends. The straight horizontal segment of each curve refers to the point at which the curve converted from elastic to plastic behavior. In other words, this was the yield point of column, whereas at the test, it was observed that the load was approximately constant with the increase of mid height and vertical displacement. The columns (SE0.2r 0 and RE0.2r 1, together) and (SE0.2r 1 and SE0.2r 2, together) remained close to each other with low difference in displacement to the end. It is clear form **Fig.9** that the addition of WWM layers does not have obvious effect on the ultimate HD, but the effect on the ultimate load is clear. That means, that the eccentric loading with the kern area has approximately same ultimate horizontal displacement of the specimens, whereas the ultimate load increased with parallel results.

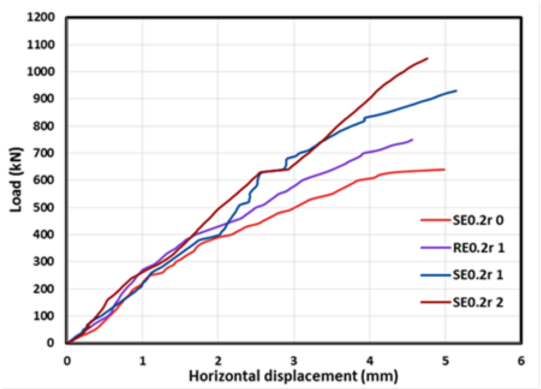


Figure (9): Effect of WWM layers on the (L-HD) curves with e = 0.2r

Fig. (10) shows the effect of WWM layers on the (L-HD) curves of columns with eccentricity equal to (0.6r). The results showed that the (L-HD) curves of these columns behave linearly from the beginning with separate form to the load of (250 kN), where the (SE0.6r 1) failed at (270 kN, 3.21 mm). Continual increase of the load and HD was detect for column (SE0.6r 2), where it converted at yield point (410 kN, 2.5 mm) to less slope to the failure at (480 kN, 4.5 mm). Its horizontal displacement was less than that of the column (SE0.6r 1) at the same load, but it ultimate HD was the maxima. The increase of WWM layers from one layer (SE0.6r 1) to two layers (SE0.6r 2) resulted in a (40%) increase in the ultimate HD. The main differences of the eccentric results may be because the loading points are out of kern area region. Also the confinement stress of two layers is more than one layer repairing ferrocement composites.

7.2 *Effect of Eccentricity on the Load (L)-Horizontal Displacement (HD) Curves*

Fig. (11) shows the effect of eccentricity on the (L-HD) curves of columns with zero layer of WWM (reference columns). The results showed that the horizontal displacement of (SE0.2r 0) column was greater than (SA 0) column from beginning until the load reaches (570) kN, because the transition zone of stresses between the main core and strengthened layers. In this comparison the difference in the horizontal displacement at all load stages was very little, and we can say that the eccentricity has low effect on the horizontal displacement of these two column, when it changed from axial loading to eccentrical loading with (e = 0.2r). The ultimate load of each column was (640) kN, that means that there is no effect of the change from axial loading to eccentric loading with (e = 0.2r) for reference columns on the ultimate load, but it resulted in a decrease of (27.4%) of the horizontal displacement.

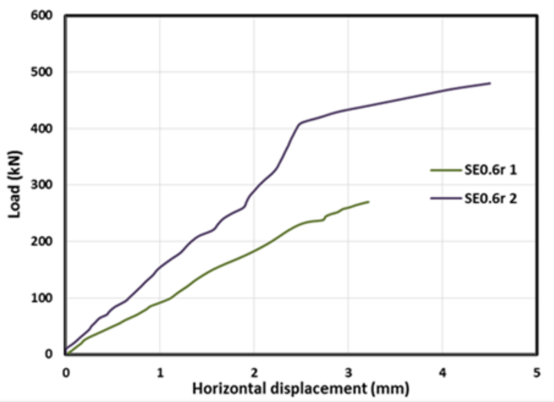


Figure (10): Effect of WWM layers on the (L-HD) curves with e = 0.6r

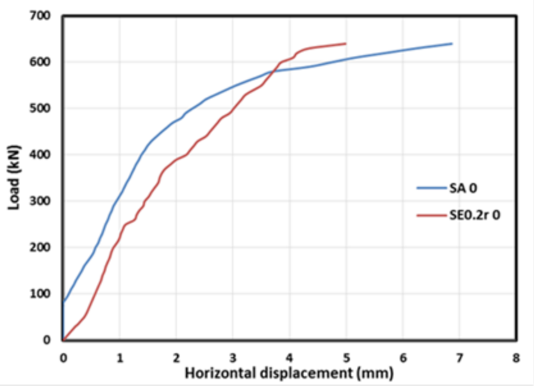


Figure (11): Effect of eccentricity on the (L-HD) curves with zero layer of WWM

Fig. (12) shows the effect of eccentricity on the (L-HD) curves of columns with one layer of WWM. The results showed that the (L-HD) curves of retrofitted columns were approximately identical until the load reached 400 kN with low decrease in the mid height displacement of (RA 1) column. The curve slope of the retrofitted columns converts different load and horizontal displacement, but the HD of (RA 1) column was uppermost. The horizontal displacement of the (RA 1) column was less than that of (RE0.2r 1) column at the same load level from the beginning. Then, at final the change from axial loading to eccentrical loading with (e = 0.2r) for retrofitted columns results in a decrease of (9.7%) of the ultimate HD.

The strengthened columns except (SE0.6r 1) column were approximately identical from the beginning until the load reached 260 kN, the HD of the (SA 1) column was the least after the load of 260 kN until the end, but there was no obvious effect of eccentricity (0.2r) of the one layer of WWM strengthened columns on the ultimate HD. The (SE0.6r 1) column was separated from the strengthened columns from the beginning until the failure with linear behavior. The change from axial loading and eccentric loading with (e = 0.2r) to eccentric loading with (e = 0.6r) resulted in a decrease of (34.6%) and (37.5%) of the ultimate HD respectively. Finally, the retrofitted columns were somewhat weaker than the corresponding strengthened columns, in other words, the retrofitted columns can upgrade to the strengthened columns.

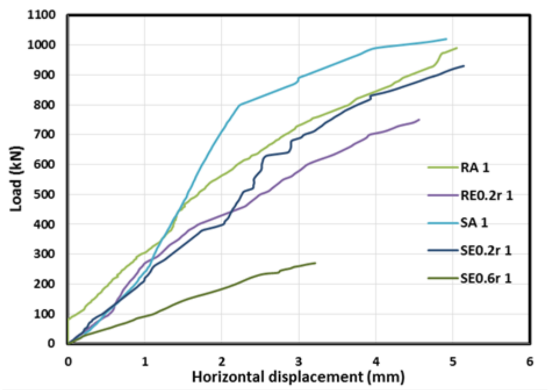


Figure (12): Effect of eccentricity on the (L-HD) curves with one layer of WWM

Fig. (13) shows the effect of eccentricity on the (L-HD) curves of columns with two layers of WWM. The results showed that the (L-HD) curves of all columns were separated from each other, where the large difference of the HD for each column was very clear, and the horizontal displacement of the (SA 2) column was less than that of the (SE0.2r 2) column as well as the (SE0.6r 2) column from the beginning at the same load level. The yield load of each column was different, and the maximum value was taken for the (SA 2) column which was equal to 640 kN. The effect of the change from axial loading to eccentrical loading with (e = 0.2r) and (e = 0.6r) results in an increase of (8.9%) and (3%) of the ultimate HD respectively. The effect of the eccentricity on the ultimate load for these columns was clear with converting from axial to eccentrical loading with (e = 0.6r), but there was low effect with converting from axial to eccentrical loading with (e = 0.2r).

From all previous effects, the increasing percentages of horizontal displacements reported because the secondary moment effects with eccentric loading. However, there lead to significant of increasing eccentricity, within a same strengthening technique.

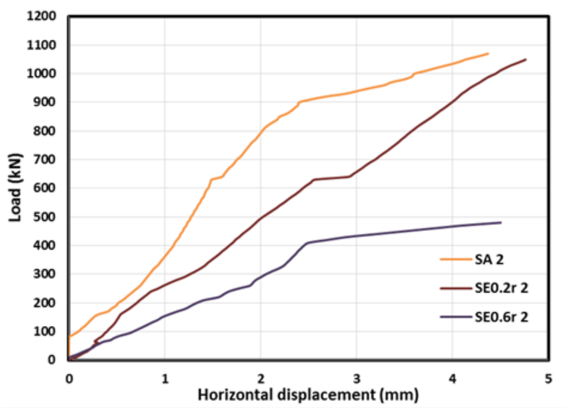


Figure (13): Effect of eccentricity on the (L-HD) curves with two layers of WWM

It can be shown that the behavior of the control columns (SA 0) and (SE0.2r 0) is typical example of an unstrengthened reinforced concrete column specimen, showing similar behavior up to yielding of reinforcement (where YHD measured (1.74 and 2.59) mm) followed by a change in stiffness and increased deformation until failure (640 kN, with corresponding displacement of (6.86 and 4.98) mm as UHD).

The cracking load was generally apparent from the curves for strengthened specimens, although a slight change in the slope at roughly (130.5 kN) was noticed for SA 1 column and (150.8 kN) for SA 2 column, for instance, which was higher than the cracking load observed in the control specimen (80.1 kN). The yield load of the strengthened and retrofitted columns except (SE0.6r 1 and SE0.6r 2) columns was approximately 640 kN which in turn the failure load of reference columns, with different horizontal and vertical displacements, where the least YHD was (1.6) mm for (SA 2) columns. This was attributed to the contribution of the WWM and ferrocement composite action, which increased the stiffness, giving smaller displacements at the yield of steel. At ultimate stage, the difference in the ultimate horizontal displacements was very low except the (SA 0, RA 1, SE0.6r 1 and SE0.6r 2) columns. However, the strengthened specimens achieved higher load capacities than the unstrengthened specimens, the two WWM layers strengthened columns were the highest. The strengthened specimens also exhibited substantially large displacements beyond the yielding of steel. All the strengthened specimens exhibited an approximately bilinear load deformation response characteristic with the change in the slope of each plot occurring at a point corresponding to the yield of the steel.

8. Modes of Failure of the Specimens

As in beams, failure of the columns may be one of three cases depending on the eccentricity value. These cases are, (***Park and Paulay, 1975***):

- Balanced failure, occurs when the tension steel just reaches the yield strength and the extreme fiber concrete compressive strain reaches 0.003 at the same time.
- Tension failure, occurs when $\boldsymbol{e} > \boldsymbol{e_b}$ which means that the failure occurs when the steel reaches the yield strength before the extreme fiber compressive strain reaches 0.003. After that the column will arch with increasing of $\boldsymbol{c}$ until the concrete reaches the ultimate strain and results in crushing of concrete. In this case $\boldsymbol{c} < \boldsymbol{c_b}$ which means $\boldsymbol{P_n} < \boldsymbol{P_{nb}}$.
- Compression failure, occurs when $\boldsymbol{e} < \boldsymbol{e_b}$ which means that the failure occurs when the extreme fiber compressive strain reaches 0.003 before the steel reaches the yield strength. In this case $\boldsymbol{c} > \boldsymbol{c_b}$ which means $\boldsymbol{P_n} > \boldsymbol{P_{nb}}$.

Where: $\boldsymbol{e}$ = eccentricity, $\boldsymbol{e_b}$ = eccentricity for balanced failure, $\boldsymbol{c}$ = distance from extreme compression fiber to neutral axis, $\boldsymbol{c_b}$ = distance from extreme compression fiber to neutral axis for balanced failure, $\boldsymbol{P_n}$ = nominal axial load, and $\boldsymbol{P_{nb}}$ = nominal axial load for balanced case. The **figures (14) to (23)** explain the failure modes of all columns.

Figure (14): Failure mode of SA 0 column (crushing of concrete)

Figure (15): Failure mode of SE0.2r 0 column (crushing of concrete with moderate tension face failure)

Figure (16): Failure mode of RA 1 column (yielding and partially pull off of strengthened layer)

Figure (17): Failure mode of RE0.2r 1 column (crushing of concrete and yielding)

Figure (18): Failure mode of SA 1 column (Partially pull off with concrete crushing)

Figure (19): Failure mode of SE0.2r 1 column (crushing of concrete with yielding main reinforcement)

Figure (20): Failure mode of SE0.6r 1 column (tension failure)

Figure (21): Failure mode of SA 2 column (aggressive crushing of concrete)

Figure (22): Failure mode of SE0.2r 2 column (crushing of concrete with yielding in tension face)

Figure (23): Failure mode of SE0.6r 2 column (tension failure with crushing of concrete)

8. Conclusions

1. Initial cracking was observed at loads ranging from 5.9% for (SE0.2r 1) column to 20.8% for (SE0.6r 2) column of the column ultimate load.
2. Steel yielding load was varied between 59.8% for (SA 2) column to 87.03% for (SE0.6r 1) column of the ultimate load. The strengthened specimens also exhibited substantially had large displacements beyond the yielding of steel.
3. At ultimate stage, the difference in the ultimate horizontal displacements was very low except the (SA 0, RA 1, SE0.6r 1 and SE0.6r1212 2) columns. However, the strengthened specimens achieved higher load capacities than the unstrengthened specimen, the two welded wire mesh layers strengthened columns being the highest.
4. For both the one-layer welded wire mesh columns and the two-layer ones, the load-displacement curves were almost identical from beginning until the load reaches ultimate stages, where the two-layer welded wire mesh columns showed higher strengths and lower displacement at same load level.
5. The two welded wire mesh layers strengthened columns have improvements over the one layer ones. In terms of ultimate loads, the increase was approximately;
   - (5%) for axially loaded columns.
   - (13%) for eccentrically loaded columns with e = 0.2r.
   - (78%) for eccentrically loaded columns with e = 0.6r.

   In average, approximately 32% increase in ultimate strength was gained by strengthening with an additional welded wire mesh layer.

9. References

1. ***Kaminski, M., and Trapko, T., (2006),*** "Experimental Behavior of Reinforced Concrete Column Models Strengthened by CFRP Materials," Journal of Civil Engineering Management, Vol. 12, No. 2, pp. 109-15.
2. ***Waghmare, S. P B., (2011),*** "Materials and Jacketing Technique for Retrofitting of Structures," International Journal of Advanced Engineering Research and Studies, Vol. 1, Issue 1, E-ISSN2249 - 8974, pp. 15-19.
3. ***ACI Committee 549 (1997),*** "State-of-The-art Report on Ferrocement (ACI 549.1R-97)," American Concrete Institute, Detroit.
4. ***Shah, S. P. and Naaman, A. E., (1978)*** "Crack control in ferrocement and its comparison with reinforced concrete," Journal of Ferrocement, Vol. 8, No. 2, pp. 67-80.
5. ***Razvi, S., and Saatcioglu, M., (1989),*** "Confinement of reinforced concrete columns with welded wire fabric," ACI Structural Journal, Vol. 86, pp. 615-23.
6. ***Takiguchi, K., (2003),*** "An investigation into the behavior and strength of reinforced concrete columns strengthened with ferrocement jackets," Cement and Concrete Composites, Vol.25, No. 2, pp. 233-42.
7. ***Shahzada, K., Alam, B., Javed, M., Ali, Z., Khan, H. and Shah, S. S. A., (2012),*** "Retrofitting of Brick Masonry Columns by Ferocementing," International Journal of Advanced Structures and Geotechnical Engineering ISSN: 2319-5347, Vol. 01, No. 02, pp. 50-54.
8. ***AL-Sulyfani, B. J., Mahmood, M. N. and Abdullah, S. M., (2013),*** "Influence of Number of Wire Mesh Layers on the Behavior Strengthened Reinforced Concrete Columns," Al-Rafidain Engineering, Vol. 21, No. 5, pp. 80-91.
9. ***Sirimontree, S., Witchayangkoon, B. and Lertpocasombut, K., (2015),*** "Strengthening of Reinforced Concrete Column via Ferrocement Jacketing," American Transactions on Engineering and Applied Sciences, Vol. 4, No. 1, pp. 39-47.
10. ***American Specification for Testing and Materials, ASTM, (2000),*** "Standard specification for Portland cement," C 150 - 00.

11. ***American Specification for Testing and Materials, ASTM, (2003),*** "Standard Specification for Concrete Aggregates," C 33 - 03.
12. ***American Specification for Testing and Materials, ASTM, (2003),*** "Standard Specification for Deformed and Plain Billet-Steel Bars for Concrete Reinforcement," A 615M/A 615 - 03.
13. ***American Specification for Testing and Materials, ASTM, (2000),*** "Standard Test Method for Slump of Hydraulic-Cement Concrete," C 143/C 143M - 00.
14. ***American Specification for Testing and Materials, ASTM, (2001),*** "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," C 39/C 39M - 01.
15. ***Don Construction Products (DCP), (2010),*** "Product Catalogue," third edition, 795pp.
16. ***American Specification for Testing and Materials, ASTM, (1999),*** "Standard Specification for Latex Agents for Bonding Fresh to Hardened Concrete," C 1059 - 99.
17. ***American Specification for Testing and Materials, ASTM, (1999),*** "Standard Test Method for Bond Strength of Latex Systems Used with Concrete by Slant Shear," C 1042 - 99.

Notations

Symbol	*Definition*
e	*Eccentricity, mm*
e_b	*Eccentricity for balanced failure, mm*
E_c	*Chord modulus of elasticity, GPa*
f'_c	*Specified compressive strength of concrete, MPa*
h	*Thickness of ferrocement, mm*
L	*Length, mm*
N	*Number of layers of mesh reinforcement*
P	*Predicted ultimate load, kN*
P_n	*Nominal axial load, kN*
V_f	*Volume fraction "ratio of the volume of the mesh reinforcement to the volume of the composite"*

Abbreviations

Symbol	*Definition*
ACI	*American Concrete Institute*
AFRP	*Aramid Fiber Reinforced Polymer*
ASTM	*American Specification for Testing and Materials*
CFRP	*Carbon Fiber Reinforced Polymer*
FRP	*Fiber Reinforced Polymer*
HD	*Horizontal Displacement*
NSM	*Near Surface Mounted*
PP Fiber	*Polypropylene Fiber*
RC	*Reinforced Concrete*
RCC	*Reinforced Cement Concrete*
UHD	*Ultimate Horizontal Displacement*
UV	*Ultra Violet*
UVD	*Ultimate Vertical Displacement*
VD	*Vertical Displacement*
WWF	*Welded Wire Fabric*
WWM	*Welded Wire Mesh*
YHD	*Yield Horizontal Displacement*
YVD	*Yield Vertical Displacement*

تقوية وإعادة تأهيل الأعمدة الخرسانية المسلحة المجوفة باستخدام الفيروسمنت المركب ذي الألياف عالي المقاومة

أكرم شاكر محمود
قسم الهندسة المدنية –
كلية الهندسة – جامعة الانبار

سنان عبد الخالق ياسين
قسم الهندسة المدنية –
كلية الهندسة – جامعة صلاح الدين

سمر صبري شفيق
قسم الهندسة المدنية –
كلية الهندسة – جامعة الانبار

الخلاصة:

في هذه الدراسة تم صب ثمانية أعمدة خرسانية مسلحة مجوفة دائرية (القطر الخارجي = 220 ملم، القطر الداخلي = 100 ملم، الطول = 1000 ملم و الجزء المجوف = 700 ملم) مقواة بالفيروسمنت المركب ذي الألياف لتوضيح سلوك هذه الأعمدة تحت نظام التحميل المحوري (المركزي) واللامركزي. تم أعتبار عمودين من الأعمدة كأعمدة مرجعية ثم أُعيد تصليحها بعد الفشل لتكون أعمدة معاد تأهيلها. العينات الستة الباقية قويت بطبقة أو طبقتين من شبكات السلك الملحوم كما هو مطلوب. إن المتغيرات التي تم أخذها بنظر الإعتبار شملت عدد شبكات السلك الملحوم، نظام التحميل وكذلك قيمة اللامركزية للتحميل ثنائي المحور. إن سمك الفيروسمنت كان ثابتاً بـ 20 ملم في كل العينات المقواة والمعاد تأهيلها.

النتائج المختبرية وضحت بأن أعظم زيادة في الحمل الأقصى للأعمدة المحملة محورياً كانت 67% عند تقوية العمود المرجعي بطبقتين من شبكات السلك الملحوم (SA 0 → SA 2)، كما إن أعظم زيادة في الحمل الأقصى للأعمدة المحملة لا مركزياً كانت 78% عند زيادة شبكات السلك الملحوم من طبقة إلى طبقتين (SE0.6r 1 → SE0.6r 2). عند ثبوت عدد شبكات السلك الملحوم، فإن تغيير نظام التحميل من نظام محوري إلى نظام لا مركزي يسبب نقصان في الحمل الأقصى وإن أعظم نقصان كان 73.5% للأعمدة المقواة بطبقة واحدة من شبكات السلك الملحوم (SE0.6r 1 → SA 1). إن الفشل الحاصل في الأعمدة حدث بخضوع حديد التسليح متبوعاً بوصول الإنفعال في الخرسانة إلى 0.003 وتهشم الخرسانة (بما معناه فشل شد).