Strengthening of Reinforced Concrete Short Columns using Ferrocement under Axial Loading

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Abstract- Reinforced concrete columns play an important role in distributing loads from slabs and beams to foundations. As a result of time, fatigue, or other factors, the reinforced columns are exposed to deterioration, and it is required to strengthen or repair these columns. Ferrocement jacketing can be considered as an easy and cheap method which has a significant effect on strengthening members. The main objective of this research is to study the effect of strengthening short columns using ferrocement jackets. Fourteen short square columns having the same dimensions were tested under axial loading. One column was designed as a control specimen and the other thirteen specimens were strengthened with ferrocement while changing the type and number of layers. It was found that using ferrocement as strengthening method increased the strength of columns in average from 11 to 40 %. Following that, a finite element analysis was conducted using the tested column specimens to further assess the usage of ferrocement jackets for strengthening concrete columns. A modified equation was proposed to calculate the capacity of short square columns strengthened using ferrocement jackets. Comparison with experimental data showed that the proposed equation gives good correlation compared to the experimental data.

Keywords: ***Ferrocement; short columns; strengthening; Finite element modeling; wire mesh***

1. INTRODUCTION

Ferrocement is considered a form of reinforced concrete. However, ferrocement differs in the type of reinforcement used which consists of layers of steel mesh surrounded by specially designed concrete mortar. Ferrocement is defined by the IFS10-01[1] as mentioned in the American Concrete Institute committee report 549 R-18 [2] as: "a type of reinforced concrete commonly constructed of hydraulic cement mortar reinforced with closely spaced layers of relatively small wire diameter mesh. The mesh may be made of metallic or other suitable materials. The fineness of the mortar mixture and its composition should be compatible with the opening and tightness of the reinforcing system it is meant to encapsulate. The matrix may contain discontinuous fibers."

Ferrocement has been used for quite some time now. Previous studies recommended ferrocement jacketing techniques as a strengthening and rehabilitation technique for various reinforced concrete members [3,4]. Columns are the main structural element used to distribute loads from slabs and beams to the footings. However due to time, fatigue, change of loads and other circumstances, the capacity of the columns can get reduced. There are many ways for strengthening or retrofitting columns such as fiber reinforced polymer (FRP) sheets, steel or ferrocement jacketing [4,5]. FRP sheets can be considered a very reliable method of strengthening due to its ability to enhance the reinforced concrete strength and durability. However, their construction is quite expensive due to the cost of material and the experienced labors required. Steel jacketing on the other hand is difficult to install. The use of ferrocement jackets for column strengthening is rather attractive due to the many advantages of ferrocement as its raw materials are available in most of the countries, cost of the construction is low, it can be fabricated into any desired shape, the construction work is easy, it has less weight and is durable, the labor is not required to be very experienced, it has good impermeability and fire resistance, and it is a cracking and impact resisting material. Also, special measures are not needed to ensure the bond between ferrocement and the underlying concrete which is an added advantage over FRP and steel jackets. In addition, using ferrocement can improve the reinforced concrete properties such as cracking as well as ductility and energy absorption which was found to be even better than in case of FRP sheets [6-10].

Ferrocement is a composite material consisting of two components: traditional mortar and steel wire mesh. Steel wire mesh usually has a very small cross sections and is made of galvanized iron, so that any shape could be formed with the wire meshes. The behavior of the mortar layer reinforced with the wire mesh was found to be significantly different from ordinary concrete in tension, cracking as well as flexural behavior and ductility [3,5&6]. The mix design of mortar has a great influence on the properties and behavior of the ferrocement layer. The properties of ferrocement are mainly derived from the relatively large amount of two-way wires reinforcement. The reinforcement is made up of small elements with a much higher surface area than conventional reinforcement. Thus, the reinforcement has greater elasticity and cracking resistance together with narrow cracks. The thickness of the covering matrix is about 5 mm. Based on the Ferrocement Model Code (IFS 10-01) [1], specific surface and volume fraction are used to describe the amount of mesh.

The ferrocement properties on the material level have been studied and it was found that the behavior of ferrocement varies under different types of loading. Somayaji and Shah [11] carried out several tests and experiments to study the behavior of ferrocement under tensile loading. Many parameters were investigated such as the type of mesh, transverse wires, spacing between the transverse wires and volume fraction of mesh reinforcement. It was reported that the ferrocement's stress-strain curve can be divided into three stages: elastic stage, elastic-plastic stage, and plastic stage. They concluded that that the smaller the spacing between the transverse wires of mesh, the smaller cracking widths occur and that increasing the specific surface of reinforcement decreases the width of cracks. They also reported that the matrix is cracked long before failure, so the ultimate tensile load capacity is independent of specimen's thickness, and this gives an advantage where there is residual strength after the occurrence of cracks, and this gives signs and chances for repairing after visual inspections. Several parameters affect the ultimate tensile strength of ferrocement such as volume fraction of mesh, strength, and orientation of wires. Khanzadi and Ramesht [12] studied the effect of arrangement of mesh reinforcement on the behavior of ferrocement under tension. It was concluded that the ultimate load is not affected by the arrangement of mesh reinforcement. The tensile strength of matrix and thickness of specimens have influence on the strength at which the first crack occurs, but not on the ultimate strength. Naaman and shah [13] carried out many tests on ferrocement specimens subjected to tension. They studied the effect of types, sizes, and volume fraction of meshes.

In compression, the matrix strongly affects the compressive loading capacity of ferrocement. Desayi and Joshi [14] reported that in ferrocement the compressive strength depends mainly on the matrix and the large increase in meshes volume fraction cannot affect the compressive strength. Nathan and Paramasivan [15] reported that the orientation of reinforcement has relatively small effect on ferrocement's compressive strength. They found that the case where the longitudinal wires are in the same direction of the applied load is the best orientation case. Johnston and Mattar [16] conducted an experimental program on 23 uniaxial tension specimens and 25 compression column specimens. They studied the type, strength, and orientation of the mesh. They found that under uniaxial tension, expanded metal mesh is superior to welded wire mesh while in compression welded wire mesh is much superior. Geometry and orientation of the reinforcement are the main cause for the major differences in performance observed. Mansur and Paramasivan [17] tested three ferrocement sections under combined bending and axial loads. The three sections contained different volume fractions of reinforcement. A method was presented for predicting the ultimate load capacity, and hence the interaction behavior of a ferrocement section. The theoretical predictions were found to be in good agreement with the experimental data.

According to ACI 549R-18 [1], most basic research on ferrocement has already been done and that any new research on the material level or reinforcement level will be very beneficial. The report also stated that there are many future uses and trends where ferrocement can be utilized such as repair and strengthening, jacketing for seismic retrofit, ultra-high-performance fiber-reinforced concrete matrix, self-stressing using shape memory alloys and large roof structures.

Strengthening of columns using ferrocement has been studied by past researchers. Fahmy et al. [18] tested the usage of ferrocement laminates in repairing reinforced concrete columns. Twenty-four reinforced concrete columns were tested under concentric axial compression loading. Each specimen was loaded up to failure or to either 67% or 85% of the ultimate load of the control specimen. The specimens were repaired with ferrocement jackets. The investigated parameters were the preloading level, type of mesh, volume fraction of reinforcement and mesh opening direction and the results showed that ferrocement jackets provided a good level of confinement to the column specimens. Shaheen and Hassanen [19], studied the behavior of 16 circular concrete column (diameter = 72 mm and height = 1000 mm) reinforced with various types of reinforcing materials and strengthening. A comparative study was performed with welded steel meshes, fiber glass meshes, polypropylene meshes and bamboo meshes. They concluded that high strength and durable columns were developed with high ductility and energy absorption properties which are very useful for dynamic applications. Mourad and Shannag [20] carried out an investigation of loading and repairing on 10 one-third scale square columns using ferrocement jackets. They were preloaded under axial compression to different percentages of (0%, 60%, 80%, and 100%) of their ultimate load according to the control one. They were then repaired using ferrocement jackets with high strength mortar and then retested until failure. The test results indicated that there was about 33% increase in axial loading capacity and 26% increase in the axial stiffness comparing with the control specimen.

Ho et al. [21] strengthened 19 circular plain and RC columns with high performance ferrocement jackets (comprising rendering material and wire mesh). They studied the effect of the volumetric ratio of the mesh, the number of layers and the type of mesh. Equations for calculating the capacity of the columns were proposed. El-Kholy and Dahish [22] reinforced sixteen short square RC column specimens of slenderness ratios k = 7.33 and 14 laterally with various volumetric ratios of ties. The confinement of twelve column specimens was enhanced by warping single expanded metal mesh layer around the ties. The column specimens were tested under axial compression until failure. They concluded that adding single layer of expanded metal mesh as lateral reinforcement increases the ultimate load capacities with 11 % and 18.55 % for short square RC columns with slenderness ratios of k = 7.33 and 14 respectively. Also, wrapping additional expanded metal mesh layer could give higher ultimate capacity, improved ductile behavior and larger dissipation of energy. Anagha and Varghese [23] studied the effect of using ferrocement jacketing on ultimate load. They also studied the effect of adding steel fibers in mortar with different volumetric ratios of mortar mix and adding corner steel angles. The tested 27 specimens with cross section dimensions 150 mm * 150 mm. They found that adding steel fibers with 1.25% of mortar mix gave the ideal results and using steel angles at corners enhanced the ultimate load capacity.

Elsibaey et al. [24,25] tested ten reinforced concrete short columns with nominal cross- sectional dimensions of 200*200 mm with 120 mm length under axial loading until failure. The main parameters investigated were the number of layers of wire mesh, type of wire mesh and the cement mortar strength. The results showed that confinement with ferrocement can improve the strength of columns. Takigushi and Abdallah [26] studied the behavior of square columns strengthened by circular ferrocement jackets. The columns were tested under cyclic and axial loading. The results showed significant improvement in the displacement ductility of the columns.

Some researchers studied ferrocement strengthening combined with other techniques. Sirimontreea et al. [27] studied six short square columns strengthened using two alternatives. First with prestressed steel straps and four steel angles at each corner and second with steel angles confined with prestressed steel straps and ferro-cement. Significant improvement in the load carrying capacity and ductility was obtained. Aules et al. [28] compared different materials for strengthening of columns namely ferrocement, CFRP or both on different shapes of columns and the results showed that ferrocement is very effective if combined with CFRP.

Other researchers extended the study of ferrocement strengthened columns to damage by fire where Fayzul Bari et al. [29] studied six short rectangular columns damaged by fire and then strengthened using ferrocement. The capacity of the columns showed an increase using one and two layers of mesh. Yaqub et al. [30] tested repaired post-heated square and circular RC columns. They compared the effectiveness of carbon fiber reinforced polymers (CFRP), glass fiber reinforced polymers (GFRP) and ferrocement jackets. All columns were tested under axial compression. The results showed that the FRP jackets increased the compressive strength and ductility but didn't increase the stiffness. However, the ferrocement jackets increased both strength and stiffness of post-heated columns. It was concluded that a possible combination between FRP and ferrocement jacketing could increase strength, ductility and stiffness of columns damaged from fire.

The problem of stress concentration at the corners of strengthened columns presents a point of high concern. Kaish et al. [31] addressed this problem where improvements were presented to the conventional ferrocement jacketing of square columns by rounding the corners, adding shear keys, or adding two extra layers of mesh at the corners. They concluded that the later technique had the best results in case of concentric loading while the former was more suitable under eccentric loading. Soman and Mohan [9] studied the same problem where rounding of corners was done for all 20 square and rectangular columns under study.

Research significance

Based on the above literature review, strengthening of columns using ferrocement jacketing is effective in improving the capacity of the columns as well as other properties such as ductility and energy dissipation. Ferrocement is a low-cost material readily available and thus is more suitable to the Egyptian market than other methods of strengthening. Different types of wire mesh are also locally available. This research aims to study the effect of using the available common types of steel wire meshes with various shapes and properties on the strength of ferrocement jackets wrapping the reinforced concrete columns. In addition, this research also investigates one of the techniques that could reduce the stress concentration problem around the corners through adding additional layers of mesh. For practical consideration the application of one layer over the full length of the column is not always possible and the need for using separated parts sometimes arises. Thus, the main parameters under study are: 1) the type of mesh, 2) the number of layers, 3) the additional strengthening of corners, and 4) the overlapping of the wire mesh along the length of the column.

An analytical study using the commercially available finite element program ANSYS is performed, and results are compared to the experimental data. A proposed modified equation to the Egyptian code of practice is introduced to calculate the ultimate capacity of short square columns strengthened using ferrocement jacketing.

2. EXPERIMENTAL PROGRAM

2.1 Details of Specimens

The experimental program consisted of testing fourteen short column specimens subjected to axial loading. The main parameters under study were the effect of the type of mesh and the number of layers used. In addition, two different mesh layouts were also studied. The details of the fourteen specimens are shown in Table 1. All specimens had the same dimensions with a square cross section of 150 *150 mm and total height of 1200 mm. The reinforcement was also kept constant with four 10 mm diameter steel bars as the main longitudinal reinforcement and stirrups of 6 mm smooth mild bars were used every 200 mm. Two additional stirrups were added at the top and bottom sections of the columns to strengthen this area where contact with the loading plates occurs. The details of the column specimens are shown in Figure 1. One specimen was designed as a control specimen with no strengthening and the other 13 specimens were all strengthened using different ferrocement jackets. The ferrocement jackets used consisted of layers of different types of steel meshes wrapped around the columns and covered using mortar mix. Five different types of steel mesh were used:

1. Diagonal mesh with 0.8 mm thickness rods.
2. Diagonal mesh with 1.5 mm thickness rods.
3. Diagonal mesh with 2.0 mm thickness rods.
4. Welded square mesh.
5. Hexagonal mesh.

The general notations (S-XX-YL) used for specimen designations shown in Table 1 can be explained as follows:

S : refers to Specimen,

XX : refers to the type of the mesh where D8 is used for diagonal mesh with 0.8 mm thickness, D15 refers to diagonal mesh with 1.5 mm thickness, D20 refers to diagonal mesh with 2.0 mm thickness, HE is used for hexagonal mesh and WE for square welded mesh.

Y : refers to the number of layers used either 1 Layer or 2 Layers or 3 Layers.

For the diagonal mesh with 0.8 mm, six specimens were cast. Three specimens with one, two, and three layers to study the effect of the number of layers. In addition, two mesh layouts were used. First, specimen S-D8-1L-CR had one layer and an added corner layer strengthening. Second, Specimens S-D8-1L-O and S-D8-1L-N were used to study the effect of the length of the mesh with respect to the height of the column. In real practice the mesh cannot always be applied as one layer along the whole length of the column and the need may arise to apply it into parts.

Table 1: Details of column specimens

	Specimen	Dimensions	Ferrocement Jacket		Comments
			Number of layers	Mesh type	
1	SC	150*150*1200 mm	None		
2	S-D8-1L		1	diagonal mesh with 0.8 mm thickness	------
3	S-D8-2L		2		------
4	S-D8-3L		3		------
5	S-D8-1L-CR		1		Corner strengthening added
6	S-D8-1L-O		1		The mesh is divided into three equal parts with 10% overlap
7	S-D8-1L-N		1		The mesh is divided into three equal parts with no overlap
8	S-D15-1L		1	diagonal mesh with 1.5 mm thickness	------
9	S-D15-2L		2		------
10	S-D15-3L		3		------
11	S-D15-1L-CR		1		Corner strengthening added
12	S-D20-2L		2	diagonal mesh with 2.0 mm thickness	------
13	S-HE-2L		2	Hexagonal mesh	------
14	S-WE-2L		2	Welded mesh	------

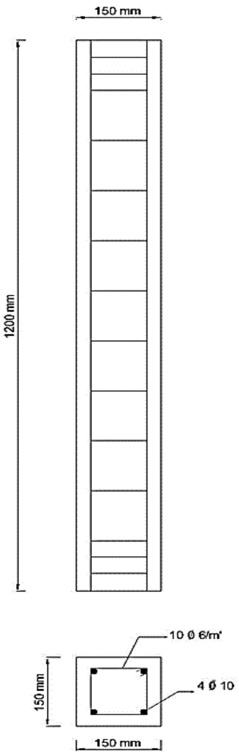


Figure 1: Concrete columns details.

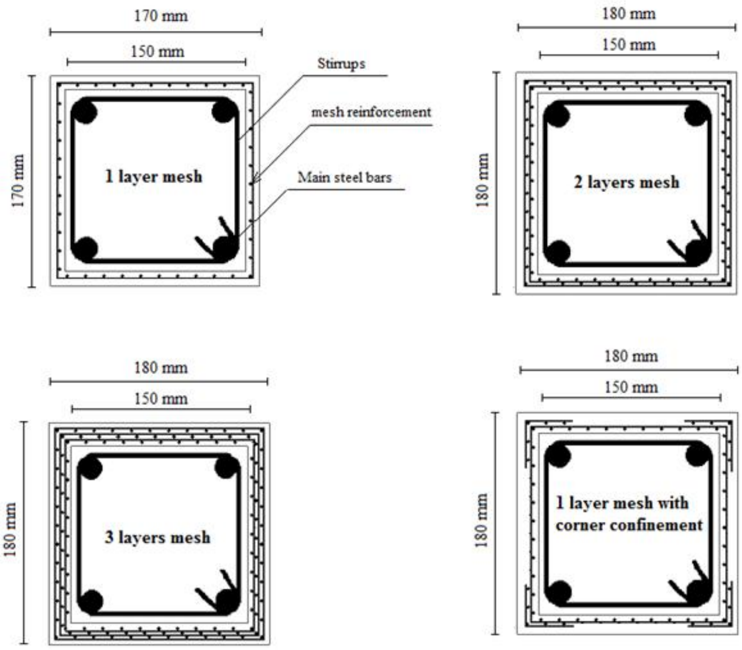


Figure 2: Different ferrocement jackets used for strengthened specimens.

In these two specimens, the mesh is divided into three parts along the length of the column one with 10% overlap and the other without any overlap. For the diagonal mesh with 1.5 mm, four specimens were used with one, two, three layers and specimen S-D15-1L-CR with an added corner layer strengthening. To study the effect of the mesh type, three specimens S-D20-2L, S-HE-2L and S-WE-2L using diagonal mesh with 2 mm thickness, hexagonal and welded mesh were studied in addition to the previous specimens. Two layers were applied in this case because based on previous research it was found that using two layers of mesh give good enhancement in column capacity in addition to ease of manufacturing and handling [20]. The details of the ferrocement jackets used can be seen in Figure 2.

2.2 Material properties

The concrete mix used for the columns was designed to give a characteristic compressive strength of 35 N/mm^2 after 28 days. It was developed by using trial batching. Table 2 shows the components for one cubic meter of concrete. Crushed dolomite size no.1 and 2 with a 20 mm maximum particle size and clean sand with medium size were used.

Ordinary Portland cement 42.5 N was used in the reinforced concrete mix while super plasticizers were used to improve the strength of concrete.

The mix used to cast the mortar of the ferrocement was developed according to the ACI committee 549 [2]. The cement, sand and water were mixed in the ratio of 1:2:0.4 by weight. Clean sand with medium size and Ordinary Portland cement 52.5 N were used for the mortar. The admixtures added were silica fume and it was 10% of cement by weight and super plasticizer with 1.5% percentage of cement by weight. That mix was chosen for the development of 35 N/mm^2 compressive strength. Table 3 shows the components for producing one cubic meter of mortar.

High grade steel bars with 10 mm diameter were used as the main longitudinal bars for the reinforced concrete columns while 6 mm smooth mild steel bars were used for stirrups. The mechanical properties of steel bars are shown in Table 4. Five different types of steel mesh that are available in the Egyptian market were used for the ferrocement jacketing namely: diagonal mesh with 0.8 mm thickness rods, diagonal mesh with 1.5 mm thickness rods, diagonal mesh with 2.0 mm thickness rods, welded square mesh and hexagonal mesh. The details of the steel mesh used are shown in Figure 3. The properties of the wire mesh were obtained from the literature [32-36] and are shown in Table 5.

Table 2: Mix proportions required to cast one cubic meter of concrete

Material	Cement	Fine Aggregate	Coarse Aggregate	Water	Admixtures (super plasticizers)
Weight(kg)	350	650	1150	190	4

Table 3: Mix portions required to cast one cubic meter of mortar.

Material	Cement	Fine Aggregate	Water	Admixtures (silica fume)	Admixtures (super plasticizers)
Weight(kg)	400	800	200	40	4

Table 4: Mechanical properties of steel bars

Type	Diameter (mm)	Yield strength (MPa)	Ultimate strength (MPa)	Elongation%
High strength steel	10	465	707	15.5
Mild steel	6	320	453	23

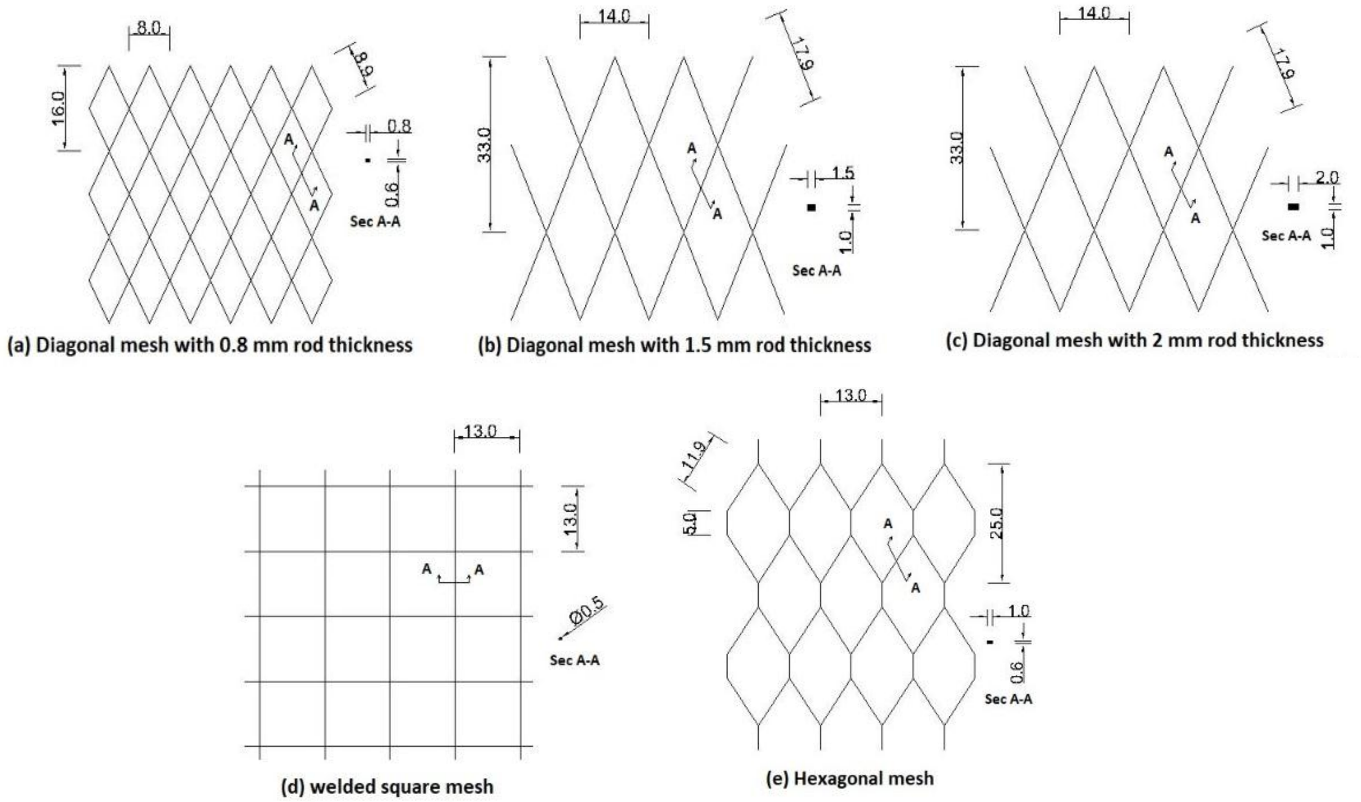


Figure 3: The Five different types of steel mesh used.

Table 5: Wire mesh properties [32-36]

Type	Diameter (mm)	Poisson ratio	Yield strength (N/mm^2)	Modulus of elasticity
Hexagonal mesh	2	0.3	343	2x10^5
Welded square mesh	0.7	0.3	400	3.42x10^5
Diagonal mesh 0.8 mm	0.8	0.3	290	1.38x10^5
Diagonal mesh 1.5 mm	1.5	0.3	250	1.2x10^5
Diagonal mesh 2 mm	2	0.3	400	2x10^5

2.2 Preparation of specimens and strengthening procedure

The longitudinal and transverse reinforcement bars for the specimens were arranged, tied, and placed in their positions in the wooden forms. Mixing was performed using concrete mixer and the concrete was poured in the wooden forms and an electric vibrator was used for good compaction and removing the air voids. Six standard cubes (150 mm * 150 mm * 150 mm) were cast during the operation. After 24 hours the wooden sides of forms were removed. All specimens were cured for seven days, and they were strengthened and tested after completion of 28 days. Three cubes were tested at the end of curing after 7 days and the other three cubes were tested after 28 days. The average compressive strength obtained by testing the standard cubes after 28 days was 39.1 N/mm^2.

The control specimen was tested after 28 days while the other columns were strengthened using ferrocement jackets and then tested. The strengthening procedure was conducted for the 13 specimens as shown in Figure 4 and Figure 5. First, the faces of all columns were roughened by using an electric hammer to improve the bond with the mortar of ferrocement then compressed air was applied to remove any dust. Mesh layers from different types and forms were cut and trimmed to the required sizes and shapes. Layers of meshes were then wrapped and fixed well to the columns using electric drill and nails. Compressed air was used again to remove any fine dust on the surfaces after fixing the mesh layers. Mortar constituents were batched separately by using mechanical balance and mixing was performed using a mixer for about 3 minutes for adequate mixing.

To ensure good bond between concrete and ferrocement mortar, Addibond 65 [37] slurry was applied on columns faces as an adhesive material. A steel trowel was used strongly to ensure full penetration of mortar into mesh layers and to make a smooth surface. Strengthened columns were again cured and left for 28 days. After that they were painted with a layer of white color for easy cracks observation during testing. Six standard cubes (150 mm * 150 mm * 150 mm) were cast during the mixing of the mortar. Three cubes were tested after 7 days and other three cubes after 28 days. The average compressive strength for mortar obtained after 28 days was 35 N/mm^2.

2.3 Test Setup

Tests were carried out at the Concrete research laboratory at the Faculty of Engineering, Cairo University. A 500 tons capacity hydraulic machine was used for testing as shown in Figure 6. Specimens were tested under axial loading. Steel cube heads (150.5mm * 150.5 mm * 150.5 mm) were attached at the top and bottom of specimens to avoid local or premature failure at column ends. Strain gauges were connected to the longitudinal steel bars for all specimens. One strain gauge was attached at mid height at one steel bar for each specimen. A wax film was used to cover the top of strain gauges to protect them from any damage. Strain gauges were connected to a data acquisition system. The load was applied uniformly at 0.5 mm/s which guaranteed sufficient data collection.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

In this section the results of the control specimen and the 13 strengthened columns are discussed in terms of the cracking patterns, modes of failure and the ultimate load capacity. The specimens will be divided into three groups each discussing one of the parameters under study as shown in Table 6. Group 1 studies the effect of the number of the steel mesh layers used in the ferrocement jacket whether one, two or three layers as well as the specimen with additional corner strengthening. This is subdivided into Group 1-A for diagonal mesh with 0.8 mm thickness and group 1-B for diagonal mesh with 1.5 mm thickness. Group 2 deals with the type of steel mesh used and group 3 studies the effect of overlapping along the length of the column.

Table 6: Specimen groups

Group	Parameter studied	Specimens Notations
Control specimen	----	SC
Group 1-A	Effect of number of layers	S-D8-1L
		S-D8-2L
		S-D8-3L
		S-D8-1L-CR
Group 1-B	Effect of number of layers	S-D15-1L
		S-D15-2L
		S-D15-3L
		S-D15-1L-CR
Group 2	Effect of type of mesh	S-D8-2L
		S-D15-2L
		S-D20-2L
		S-HE-2L
		S-WE-2L
Group 3	Effect of overlap of the mesh parts	S-D8-1L
		S-D8-1L-O
		S-D8-1L-N

(a) (b) (c)

(d) (e) (f) (g)

Figure 4: Strengthening procedure for jacketed specimens

3.1 Modes of failure and crack patterns

Since all specimens were short columns, no middle buckling was observed in any of the specimens. Figure 7 shows the cracking pattern for the control specimen SC at failure. No cracks were observed at the early stage of loading then cracks started to appear at the top and bottom of the column near the edges. This behavior can be because of the constraint imposed by the loading plates at the two ends of the specimens causing the cracks to start at the top and bottom of the columns. The same behavior of cracking was reported in previous research [9,38,39]. As the loading increased, the width of the cracks increased, and new cracks started to develop propagating towards the mid height of the specimen. . Compression failure occurred at load level of 532 kN near the bottom part of the column.

Figure 5: Column specimens after applying ferrocement jacket.

Figure 6: Testing setup

Figure 7: Cracking pattern at failure for control specimen SC

Figure 8: Cracking pattern at failure for sample strengthened specimens

For the strengthened specimens, cracks again started near the edge of the column at the top and bottom parts. With increasing the applied load, the width of these cracks increased slightly, and new cracks developed and began to propagate generally towards the middle and the edges of the column. Figure 8 shows the cracking pattern at failure for some of the specimens. Failure occurred in the ferrocement jacket with crushing clearly visible at the corners in specimen S-D15-2L, S-HE-2L and S-WE-2L. For the latter specimen with welded mesh, rupture of the mesh occurred and the ferrocement jacket separated from the specimen. This is because welded mesh did not exhibit any plastic deformation as opposed to the hexagonal and diagonal meshes. A slightly different behavior was seen for specimens with additional corner strengthening where the cracks propagated mainly at the middle of the column face and propagated parallel to the column edges as seen in Figure 9. This could be because the corner layers helped ease the stress concentration at the edges. A schematic representation of the cracking pattern of all specimens can be seen in Figure 10.

3.2 Ultimate load capacity

Table 7 shows the experimental data output for all groups of specimens. The results showed that the ultimate load capacity of the strengthened columns improved compared to the control specimen without the ferrocement jacketing**.**

Regarding Group 1-A where the number of layers was increased for the diagonal mesh with 0.8 rod thickness, it was observed that the ultimate capacities for specimens S-D8-1L, S-D8-2L, S-D8-3L and S-D8-1L-CR were increased by 11.2 %, 31.7 %, 35.9 % and 12.7 % respectively. While for Group 2-A, the ultimate load capacity for specimens S-D15-1L, S-D15-2L, S-D15-3L and S-D15-1L-CR were increased by 30.2 %, 37 %, 43 % and 33.4 % respectively.

Using additional corner layers showed an insignificant increase compared to the specimen with one layer. This is because the confining of the corner mesh was not properly achieved. More investigation needs to be conducted regarding different corned strengthening arrangements. It can also be seen that the specimens needed two layers of diagonal mesh 0.8mm to have a significant improvement of 31.7% while for the diagonal mesh 1.5 mm, only one layer gave an enhancement of 30.2%.

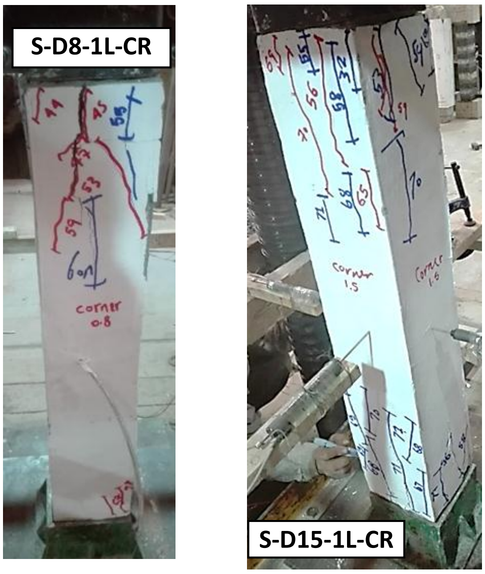


Figure 9: Cracking pattern at failure for specimens S-D8-1L-CR and S-D15-1L-CR

Table 7: Experimental data for all specimens

Group	Specimen	First crack load (kN)	Ultimate Load (kN)	Strain (με)	Increase in Ultimate load (%)
Control	S C	290	532	1033	---
Group 1-A	S-D8-1L	310	592	1163	11.2
	S-D8-2L	340	701	1215	31.7
	S-D8-3L	360	723	1220	35.9
	S-D8-1L-CR	330	600	1178	12.7
Group 1-B	S-D15-1L	370	693	1250	30.2
	S-D15-2L	490	729	1200	37
	S-D15-3L	370	761	1452	43
	S-D15-1L-CR	320	710	1445	33.4
Group 2	S-D8-2L	340	701	1215	31.7
	S-D15-2L	490	729	1200	37
	S-D20-2L	490	746	1302	40.2
	S-HE-2L	310	680	1209	27.8
	S-WE-2L	340	715	1310	34.4
Group 3	S-D8-1L	310	592	1163	11.2
	S-D8-1L-O	410	614	1123	3.7
	S-D8-1L-N	373	571	1091	-3.5

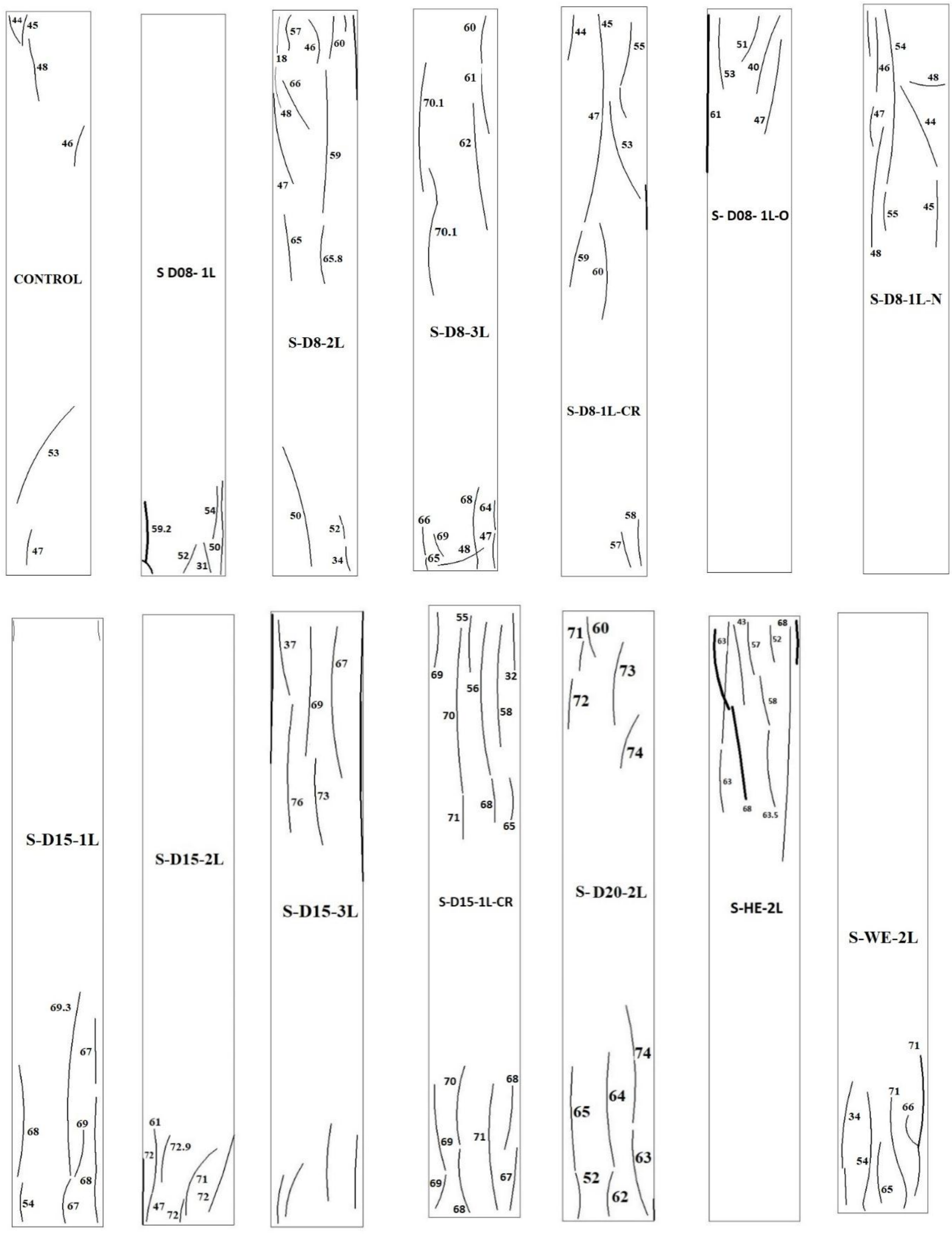


Figure 10: Schematic representation of cracking patterns at failure.

For Group 2 where the different types of mesh were compared through specimens having 2 layers of mesh, it was observed that ultimate loads for specimens S-HE-2L, S-WE-2L, S-D8-2L, S-D15-2L and S-D20-2L were increased by 27.8 %, 34.4 %, 31.7 %, 37 % and 40.2 % than that of the control specimen respectively. Hexagonal mesh ferrocement laminates showed the weakest strengthening case, while diagonal mesh with 2 mm thickness rod showed the strongest one. Group 3 studied the construction of the mesh as one part over the whole length of the column compared to dividing it into three separate parts either with overlapping or without. The data showed that no significant change occurred in either case compared to the specimen S-D8-1L.

3.3 Load – strain relationships

The load strain curves for the four groups are shown in Figure 11 to Figure 14. The main longitudinal reinforcement of the columns did not reach the yield strain in any of the specimens. The control specimen showed a maximum strain of 1033 µε as shown in Table 7. The maximum strain for the rest of the specimens was about 1200 µε with specimen S-D15-3L and specimen S-D15-1L-CR showing the highest values of strain of 1450 µε.

4. FINITE ELEMENT ANALYSIS

In this part the 14 column specimens tested experimentally were analyzed using the 3D finite element ANSYS program. ANSYS can easily simulate engineering models accurately through its simulations of time dependent behavior, contact algorithms and material models of nonlinear properties. Also, ANSYS can illustrate features of engineering simulations such as boundary conditions and the behavior of model under various norms. ANSYS [40] uses the "Newton-Raphson" method to handle nonlinear problems. This method divides solution into load increments which are defined in the program as load steps. At each incremental end, the model stiffness matrix is adjusted to reflect changes in the whole structural stiffness, then it moves to the following load increment.

4.1 Modelling of the column specimens

Each component of the column was modeled using the appropriate element chosen from the ANSYS program library. Solid65 element was used for concrete, mortar, and the wire mesh. It is an eight-node solid element, and each node has three degrees of freedom which are translations in the x, y, and z directions as shown in Figure 15(a). This element can resist plastic deformation, crushing, and cracking in the three orthogonal directions [40]. The main longitudinal reinforcing bars and the stirrups were modeled using the element link 180. Link 180 had two nodes each with three degrees of freedom as shown in Figure 15(b).

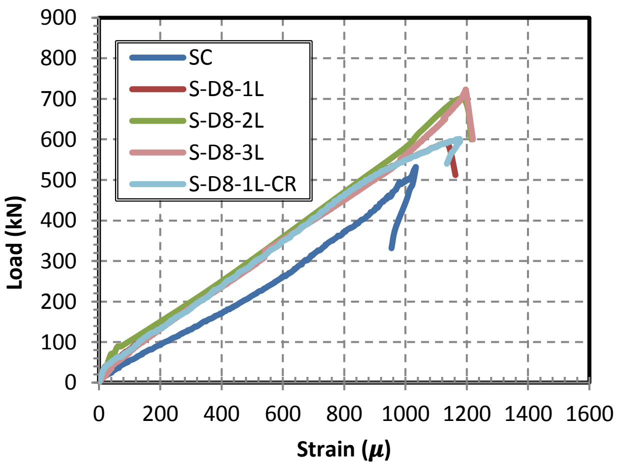


Figure 11: Load strain curve for Group 1-A.

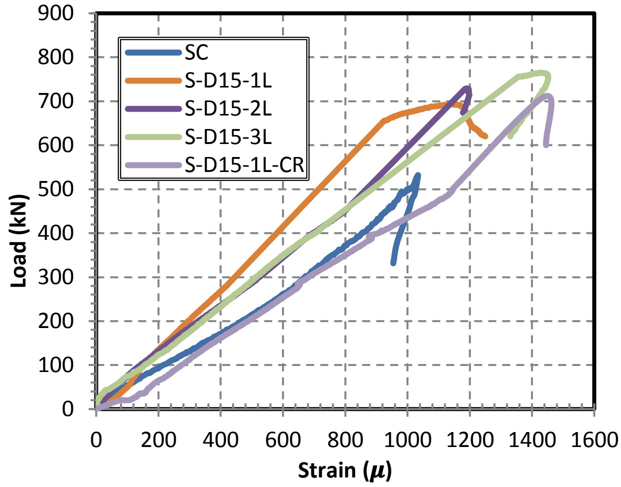


Figure 12: Load strain curve for Group 1-B.

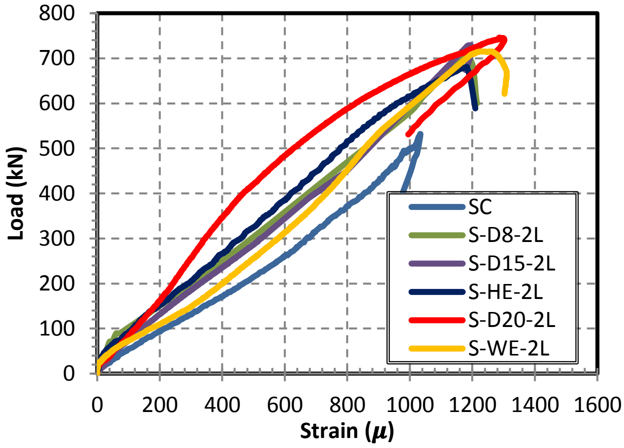


Figure 13: Load strain curve for Group 2.

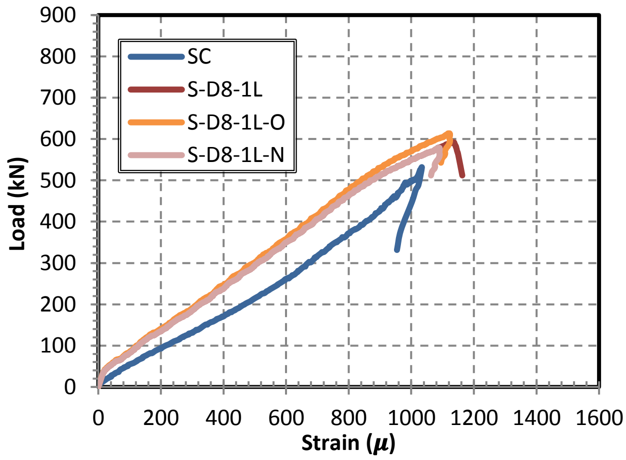
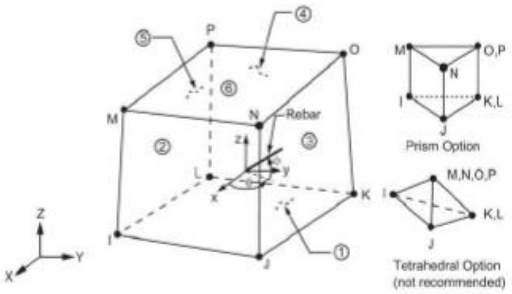


Figure 14: Load strain curve for Group 3.

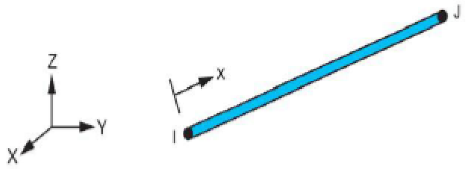
Solid185 element in ANSYS software was used to simulate steel plates used in the loading setup. It is considered as an eight-node solid element, and each node also has three degrees of freedom as shown in Figure 15(c). Generally, this element could be accessed in two types of structures: homogeneous and layered structure.

To simulate the actual boundary conditions during the experiment, all degrees of freedom were restrained at the bottom of the columns, and both horizontal directions at the top were also restrained. All specimens were built with a constant concrete compressive strength of 39 N/mm^2 and mortar compressive strength of 35 N/mm^2 which are the actual values obtained from the compression test conducted during the experimental program. Each model had four 10 mm diameter bars as longitudinal steel reinforcement and 6 mm diameter as stirrups.

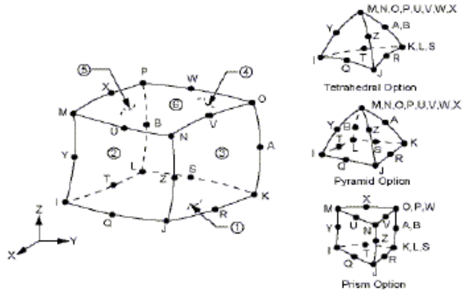
The mechanical properties of the longitudinal steel reinforcement and stirrups were taken according to Table 4 while for the wire mesh they were taken according to Table 5 to simulate the actual experimental conditions. Stirrups spaced at 30 mm were applied at both ends of the models to prevent premature failure at the locations and were spaced at 200 mm at the rest of column. The control column and the strengthened columns were modeled as shown in Figure 16 and Figure 17.



(a)

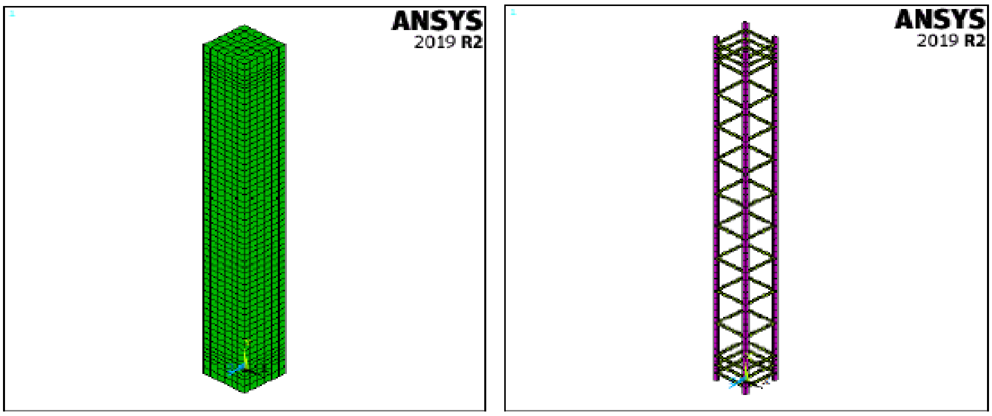


(b)



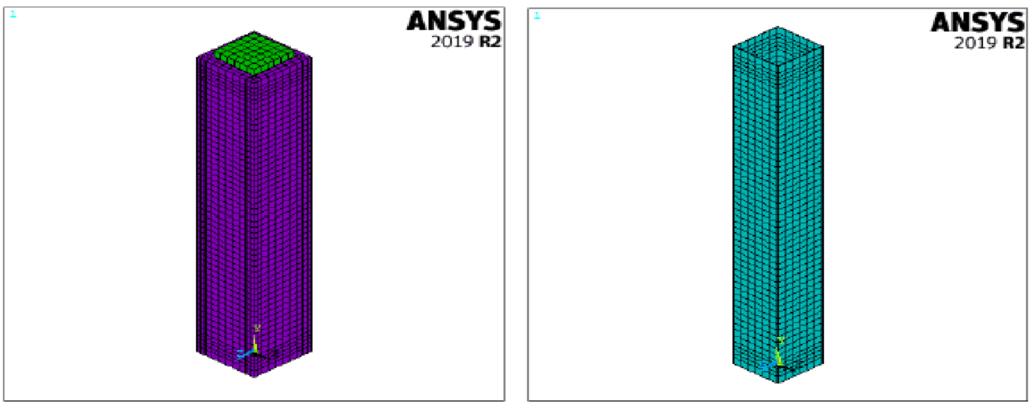
(c)

Figure 15: Different elements using in the FEM. (a) Solid 65, (b) Link 180, (c) Solid 185 [40]



(a) **(b)**

Figure 16: Model used for the control specimen SC. (a) concrete mesh, (b) reinforcing steel bars.



(a) **(b)**

Figure 17: Model used for the strengthened specimens. (a) Concrete and mortar mesh, (b) Wire layer mesh.

Concrete and ferrocement mortar were defined by stress–strain curve, density, poison ratio, and modulus of elasticity. The program allows the use of a multilinear inelastic model for the concrete. The model can consist of a multi-linear elastic component up to yielding, and a strain hardening portion. Concrete and mortar were defined by the stress-strain curve using Equation (1) according to the Egyptian code of practice ECP 203-2018 [41] and is shown in Figure 18(a).

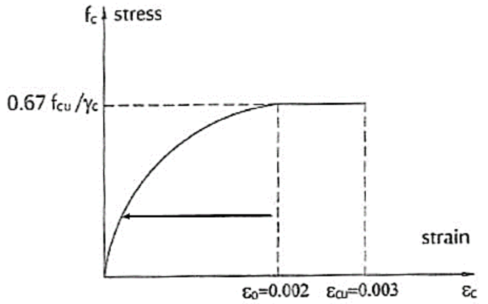
$$f = Fcu\left(\frac{2\varepsilon}{0.002} - \left(\frac{\varepsilon^2}{0.002^2}\right)\right) \quad (1)$$

Where f refers to concrete stress, Fcu refers to the concrete compressive strength (N/mm^2), and ε refers to the concrete strain.

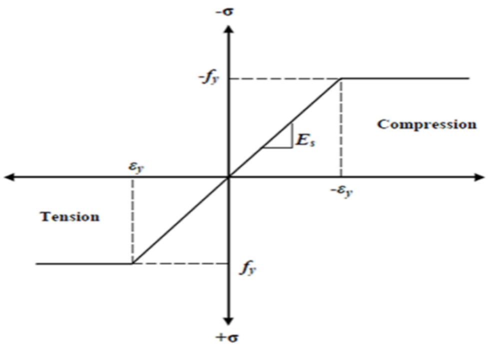
Other factors such as density, modulus of elasticity, poison ratio, uniaxial cracking stress, and uniaxial crushing stress were also defined for concrete and mortar according to the following:

- Density = 25 N/mm^3
- Modulus of elasticity = f/ε
- Poison ratio = 0.2
- Uniaxial cracking stress = 0.6√Fcu (N/mm^2)
- Uniaxial crushing stress = 0.8Fcu (N/mm^2)

In addition, βt which refers to the value of coefficient shear transfer in ANSYS software has a value range from 0 to 1 in case of concrete and mortar. The value of 0 is used for smooth cracks without shear transfer, and the value of 1 is used for rough cracks with a peak shear transfer [40]. It was stated that when this value is less than 0.2, it causes a convergence concern in the program solution, so, it was taken as 0.3 in this study [42].



(a)



(b)

Figure 18: Stress-strain curve: (a) concrete and mortar, (b) reinforcing bars and wire mesh

Reinforcing steel bars and wire mesh were defined by yield stress, poison ratio, and modulus of elasticity. The ANSYS program uses a bilinear model for the reinforcement as shown in Figure 18(b). The model consists of a linear elastic component up to yielding, and a strain hardening part. The data required to define the shape of the stress-strain relationship was used according to Table 5.

4.2 Finite element analysis results

The output results from the finite element analysis conducted using the ANSYS program on the 14 column specimens are shown in Table 11. Good correlation can be seen between the experiment and the ANSYS where the ratio between the two sets of results varied between -10% to +8.2%. This proves that ANSYS can be an effective tool in the analysis of columns reinforced using ferrocement mesh. An extensive parametric study is planned in an ongoing analytical study to explore more parameters related to the strengthening of columns using ferrocement jackets and the results will be published in subsequent work by the authors.

5. PROPOSED DESIGN EQUATION

ANSYS proved a successful tool in simulating columns strengthened using ferrocement jackets, but the use of the program is not always possible. The need for a formula to calculate the capacity of columns in this case is a necessity. Currently there are no provisions in the design codes for such a formula. A modified formula is proposed here to calculate the ultimate capacity of strengthened columns based on the provision of the Egyptian code of practice (ECP 203-2018) [41] for short columns under axial load. The current formula presented by ECP 203-2018 [41] is shown by Equation 2.

$$Pn = 0.35.\ Fcu.\ Ac + 0.67.\ As.\ Fy \quad (2)$$

To take the effect of strengthening using ferrocement jacket into consideration, the capacity of the strengthened columns is assumed to be divided into two main parts: the part carried by the original column and an additional part carried by the ferrocement component. Equation 3 can be used to represent this as follows:

$$Pn = 0.35.\ Fcu.\ Ac + 0.67.As.\ Fy + C1.\ Fcum.\ Acf + C2.\ Asf.\ Fsf \quad (3)$$

Where:

Pn = Ultimate capacity of reinforced column (N)
Fcu = Concrete compressive strength (N/mm^2)
Fcum = Mortar compressive strength (N/mm^2)
Fy = Reinforcing steel bars yield strength (N/mm^2)
Ac = Concrete gross area (mm^2)
Acf = Mortar area (mm^2)
Asf = Wire mesh area (mm^2)
Fsf = Wire mesh yield strength (N/mm^2)
C1 = Constant Factor for mortar
C2 = Constant Factor for wire mesh

C1 and C2 are two factors introduced to account for the effect of the confinement caused by the ferrocement layer. As a tentative assumption based on mathematical regression, C1 and C2 are assumed to be 0.15 and 0.6, respectively. To determine the value of Asf, the column cross section shown in Figure 19 is used where the wire mesh appears as nodes with constant spacing S which is taken as the opening size according to Table 8.

To calculate the area of the wire mesh, the method implemented by IFS 10-01-Ferrocement Model Code [1] is adopted in this research. The area of the wire mesh is assumed to be the number of nodes multiplied by the cross-section area of wire mesh, taking into consideration the global efficiency factor of the wire mesh as shown by Equation 4. Due to the geometry of the mesh layers, the behavior in the longitudinal and transverse directions can be different and may need to be calculated separately. The value of η varies with the mesh orientations. The mesh orientations should be considered in the longitudinal direction, transverse direction, or any other angular directions. Figure 20 shows the direction of reinforcement, and Table 9 shows the values of η in the longitudinal, transverse and 45° directions according to the recommendations of the ACI 549 R-18 [2].

$$Asf = \eta n A \tag{4}$$

Where:

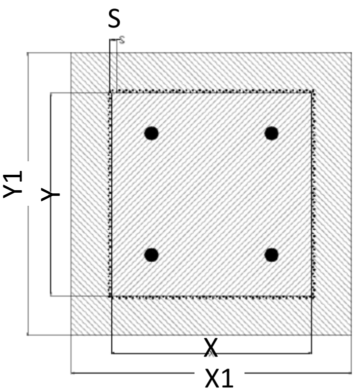
n = Number of nodes

A = Wire mesh cross section area (mm^2)

η = Global efficiency factor for the wire mesh, as shown in Table 10.

The number of nodes is determined by number of nodes in one meter multiplied by the length of wrapping as shown by Equation 5.

$$n = NL \tag{5}$$



X, Y = Column dimensions (mm)

X1, Y1 = Column dimensions after strengthening (mm)

S = Spacing between two nodes (mm)

Figure 19: Cross section of the column and the ferrocement layer with the wire mesh

Table 8: Opening sizes for the different types of mesh [36]

Type of wire mesh	Opening size (mm)
Welded square mesh	1.25 x 1.25
Hexagonal wire mesh	13 x 22
Diagonal wire mesh 0.8 mm	8 x 17
Diagonal wire mesh 1.5 mm	15 x 35
Diagonal wire mesh 2 mm	15 x 35

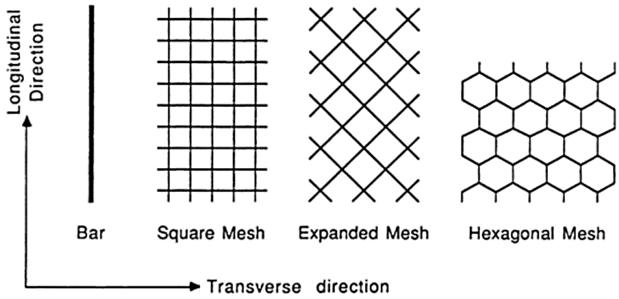


Figure 20: Proposed longitudinal and transverse directions of reinforcement mesh [2].

From Equation 4 and Equation 5, we can get the area of the wire mesh using Equation 6.

$$Asf = \eta NLA \tag{6}$$

Where: N = Number of nodes per meter, L = Length of wrapping (mm)

In case of hexagonal and diagonal wire mesh, each node branches out into 2 branches as shown in Figure 3. So, Equation 7 need to be used in this case.

$$Asf = 2\eta NLA \tag{7}$$

For the case of wire mesh overlapping such as specimen S-D8-1L-O, it is assumed that the factors related to ferrocement are multiplied by the overlapping value where the overlap was twice with 10% of column height, so, the component of the load capacity carried by the ferrocement is multiplied by 1.2.

Table 10 shows the proposed modified equation, experimental and ANSYS results, and Figure 21 shows the modified equation validation with the experimental and ANSYS results. When comparing the experimental results with the results computed using Equation (3), the material factors of safety were set to 1. The results obtained from the proposed equation are generally in good agreement with the experiment. The calculated ultimate capacity is higher than the experiment by about 10% except for the specimens strengthened with one layer of diagonal mesh 0.8 mm where the ultimate load is higher by 25%. The modified proposed equation shows good potential for calculating the load capacity. However, more investigation needs to be conducted for improvement of the parameters used in the equation and validation with a wider range of data need to be conducted.

6. CONCLUSIONS

An experimental study was conducted on 14 columns to study their behavior when strengthened using ferrocement jackets with different types of wire mesh and varying number of layers. A finite element analysis using the ANSYS program was conducted on the tested specimen and a modified equation was proposed to calculate the ultimate load capacity of the columns. Based on the results obtained it was concluded that:

Table 9: Global efficiency factor for the different types of mesh [2]

Mesh type	Global efficiency factor (η)		
	Longitudinal (ηL)	**Transverse (ηt)**	**AT $\eta\theta$ = 45**
Welded square mesh	0.5	0.5	0.35
Hexagonal wire mesh	0.45	0.45	0.3
Diagonal wire mesh	0.65	0.2	0.3
Longitudinal bars	1	0	0.7

Table 10: Comparison between experimental data and analytical results

Group	Specimen	Ultimate Load Experiment (kN)	Ultimate Load ANSYS (kN)	ANSYS / EXP (%)	Ultimate Load Proposed equation (kN)	Proposed equation / EXP (%)
Control	S C	532	543.2	102.1	532	100
Group 1-A	S-D8-1L	592	607.4	102.6	742.85	125.5
	S-D8-2L	701	637.6	91.0	751.51	107.2
	S-D8-3L	723	668.9	92.5	760.27	105.2
	S-D8-1L-CR	600	594.1	99.0	748.63	126.9
Group 1-B	S-D15-1L	693	626.5	90.4	748.2	108.0
	S-D15-2L	729	704.2	96.6	762.39	104.6
	S-D15-3L	761	758.9	99.7	776.86	102.1
	S-D15-1L-CR	710	671.7	94.6	757	103.7
Group 2	S-D8-2L	701	637.6	90.0	751.51	107.2
	S-D15-2L	729	704.2	96.6	762.39	104.6
	S-D20-2L	746	807	108.2	814.75	109.2
	S-HE-2L	680	694.1	102.1	738.69	108.2
	S-WE-2L	715	739.7	103.5	779.01	109.0
Group 3	S-D8-1L	592	607.4	102.6	742.85	125.5
	S-D8-1L-O	614	628.2	102.3	681.87	111.0
	S-D8-1L-N	571	595.5	104.3	651.38	114.0

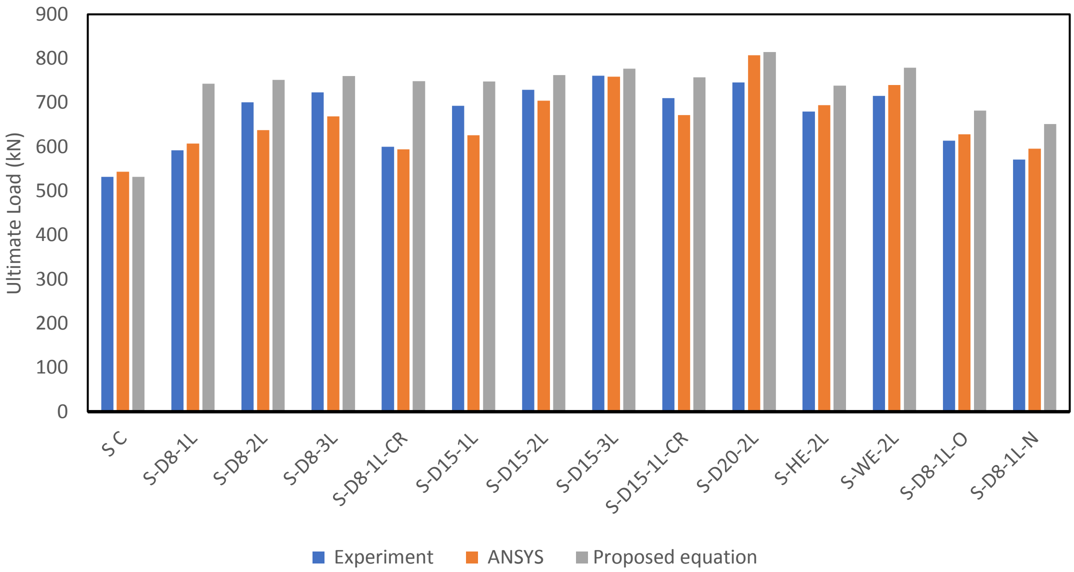


Figure 21: Comparison between experimental data and analytical results.

1. Strengthening using ferrocement jacketing proved an effective method where the load capacity of the tested specimens improved in all cases.
2. Comparing two layers of the five types of mesh used diagonal mesh with 2 mm thickness showed the highest improvement.
3. Increasing the number of layers for the same mesh type typically increases the load capacity. However, the gain when the number of layers was increased from two layers to three layers is not much significant. From the economical and construction point of view, the use of two layers of diagonal mesh with 0.8 mm or square welded mesh or one layer of diagonal mesh 1.5 mm is recommended where the load capacity increased by about 30%.
4. Adding additional mesh at the corners to overcome stress concentration did not prove to be very effective.

The additional mesh strips need to be confined in the transverse direction.

5. There is no significant difference between wrapping columns with layers in one part all over the height or in parts due to the standard dimensions of meshes.
6. Using the ANSYS program to analyze the tested specimens proved a good tool and good correlation was found between the analytical and experimental results. ANSYS can be further used in an extensive parametric study to further asses the behavior of columns with ferrocement jackets.
7. A proposed modified equation is presented for calculating the capacity of the columns strengthened using ferrocement. The equation showed good agreement with the experimental data and further investigation is needed to improve the parameters used.

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Conflicts of Interest:
The authors declare that there is no conflict of interest.

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