New York Science Journal

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Retrofitting Of Damaged RC Columns Using Spiral Stirrups

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Abstract: The present study deals with an experimental (EXP) and theoretical investigation of the behavior of the retrofitted damaged RC columns with different aspect ratios and different slenderness ratios. The present study presents a new technique for retrofitting of damaged RC columns using external spiral stirrups. A total of twenty RC columns specimens with different cross-sections, (100×100), (100×150), (100×200), (100×250) and (100×300) mm, fifteen of them were 1800 mm clear height and the other five specimens were 900 mm height. All columns were tested under axial loading until failure load, then replacing the damaged concrete part by using grout mortar and restoring specimens dimension and internal reinforcement. All columns were divided into four groups as follows: Group (1) consists of five specimens having cross-sections, as mentioned with a height of 1800mm, were retrofitted by using spiral stirrups with a constant pitch of 80mm and wrapped by three plies of steel wire mesh. Group (2) consists of five specimens having the same properties were retrofitted by using external longitudinal steel bars and tied by spiral stirrups with a pitch of 80mm. Group (3) consists of five specimens having the same properties were retrofitted by using spiral stirrups with a constant pitch of 120mm and wrapped by three plies of steel wire mesh. All the mentioned techniques were applied to the columns of the group (4), which consists of five specimens having the same cross-sections and height of 900mm. Five variables were investigated as follows: Aspect ratios A_{SPR} [defined as percentage of columns' length to width of cross-section (t/b)] were 1, 1.5, 2, 2.5 and 3. Slenderness ratio (λ) [defined as the percentage of the column's height to width (H/b)] were (15.3 and 7.6). Pitches of spiral stirrups (S) were (80 and 120mm). Using steel wire mesh and/or using external longitudinal bars with spiral stirrups. Using partial retrofitting of 1.5 of the defected length. All retrofitted damaged RC columns were tied at head and base of the applied jacket with steel clamp (30×3) mm then covered with 20mm grout mortar. The retrofitted damaged columns were tested again until failure load. The test results showed an increasing of carrying capacities for all presented techniques by various values. It is concluded that carrying capacities increase by decreasing the spiral pitching and by using external longitudinal steel bars which tied by spiral stirrups higher than using spiral stirrups wrapped by steel mesh. The horizontal displacements decrease by using longitudinal bars tied by spiral stirrups less than using spiral stirrups, which wrapped by steel mesh and by decreasing of spiral pitching. The slenderness ratio has no significant effect on used techniques. A fair agreement was found between finite element (FEA) results and experimental (EXP) results. However, the (FEA) models can identify the structural behavior of tested columns and can be an alternative for the destructive laboratory test. Finally, jacketing by external longitudinal steel bars tied by spiral stirrups proved to be an easy, inexpensive in retrofitting of damaged RC columns.
[Elsamny, M.K., Elbatal, S. A., Abo-Alanwar, M. M. and Abdel-Mohsen, A.M. **Retrofitting Of Damaged RC Columns Using Spiral Stirrups.** *N Y Sci J* 2020;13(3):16-38]. ISSN 1554-0200 (print); ISSN 2375-723X (online). http://www.sciencepub.net/newyork. 2. doi:10.7537/marsnys130320.02.

Keywords: (RC) Columns;buckling; aspect ratio; slenderness ratio; concrete jacketing; repair; retrofitting; partial repair; spiral stirrups; steel wire mesh; capacity; finite element; failure load; slender column; experimental.

1. Introduction

Columns are one of the most critical structural elements in the building, so needing to strengthening and retrofitting or rehabilitation of columns are widely required to correct design errors as well as defects during construction and/or a service lifetime. Several researchers have investigated the factors affecting the behavior of RC columns, besides the methods of strengthening RC columns under different loads using different techniques. Frangou, M. et al. (1995) [1] described a cost-effective and efficient technique for strengthening RC columns. The proposed technique involves post-tensioning metal strips around reinforced concrete columns, by using a strapping machine. The preliminary results of the experimental work indicate that such strengthening can increase member strength and ductility to higher levels than those possible by conventional reinforcement, at only a fraction of the time and cost required by alternative techniques. Ramirez, J.L. et al. (1997) [2] presented two different methods to strengthen short length square concrete columns. In one of this method the steel jacket is formed by two bent plates, L shaped, welded longitudinally in the two common corners, leaving a small clearance concerning the original column surface that is injected with a polymeric grout afterward. In the other method, the jacket is made by adhesion of steel plates to the complete four faces of the column, closing the jacket by narrow bent plates L shaped joined also by adhesion to the steel plates at the column corners. Complete loss of strength of the original concrete column was assumed, in centered compression, and a method of calculation for load transfer between column and jacket in the smallest length possible was presented. Good experimental behavior and correspondence between calculation and experimental results were obtained for the welded and injected jacket but these results were poor for the jacket built up by adhesion. Problems caused by the quality of adhesive and mastics have also been detected, and finally, some observations concerning the price and conditions of execution were made. Abdel-hamed, U. M. (1999) [3] investigated experimentally the partial strengthening of columns to repair the defected part only. Fourteen reinforced concrete columns were tested to achieve the purpose of the study. Four basic parameters were taken into consideration; type of defect, location of the defect, jacket height, and type of strengthening. Columns were loaded axially, the investigation summarized that; the use of RC jacket with length=1.5 the length of the defect, the use of welded stirrups in strengthening were increased of jacket efficiency. Oudah, H. K. (2009) [4] Investigated different techniques of strengthening by testing 12 reinforced concrete columns having a cross-section of (120×120mm) and length of (1000mm). A study has been done as the effect of strengthening columns using different techniques. In addition, introducing a state of the art strengthening method using skewed steel mesh, however, it was found that strengthening columns by steel angles and ties and jacketing by steel mesh is durable and easy to apply. the proposed new method of strengthening column by jacketing using steel mesh gives an increase in column carrying capacity by 3.7–27.8 % depending on number of piles around the columns, taking into consideration that special care needs to be taken in choosing the composition of the grout and in the application of the grout on the steel mesh, finally, Increasing number of horizontal external steel tie plates, as well as increasing number of plies for skew steel mesh strengthening, gives an increase of column carrying capacity. Oudah, H. K. (2011) [5] tested 41 reinforced concrete columns having a cross-section of (120×120) mm and length of (1000) mm; it has been strengthened by using different methods, steel wire mesh, additional longitudinal bars, vertical steel angles, and FRP. Specimens were loaded under different eccentricities. The columns were divided into a non-strengthened control group plus six groups having different four steel angles dimensions connected with five straps. In addition, two columns were strengthened by FRP and another two were strengthened by steel mesh. All strengthened columns as well as non- strengthened columns (control) were tested under five different eccentricities from 0 up to 30%. Every strengthening method has been applied only without the integration of two methods or more so results were different, it has been monitoring the highest result by using eight plies of steel wire mesh. Elsamny, M.K. et al. (2014) [6] used a wire mesh jacketing technique to strengthen the rectangular RC column under eccentric loads. Thirty-seven specimens with a column cross-section of (120x160) mm and a length of (800) mm were investigated. All specimens were examined under various eccentricities. It was observed that applying the wire mesh jacketing technique approach will achieve a significant increase in the load-carrying capacity up to (23%). On the other hand, employing a sandwich wrapping system technique which is consisted of both steel wire mesh and external vertical steel bars in the compression side will attain an increase in the load-carrying capacity reaches (54%). Abdel-Hay, A. S. and Fawzy, Y. A. (2014) [7] studied the efficiency of short steel jackets for the strengthening of RC defected columns. The experimental program consists of testing of seven R.C columns with dimensions 200 × 200 × 1500 mm and having stirrups in the top and bottom thirds only, while the middle third was without stirrups. The main parameters studied were the type of steel jacket used and the height of the partially strengthened part of the column. One of the tested specimens was a control specimen and the other six were partially strengthened with different types of steel jackets such as using 4 steel angles at corners connected with straps, using external ties with different spacing, and using 4 steel plates with different thicknesses welded together and connected to the column by anchor bolts. Finally, the experimental results were analyzed and compared with results obtained from finite element analysis using ANSYS program. Abd-ELhamed, M. K. and Ezz-Eldeen, H. A. (2014) [8] applied wire mesh jacketing technique in order to rehabilitate the rectangular RC column under eccentric loads. This was carried out by utilizing a total of six RC rectangular columns each has a cross-section of 120x160 mm and 800 mm length. The columns were casted and tested until failure. Two control columns were inspected under axial load and the other four columns were inspected under different eccentricities. All columns were retrofitted by substituting the loose concrete part by grout mortar. Strengthening was carried out using four vertical steel angles wrapped with expanded three plies steel wire mesh. However, the steel wire mesh jacket was injected by cement mortar. The test results observed that the columns examined under different eccentricity and strengthened with four vertical steel angles and wrapped with three plies steel wire mesh achieved a greater failure load than those wrapped with three plies steel wire mesh only. Abo-Alanwar, M. M. (2015) [9] presented an experimental study on strengthening rectangular reinforced concrete columns under eccentric loads by steel wire mesh and external vertical steel bars. Nineteen rectangular reinforced concrete columns were (120×160) cm cross-section and 800 cm height and divided into four groups in addition to controlling group, the first group was strengthened by three plies of steel wire mesh under eccentric loading, the second group has been strengthened with additional external vertical steel bars in between the plies of the steel wire mesh in compression side, the third and fourth groups were strengthened by the same technique of other groups with deferent eccentricity. The additional external vertical steel bars have been taken 2, 3, 4 and 5Ø8 in the compression side only to study the effect of increasing the additional external steel area on the strengthening of R.C. columns. The used jacketing has been grouted with cement mortar. A total of nineteen rectangular R.C. columns have been tested under eccentricities 6.25%, 12.50%, and 18.75%. El-batal, S. A. (2015) [10] conducted an experimental investigation to study twenty-one specimens having a column cross-section of (120x160) mm and a length of (800) mm. Strengthening columns subjected to eccentric load by adding external steel angles and/or steel plates in the compression side wrapped with steel wire mesh. Using Steel angles with dimensions 15×15×3 mm, 20×20×3mm, 25×25×3, and 30×30×3 mm and steel plate with dimensions 60×3 mm, 80×3mm, 100×3, and 120×3 mm wrapped by steel wire mesh and grouted by cement mortar jacketing have been used. It has been founded that the new external confinement technique under eccentric loading up to 20 % gives an increase in the load-carrying capacity up to (39%). Increasing the area of external steel angels and steel plates significantly increases the ultimate load-carrying capacity of the strengthened column. The forces in internal vertical steel reinforcement in compression side are found be to up to 4.4 % from the failure loads of the strengthening columns as well as forces in external vertical steel angles and/or steel plates in compression side are found to be up to 16.15 % from the failure loads of the strengthening columns. An important advantage was achieved that the new technique has significant improvement in the load carrying-capacity and ductility as well as the performance.

However, the need for investigation on new potential external wrapping materials has arisen, due to the high manufacturing and application costs of FRP. This paper presents a new technique to retrofitting the columns under axial load by using relatively cheap materials. Spiral stirrups with steel wire mesh and/or longitudinal steel bars for square and/or rectangular RC columns are presented in this study.

The objectives of the presented study are to determine the effect of spiral stirrups jacketing on retrofitting damaged (RC) columns as follows:-

i. Study the effect of the columns' aspect ratios on the behavior of both long and short RC columns experimentally.
ii. Study the effect of external retrofitting using spiral stirrups which wrapped by steel wire mesh on damaged (RC) columns.
iii. Study the effect of external retrofitting using longitudinal steel bars which tied by spiral stirrups on damaged (RC) columns.
iv. Presenting finite element model to simulate the behavior of the retrofitted damaged (RC) column.
v. Comparison of the results and the efficiency of the used techniques experimentally with the presented finite element model in retrofitting of both short and long damaged (RC) columns.

2. Experimental Program and Proposed Technique

2.1. Characteristics of Used Materials

i. Crushed stone with a maximum nominal size of (0.07-20.0mm) was used as the coarse aggregate in the mix design.
ii. Graded sand with sizes in the range of (0.08 - 0.3 mm) was used as the fine aggregate in the mix design.
iii. Ordinary Portland cement was used in all the experimental work.
iv. Clean drinking freshwater is used for the mixing and curing issues of the specimens. Percentage of water-cement ratio 50%.
v. Normal mild steel bars St24/37-smooth rebar of diameter 6 and 8 mm were used for internal reinforcement and external jacketing.
vi. Using cementations mix (Cetorex grout mortar) that needs only the addition of water achieving a high strength non-shrink mortar.
vii. The steel clamps used for confining both ends of the applied jacket have a yield stress of 325 N/mm^2 and a tensile strength of 420 N/mm^2.

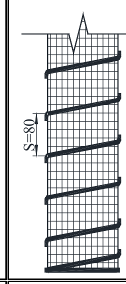
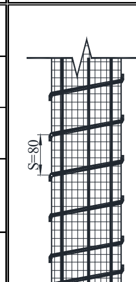
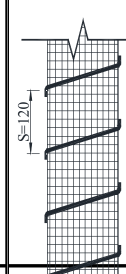
viii. Galvanized steel wire mesh used in retrofitting.

The designed concrete mix in all the tested specimens was according to the Egyptian code of practice. The concrete mix was designed to achieve compressive target strength of 25 N/mm^2 at the age of 28 days.

2.2. Details of Specimens

A total of twenty column specimens having cross-sections of (100×100), (100×150), (100×200), (100×250) and (100×300) mm, fifteen were 1800 mm clear height and the other five specimens were 900 mm have been tested in the present study. All specimens reinforced according to table [1] by (normal mild steel) for longitudinal bars and stirrups.

Table [1] Details of control column specimens and proposed techniques used for retrofitting of damaged (RC) columns

group	Existed specimen's dimension: Cross section (mm)		Existed specimen's dimension: Clear height (mm)	Aspect ratio	specimen's title	Internal Reinforcement: bars	Internal Reinforcement: stirrups	External retrofitting: technique	External retrofitting: Details	External retrofitting: No. / type	Key
group (1)	100	100	1800	1	C-1a	4 ϕ 6	ϕ6/100mm	Spiral stirrups + steel wire mesh	1 ply steel wire mesh lower+ spiral stirrupsϕ6mm /80 mm + 2 plies of steel wire mesh upper		
	100	150		1.5	C-1b	6 ϕ 6					
	100	200		2	C-1c	4ϕ8					
	100	250		2.5	C-1d (local repair)	4ϕ8+2ϕ6					
	100	300		3	C-1e	4ϕ8+4ϕ6					
group (2)	100	100	1800	1	C-2a	4 ϕ 6	ϕ6/100mm	Longitudinal steel bars + spiral stirrups +steel wire mesh	1 ply steel wire mesh lower+ Spiral stirrupsϕ6mm /80 mm	2ϕ6	
	100	150		1.5	C-2b	6 ϕ 6				4ϕ6	
	100	200		2	C-2c	4ϕ8				6ϕ6	
	100	250		2.5	C-2d (local repair)	4ϕ8+2ϕ6				4ϕ8	
	100	300		3	C-2e	4ϕ8+4ϕ6				4ϕ8+2ϕ6	
group (3)	100	100	1800	1	C-3a	4 ϕ 6	ϕ6/100mm	Spiral stirrups + steel wire mesh	1 ply steel wire mesh lower+ spiral stirrupsϕ6mm /120 mm + 2 plies of steel wire mesh upper		
	100	150		1.5	C-3b	6 ϕ 6					
	100	200		2	C-3c	4ϕ8					
	100	250		2.5	C-3d (local repair)	4ϕ8+2ϕ6					
	100	300		3	C-3e	4ϕ8+4ϕ6					
group (4) (short specimens)	100	100	900	1	C-4a	4 ϕ 6	ϕ6/100mm	1 ply steel wire mesh lower+ spiral stirrupsϕ6mm /80 mm + 2 plies of steel wire mesh upper			
	100	150		1.5	C-4b	6 ϕ 6					
	100	200		2	C-4c	4ϕ8		1 ply steel wire mesh lower+ spiral stirrups ϕ6mm /80 mm+6ϕ6			
	100	250		2.5	C-4d	4ϕ8+2ϕ6		1 ply steel wire mesh lower+ spiral stirrupsϕ6mm /120 mm + 2 plies of steel wire mesh upper			
	100	300		3	C-4e	4ϕ8+4ϕ6					

2.3. Strain Gauges and Lvdts

Strain Gauges have been mounted inside all specimens on the two longitudinal reinforcement bars at both sides of deflection and one strain mounted on stirrups, two LVDTs located on length of tested column; First LVDT located at mid-height of tested specimen and the other LVDT placed at quarter height of specimen for all non-strengthen columns, and one strain gauge has been mounted on external spiral stirrups and another strain gauge has been mounted on the surface of grout mortar and LVDTs were located at the same place mentioned in non-strengthen columns before the damaging as shown in figures [1] and [2].

The strain gauges used were manufactured by TOKYO SOKKI KENKYUJO CO. LYD. The used type named PFL-30-11-3L, which has a resistance of 120.4 ± 0.5nd % Ohms at 11ºC, and a gauge factor of 2.13 ± 1.0%. Figure (2) shows the two (LVDTs) installed on columns to measure the horizontal displacement.

The location of strain gauges mounted inside and LVDTs for all specimens as follows:-

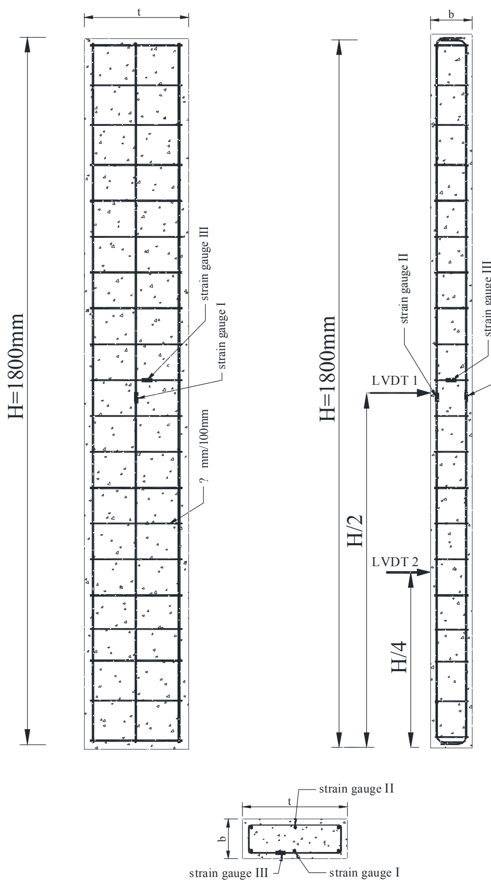


Figure [1]

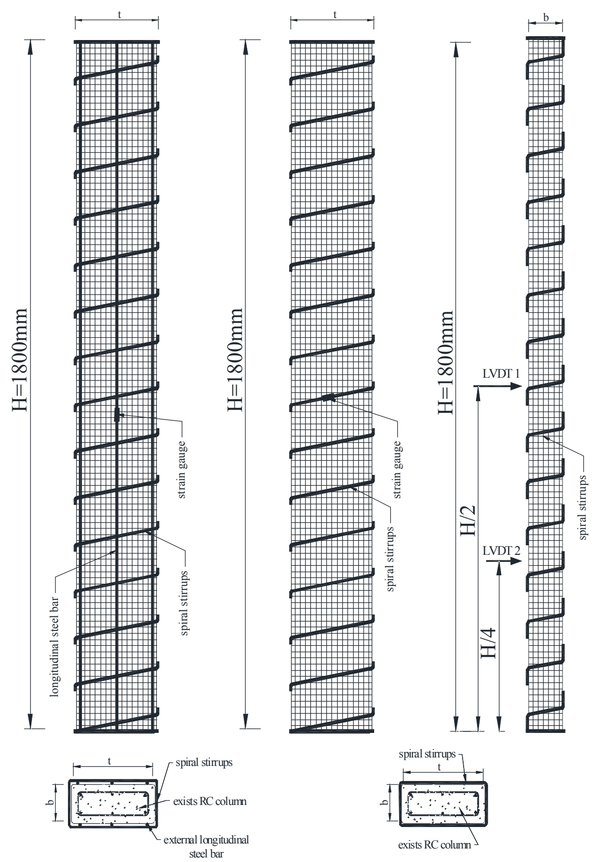


Figure [2]

Figure [1] Location of LVDTs and steel strain gauges for non-strengthen specimens[before retrofitting]

Figure [2] Location of strain gauges for retrofitted damaged RC columns

2.4 Casting of Columns

All specimens were casted in wooden forms and a mechanical vibrator was used. Columns forms were removed and columns specimens were cured. The test specimens were casted in wooden forms as shown in figure [3].

Figure [3] Wooden forms for casting

2.5. Damaged Columns

All columns without strengthening (control columns) were tested until failure after 28 days from casting to failure load as shown in Figure [4].

Figure [4] Specimens after testing before retrofitting

2.6 Retrofitting Procedure

i. All defected parts in damaged specimens cleaned from loose concrete, specimens readjusted to its exists dimensions, deformed steel bars readjusted and supplied by new steel part welded to exists bars, tainted ties were replaced by new one, then empty parts filled and vibrated well using CETOREX grout mortar with high-strength, low or non-shrink to restore specimens dimension as shown in Figure [5].

Figure [5] Replacement of damaged RC concrete by grout mortar

i. Spiral stirrups rounded exists damaged RC columns with different pitches and wrapped by steel wire mesh then covered by 20 mm grout mortar also used to tie external longitudinal steel bars and that presented techniques applied for partially retrofitting of defected parts of damaged RC columns as shown in figure [6], Figure [7] shows procedure of presented techniques and location of strain gauges on external spiral stirrups. All jackets were collared at both ends by steel clamp (30×3) mm, then all jackets covered by 20 mm grout mortar as show in figure [8].

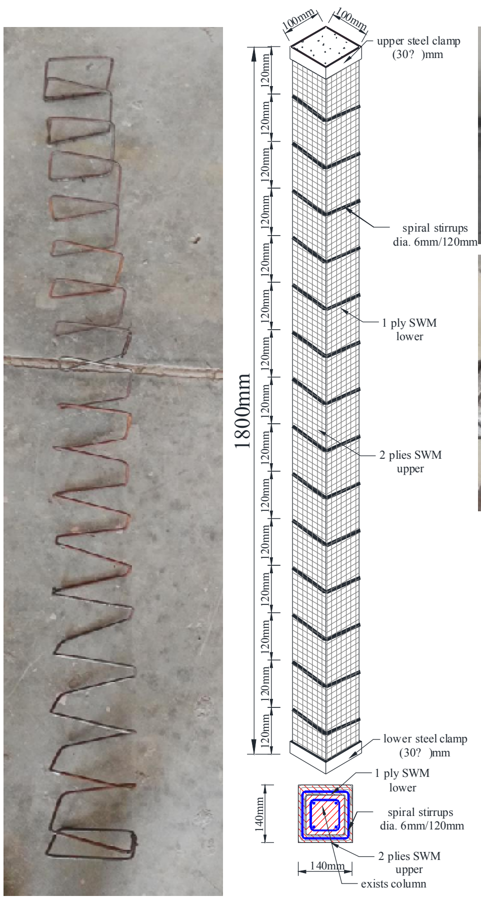


Figure [6]

Figure [7]

Figure [6] Practical and geometry of winding external spiral stirrups

Figure [7] Procedure of external winding spiral stirrups and mounting of strain gauges

Figure [8] Retrofitted of both long and short column specimens before testing

2.7. Details of Columns Retrofitting with External Spiral Stirrups

Table [2] shows details of damaged RC columns retrofitting with external spiral stirrups and presented jackets as follows:-

Group (1):-

Consists of five long RC column specimens C-1a (100×100), C-1b (100×150), C-1c (100×200), C-1d (100×250) and C-1e (100×300) with clear height 1800 mm tested under an axial load till failure then, retrofitted by rolling spiral stirrups ϕ6 mm with pitch 80 mm and wrapped by three plies of steel mesh.

Group (2):-

Consists of five long RC column specimen C-2a (100×100), C-2b (100×150), C-2c (100×200), C-2d (100×250) and C-2e (100×300) with clear height 1800 mm tested under an axial load till failure then, retrofitted by wrapping one layer of steel mesh and external longitudinal bars rolled by spiral stirrups bar ϕ6 mm with pitch 80 mm.

Group (3):-

Consists of five long RC column specimens C-3a (100×100), C-3b (100×150), C-3c (100×200), C-3d (100×250) and C-3e (100×300) with clear height 1800 mm tested under an axial load till failure then, retrofitted by rolling spiral stirrups ϕ6 mm with pitch 120 mm and wrapped by three plies of steel mesh.

Group (4):-

Consists of five short RC column specimens (λ=7.6) with columns height 900 mm tested under axial load until failure then, the column specimens C-as (100×100) and C-bs (100×150) retrofitted by using group (1) technique by wrapping one-ply of steel wire mesh tied by spiral stirrups ϕ6 by pitch 80 mm and wrapped by another two plies of steel wire mesh and specimen C-cs (100×200) retrofitted by using group (2) technique retrofitted by wrapping one ply of steel wire mesh and adding external longitudinal steel bars tied by spiral stirrups ϕ6 by pitch 80 mm and specimens C-ds (100×250) and C-es (100×300) retrofitted by using group (3) technique by wrapping one ply of steel wire mesh tied by spiral stirrups ϕ6 by pitch 120 mm and wrapped by another two plies of steel wire mesh.

All retrofitted damaged RC column specimens tied at both ends of the applied jacket by steel clamp (30×3) mm and grouted by20 mm thickness. New dimensions become C-a (140×140), C-b (140×190), C-c (140×240), C-d (140×290) and C-e (140×340).

3. Testing Setup and Procedure

3.1. Testing Setup

All column specimens were tested under static axially loads at the material laboratory of Al-Azhar University. The loading frame was manufactured to resist the expected maximum load. The test setup is shown in Figure [9].

Figure [9] Loading frame and test set up

3.3. Loads and Data Acquisition System

Data acquisition system connected to load cell consisted of a computer and the lab tech notebook software package is shown in Figure [10].

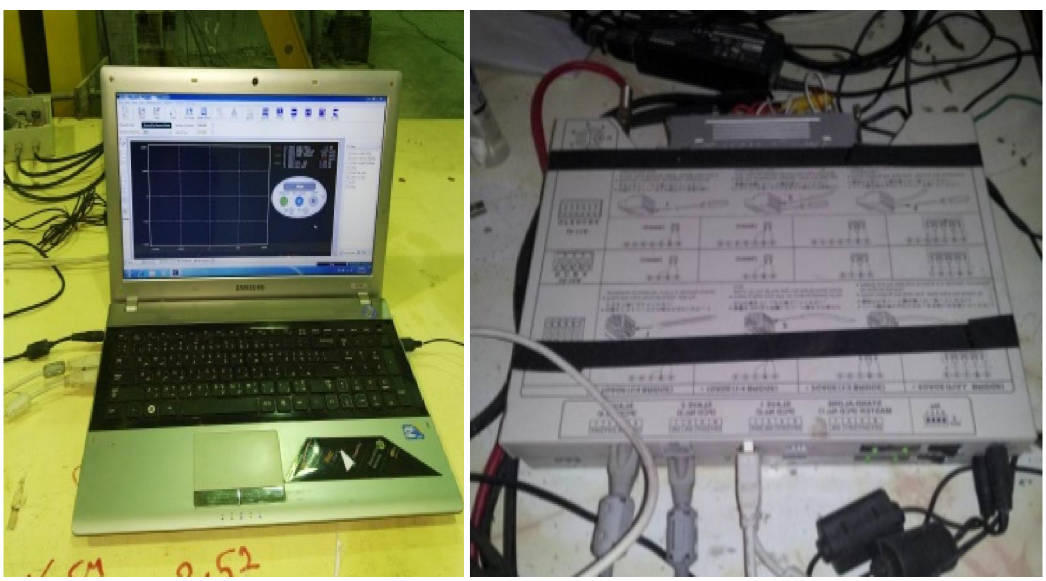


Figure [10] Data Acquisition System

4. Experimental Test Results

4.1 Relationship Between Loads And Strains

Figures [11] to [14] show the relationship between load and strain for external spiral stirrups and longitudinal steel bar and external grout mortar by three techniques applied for the specimen (C-a) [A_{SPR}=1, λ=15.3] respectively.

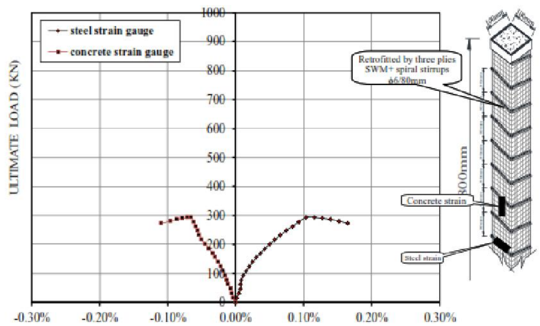


Figure [11] Relationship between ultimate load and (%) strain on external spiral stirrups and strain gauge on the surface of grout mortar for retrofitted of damaged RC column specimen C-1a; S=80mm

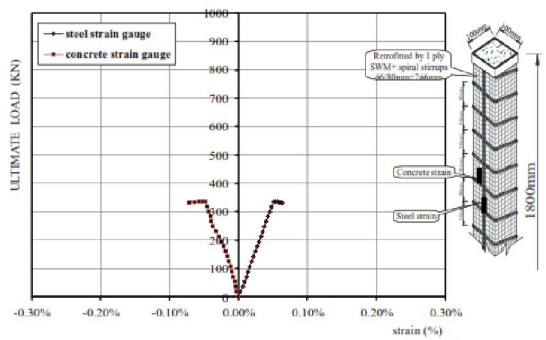


Figure [12] Relationship between ultimate load and (%) strain on an external longitudinal steel bar and strain gauge on the surface of grout mortar for retrofitted of damaged RC column specimen C-2a

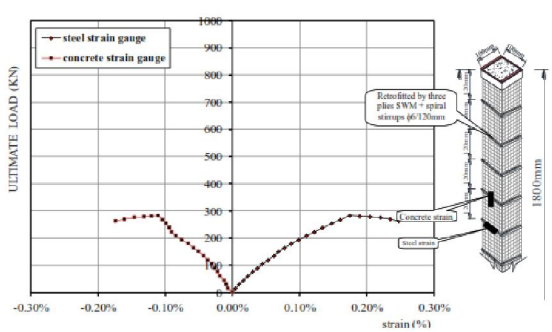


Figure [13] Relationship between ultimate load and (%) strain on external spiral stirrups and strain gauge on the surface of grout mortar for retrofitted of damaged RC column specimen C-3a; S=120mm

4.2 Results of Load Carrying Capacity

Table [2] and figures [15] and [16] introduce failure load of control specimens and carrying-capacity of retrofitted damaged RC columns, carrying-capacity increased by 151%, 145%, 142%, 135%, and 139% respectively for retrofitted columns of group (1) that retrofitted by external spiral stirrups ϕ6 with pitch 80 mm and wrapped by three plies of steel wire mesh, the increasing of carrying-capacity for retrofitted columns of group (2) that retrofitted by wrapping one-ply steel wire mesh with longitudinal steel bar tied by spiral stirrups by pitch 80 mm were 173%, 158%, 169%, 138%, and 144% respectively, the increasing of carrying-capacity for retrofitted columns of group (3) was 150%, 138%, 142%, 141%, and 140%that retrofitted by external spiral stirrups ϕ6 with pitch 120 mm and wrapped by three plies of steel wire mesh.

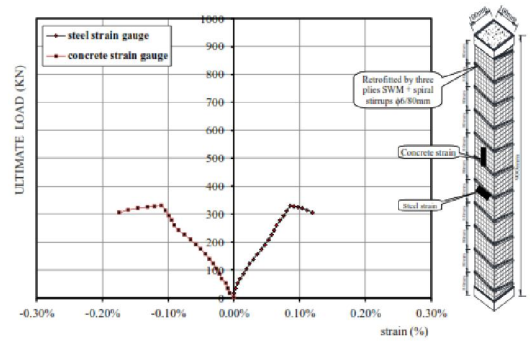


Figure [14] Relationship between ultimate load and (%) strain on external spiral stirrups and strain gauge on the surface of grout mortar for retrofitted of damaged RC column specimen C-4a; S=80mm

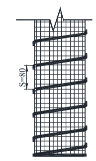
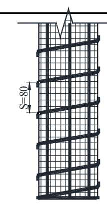
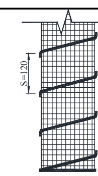
The obtained results show that retrofitting of damaged reinforced concrete columns by wrapping one-ply steel wire mesh with longitudinal steel bar tied by spiral stirrups by pitch 80 mm gave maximum carrying capacity for retrofitted RC columns more than using spiral stirrups wrapped three plies of steel wire mesh, and decreasing of pitches from 120mm to 80 mm gave increasing in carrying-capacity. The increasing of carrying-capacity of retrofitted damaged RC short columns of the group (4) was enclosed in table [2].

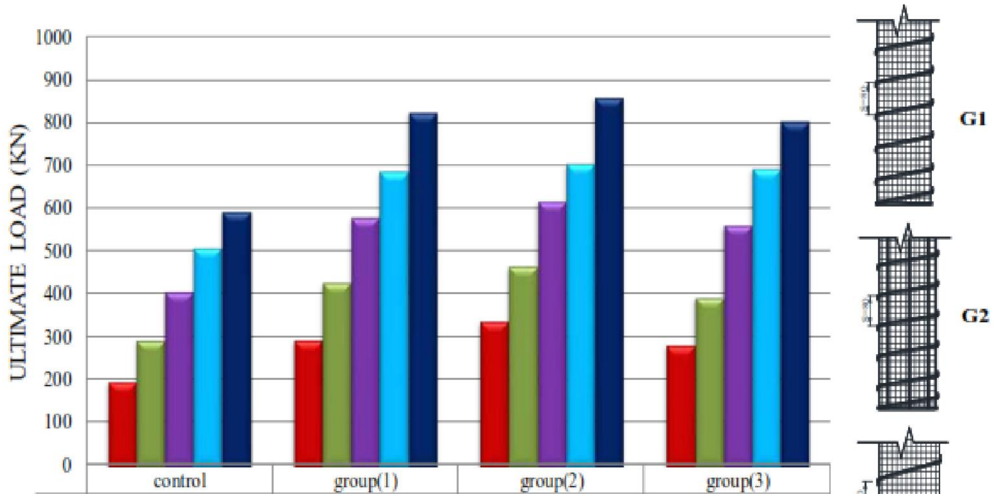
Retrofitting by presented techniques introduced carrying-capacity higher than partially retrofitting. Failure mode of columns that retrofitted totally were crushing of head, base or/and both for the tested specimen.

4.3 Effect of Steel Wire Mesh and Longitudinal Steel Bars with Spiral Stirrups on Behavior of Retrofitted Damaged (Rc) Columns

Figure [18] shows the comparison between the carrying-capacity of the group (1) (using spiral stirrups ϕ6/80mm + three plies of SWM) and group (2) (using spiral stirrups ϕ6/80mm + longitudinal bars). The obtained results show that the column's carrying-capacity increases by using external longitudinal steel bars tied by spiral stirrups higher than using spiral stirrups wrapped by steel wire mesh.

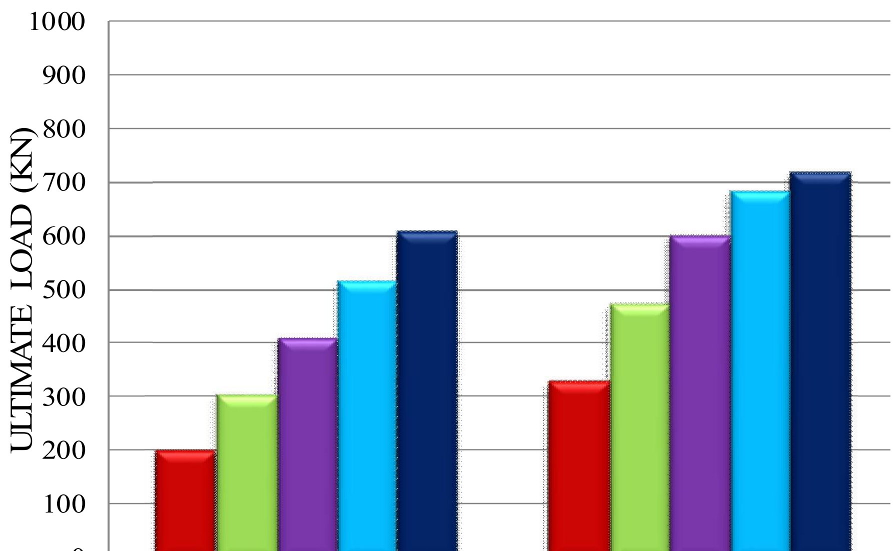
Table [2] details of applied techniques used for retrofitting and failure loads for control, retrofitted RC columns and percentage of increasing of carrying-capacity

group	specimen's title	Aspect ratio (A_{SPR})	(λ)	External retrofitting		Failure load (KN)		Columns carrying capacity	Key
				Details No. / type		Control specimens	Retrofitted specimens		
group (1)	C-1a	1	15.3	1 ply steel wire mesh lower+ spiral stirrupsϕ6mm /80 mm + 2 plies of steel wire mesh upper		194.21	293.57	151%	
	C-1b	1.5				293.41	425.4445	145%	
	C-1c	2				405.15	577.4675	143%	
	C-1d (local repair)	2.5				509.02	688.079	135%	
	C-1e	3				593.2	825.64	139%	
group (2)	C-2a	1	15.3	1 ply steel wire mesh lower+ Spiral stirrupsϕ6mm /80 mm	2ϕ6	184.49	336.04	182%	
	C-2b	1.5			4ϕ6	278.73	464.44	167%	
	C-2c	2			6ϕ6	384.89	617.54	160%	
	C-2d (local repair)	2.5			4ϕ8	483.56	704.38	146%	
	C-2e	3			4ϕ8+2ϕ6	563.54	860	153%	
group (3)	C-3a	1	15.3	1 ply steel mesh lower+ spiral stirrupsϕ6mm /120 mm + 2 plies of steel wire mesh upper		188.38	281.69	150%	
	C-3b	1.5				284.60	391.89	138%	
	C-3c	2				392.99	559.87	142%	
	C-3d (local repair)	2.5				493.74	693.74	141%	
	C-3e	3				575.40	803.32	140%	
group (4) (short specimens)	C-4a	1	7.6	1 ply steel wire mesh lower+ spiral stirrupsϕ6mm /80 mm + 2 plies of steel wire mesh upper		203.9205	329	161%	
	C-4b	1.5				305.52	475	155%	
	C-4c	2		1 ply steel wire mesh lower+ spiral stirrups ϕ6mm /80 mm+6ϕ6		412.56	601	146%	
	C-4d	2.5		1 ply steel wire mesh lower+ spiral stirrupsϕ6mm /120 mm + 2 plies of steel wire mesh upper		519.02	685	132%	
	C-4e	3				610.66	720	118%	



	control	group(1)	group(2)	group(3)
C-a	194.21	293.57	336.04	281.69
C-b	293.41	425.44	464.44	391.89
C-c	405.15	577.46	617.54	559.87
C-d	509.02	688.07	704.38	693.74
C-e	593.2	825.64	860	803.32

Figure [15] Comparison between ultimate loads of control columns and retrofitted of damaged RC columns for long column specimens (λ=15.3)



	control	group(4)
C-a	203.9205	329
C-b	305.52	475
C-c	412.56	601
C-d	519.02	685
C-e	610.66	720

Figure [16] Comparison between ultimate loads of control columns and retrofitted of damaged RC columns for short column specimens (λ=7.6)

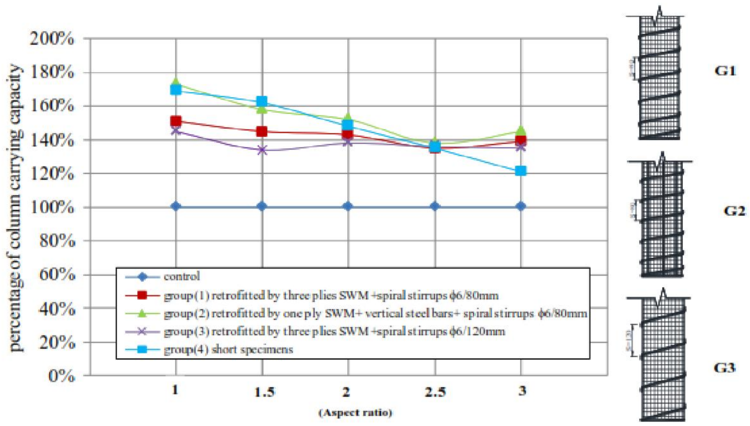


Figure [17] Comparison between percentages of carrying capacity of control RC columns and retrofitted of damaged RC columns by different techniques used in retrofitting

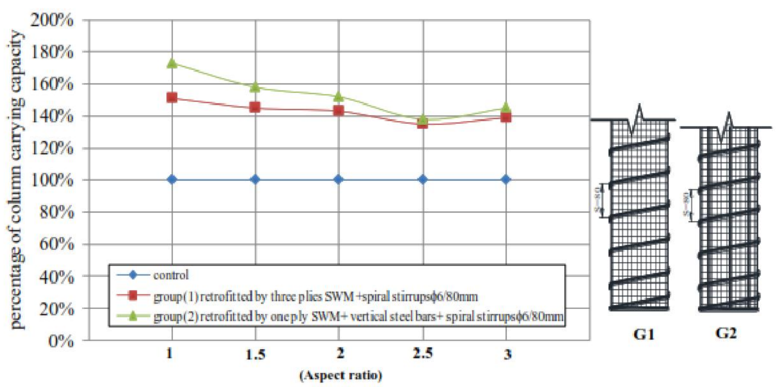


Figure [18] Comparison between ultimate loads obtained from experimental testing for the group (1) using (spiral stirrups +SWM) and retrofitted of damaged RC columns of the group (2) using (spiral stirrups + longitudinal steel bar).

4.4 Effect of Spiral Pitching on Behavior of Retrofitted Damaged (Rc) Columns

A comparison between the results has been done to investigate the effect of different pitches on the behavior of retrofitted damaged RC columns. Figure [19] shows a comparison between carrying-capacity obtained from experimental testing for group (1) (spiral pitch =80 mm) and group (2) (spiral pitch =120 mm). The obtained results show that the column's carrying-capacity increases by decreasing pitching.

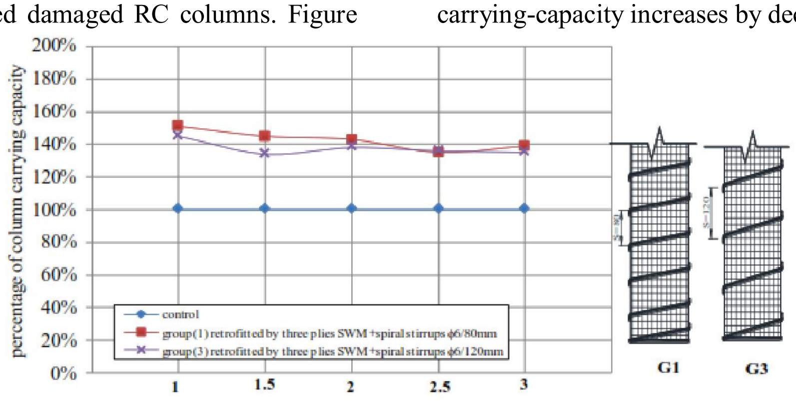


Figure [19] Comparison between percentages of carrying capacities obtained from experimental testing for retrofitted of damaged RC columns of group (1) using (spiral pitch =80 mm) and retrofitted damaged columns of group (3) (spiral pitch =120 mm).

4.5 Comparison between Using Partially Retrofitting and Totally Retrofitting By the Same Presented Techniques

Figure [20] shows the comparison between control columns and retrofitted columns C-d which retrofitted partially by different techniques compared with columns that retrofitted totally by the same techniques C-a, C-b, C-c, and C-e. The obtained results show that the column's carrying-capacity increased by using totally repair.

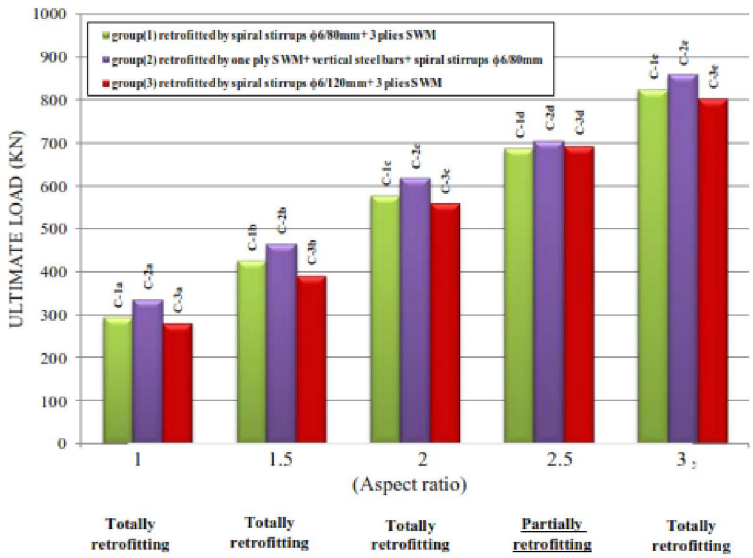


Figure [20] comparison between using partially retrofitting for the defected part and totally retrofitting by the same presented techniques

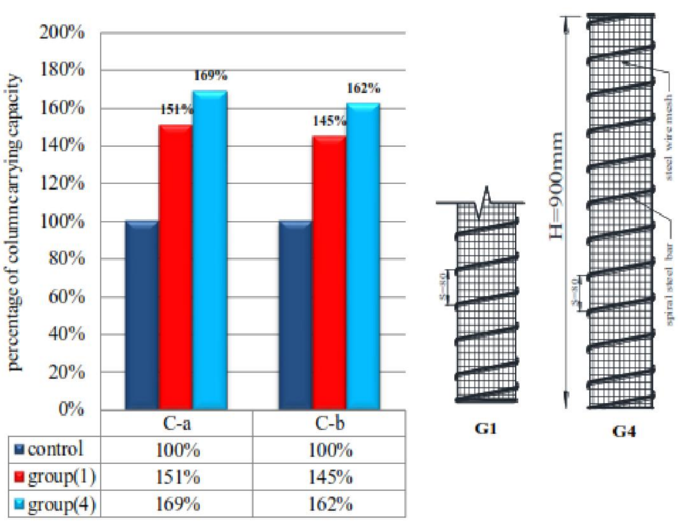


Figure [21] Comparison between carrying-capacities obtained from experimental testing for retrofitted long RC columns C-1a and C-1b [group (1)] and retrofitted short RC columns C-4a and C-4b [group (4)] which retrofitted by using spiral stirrups ϕ6/80mm wrapped by three plies of steel mesh

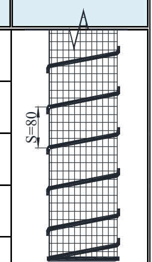
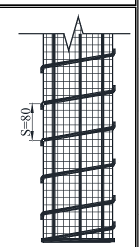
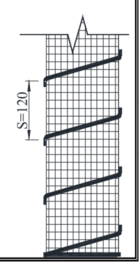
4.6 Effect of Used Techniques on Carrying-Capacity of Retrofitted Damaged Rc Columns With Different Slenderness Ratios (Λ)

A comparison between the results has been done to investigate the effect used retrofitting techniques of damaged RC columns with different slenderness ratios (λ) as shown in figure [21]. The obtained results show that the carrying-capacity decreases by increasing of slenderness ratio.

4.7 Effect of Different Retrofitting Techniques on Horizontal Displacement (Δ) Of Retrofitted Damaged Rc Columns

A comparison between the results has been done to investigate the effect of different techniques used in retrofitting on the horizontal displacement of long RC columns behavior. Table [3] and figure [22] show a comparison between horizontal displacements (δ) at mid-height for all control columns that have slenderness ratio (λ=15.3) and retrofitted columns by different techniques from experimental testing. The obtained results show that the horizontal displacement (δ) increases by increasing spiral pitch and decreases by using longitudinal steel bars with spiral stirrups less than using spiral stirrups with steel wire mesh.

Table [3] the failure loads and maximum recorded displacement at the mid-height and quarter height tested long columns before and after retrofitting by different techniques

group	specimen's title	Aspect ratio (A_{SPR})	(EXP) Failure Loads (KN)		Displacement at Mid-height (mm)		Displacement at quarter height (mm)		Key
			Control column	Retrofitted column	Control columns	Retrofitted columns	Control columns	Retrofitted columns	
group (1)	C-1a	1	194.21	293.57	9.2	2.64	6.1	1.58	
	C-1b	1.5	293.41	425.44	8.35	1.998	6.05	2.05	
	C-1c	2	405.15	577.46	7.05	1.75	4.75	2.2	
	C-1d	2.5	509.02	688.07	5.96	1.665	3.15	2.5	
	C-1e	3	593.2	825.64	4.4	1.55	2.85	2	
group (2)	C-2a	1	194.21	336.04	8.3	2.25	5.2	1.64	
	C-2b	1.5	293.41	464.44	7.32	1.95	5.3	1.64	
	C-2c	2	405.15	617.54	6.2	1.66	3.6	1.76	
	C-2d	2.5	509.02	704.38	4.8	1.56	2.2	1.81	
	C-2e	3	593.2	860	2.3	1.5	1.7	2	
group (3)	C-3a	1	194.21	281.69	8.8	4.8	6.3	3.28	
	C-3b	1.5	293.41	391.89	8.1	3.99	5.8	2.46	
	C-3c	2	405.15	559.87	7.5	3.19	4.6	3.52	
	C-3d	2.5	509.02	693.74	6.2	2.29	3.5	2.72	
	C-3e	3	593.2	803.32	3.4	1.92	2.2	2.4	

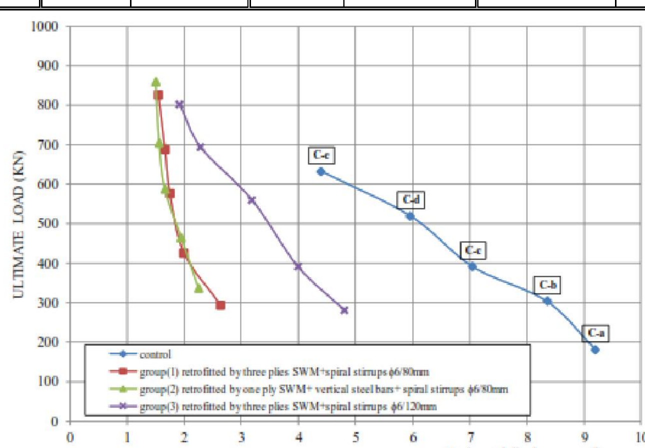


Figure [22] Comparison between horizontal displacements at mid-height of all aspect ratios of control RC columns and retrofitted damaged RC columns

It was found from Table [3] and figure [22] that horizontal displacement (δ) at the mid-height due to buckling failure for control slender columns (λ=15.3) decreases by increasing of cross-section aspect ratio 1, 1.5, 2, 2.5 and 3 by 9.2, 8.35, 7.05, 5.96 and 4.4 mm respectively, the presented retrofitting techniques effects on failure mode of retrofitted columns, the retrofitted damaged RC columns of group (2) that retrofitted by one ply steel wire mesh with external longitudinal steel bars and tied by spiral stirrups with pitch 80 mm obtained minimum horizontal displacement at mid-height, while retrofitted damaged RC columns of group (3) that retrofitted by external spiral stirrups ϕ6 with pitch 120 and wrapped by three plies of steel wire mesh with gave maximum horizontal displacement. the obtained results showed that horizontal displacement decreases by using longitudinal steel bars tied by spiral stirrups less than using spiral stirrups wrapped by steel wire mesh, also spiral pitches effects on horizontal displacement that increased by increasing of pitches.

5. Failure Mode of Columns

5.1. The Failure Mode Of Control Columns

Behavior of all columns is similar as the load increases the specimen deformed slowly and cracks started to appears horizontally at one side in middle zone of tested specimens, the other side concrete appears of crushing due to compression, failure stage started when horizontal cracks looks noticed and starts expansion and concrete cover spelled off and a buckling of the longitudinal reinforcement bars is observed as shown in Figure [23].

Figure [23] Damaged modes for tested control columns before retrofitting

5.2. The Failure Mode of Retrofitted Damaged Rc Columns

All retrofitted columns were tested under the same conditions and the same fixation, failure loads and mode of failure were different between presented techniques, group [1] that retrofitted by spiral stirrups /80 mm and wrapped by three plies of steel wire mesh collapsed slowly and concentrated at middle zone for specimens C-1a (100×100), C-1b (100×150) and C-1c (100×200) mm and located at upper and/or lower zone for specimens C-1d (100×250) and C-1e (100×300) mm, group [2] that retrofitted by longitudinal steel bars and tied by spiral stirrups /80 mm and wrapped by one ply of steel wire mesh collapsed slowly and located at head and/or base for all specimens, and group [3] that retrofitted by spiral stirrups /80 mm and wrapped by three plies of steel wire mesh collapsed slowly and located at upper and/or lower zone for all specimens, while failure modes of short column specimens were as the same before retrofitting. Figure [24] shows damaged modes for retrofitted RC columns of the group [1].

Figure [24] Damaged modes of retrofitted columns of the group (1) that retrofitted by [spiral stirrups ϕ6 /80mm+ three plies SWM]

6. Analytical Analysis by Finite Element Model

The finite element package ANSYS 15.0 was used to simulate the experimental testing by introducing a numerical model.

6.1. Defining Material Properties

6.1.1. Model of Concrete

The concrete is modeled using volume block by input dimensions. SOLID65 is used for the 3-D modeling of solids with or without reinforcing bars. The concrete is modeled using hexahedral elements (SOLID65) type with eight corner nodes. Each node posses three translation degrees of freedom. In the finite element model, Young's modulus for concrete was taken 22000 (N/mm^2) and Poisson's ratio was taken to be (0.2). Additional concrete material data needed for (SOLID65) were the shear transfer coefficients, tensile stresses, and compressive stresses. Typical shear transfer coefficients were taken ranges from 0.0 to 1.0, with 0.0 representing a smooth crack (complete loss of shear transfer) and 1.0 representing a rough crack (no loss of shear transfer).

6.1.2. Model of Internal Reinforcement

The longitudinal and transverse steel is modeled using the (LINK180) element type. Both yielding and strain-hardening failure modes can be accounted for. The yield stress, F_y = 280 (N/mm^2). Young's modulus for reinforcement was taken 2.0×10^5 (N/mm^2) and Poisson's ratio was taken to be (0.3).

6.1.3. Model of Grout Mortar

Grout mortar in practical testing used for covering external steel jacket elements by thickness about (20 mm). It was defined as (SOLID65) with different properties, SOLID65 is used for the 3-D modeling of solids with or without reinforcing bars. The 3D solid element (SOLID65) was selected to perform this analysis using "ANSYS version 15" because it is capable of both cracking in tension and crushing in compression. (SOLID65) allows for four different materials within the element, one matrix material and a maximum of three independent reinforcing materials.

6.1.4. Model of External Spiral Stirrups

External spiral stirrups in practical testing used for tied existed columns. External spiral stirrups were defined as (LINK 180) with properties. It modeled using (LINK180) element type. Both yielding and strain-hardening failure modes can be accounted for. The yield stress, F_y = 280 (N/mm^2). The Young's modulus for reinforcement was taken 2.0 ×10^5 (N/mm^2) and Poisson's ratio was taken to be (0.3).

6.1.5. Model of Galvanized Steel Wire Mesh

External galvanized steel wire mesh in practical testing used for wrapping existed columns and spiral stirrups. Steel wire mesh was defined as (LINK 180) a 3-D spar that is useful in a variety of engineering applications.

6.1.6. Model of Steel Clamp

Steel clamp with thickness 3mm and length 40 mm was in practical testing used for tied ends of used jackets. It was defined as (SOLID185), it modeled as a block with a cross-section (40×3) mm at both top and bottom of specimens. The 3D solid element (SOLID185) was selected to perform this analysis using "ANSYS version 15"0.

6.1.7. Model Of Loading Steel Plate

Steel plate with thickness 15mm was in practical testing used for distribution loads on the head of specimens totally. It was defined as (SOLID185), it modeled as a block with a thickness of 15 mm at both top and bottom of specimens. SOLID185 is used for the 3-D modeling of solids with or without reinforcing bars. The 3D solid element (SOLID185) was selected to perform this analysis using "ANSYS version 15.0".

Figure [25] shows practical spiral stirrups used in external retrofitting and modeling of all elements of the presented jacket.

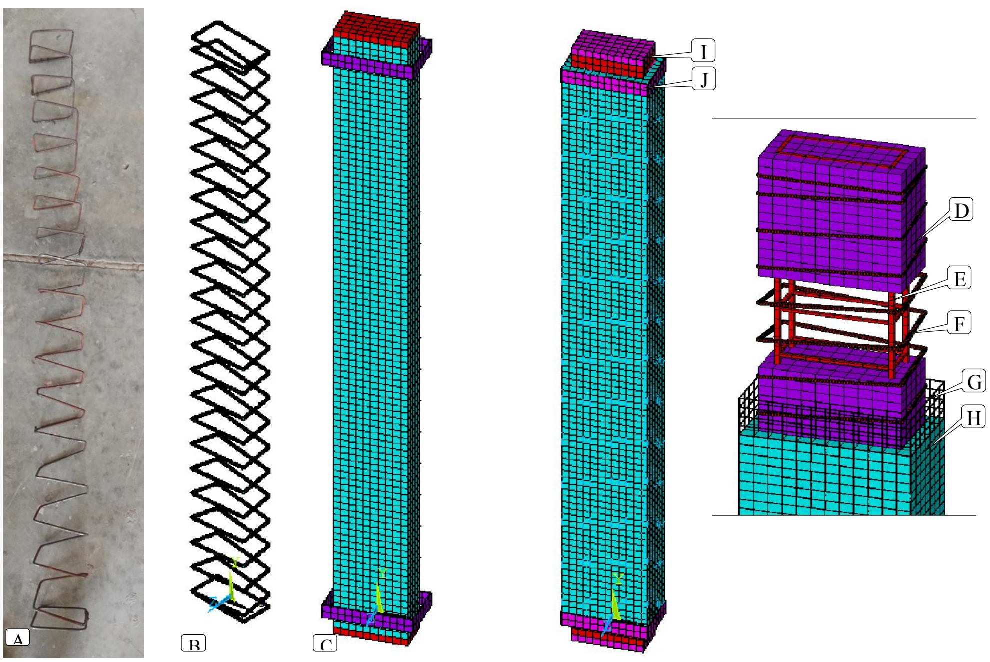


Figure [25] [A] practical spiral stirrups, [B] FE modeling of spiral stirrups [C] modeling of existed RC column with both head and base [D] existed RC column, [E] internal steel reinforcement [F] spiral stirrups, [G] steel wire mesh, [H] grout mortar, [I] steel loading plate, [J] steel clamp

7. Comparison Between Experimental And Analytical Finite Elements Results

7.1. Comparison between Carrying Capacity Of All Tested Columns Obtained From (EXP) AND (FEA)

Results

Table [5] shows the comparison between the percentage of increase in column carrying capacity for retrofitted RC columns obtained from experimental (EXP) and finite element (FEA) results.

GROUP (1); figure [26] shows a comparison between [EXP] and [FEA] carrying-capacity of retrofitted damaged specimens of the group (1) that retrofitted by rolling spiral stirrups ϕ6/80mm and wrapped three plies steel wire mesh.

GROUP (2); figure [27] shows a comparison between [EXP] and [FEA] carrying-capacity of retrofitted damaged specimens of the group (2) that retrofitted by wrapping one-ply steel wire mesh +longitudinal steel bars +spiral stirrups ϕ6/80mm.

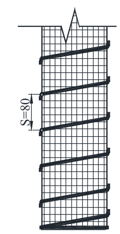
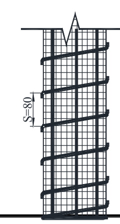
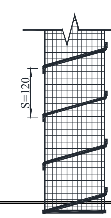
GROUP (3); figure [28] shows a comparison between [EXP] and [FEA] carrying-capacity of retrofitted damaged specimens of the group (3) that retrofitted by rolling spiral stirrups ϕ6/120mm and wrapped by three plies steel wire mesh.

GROUP (4); figure [29] shows comparison between [EXP] and [FEA] carrying-capacity of retrofitted damaged specimens of the group (4) that retrofitted by different techniques for short damaged columns.

Table [4] Materials types used in ANSYS 15.0 Program

Material type	ANSYS element type
concrete	SOLID 65
Steel stirrups	LINK 180
Longitudinal steel bars	LINK 180
Grout mortar	SOLID 65
Steel wire mesh	LINK 180
Outer spiral steel bar	LINK 180
Steel clamp	SOLID 185
Loading steel plate	SOLID 185

Table [5] shows the comparison between failure loads and carrying capacity of retrofitted columns by different techniques obtained from experimental (EXP) and finite element (FEA) results.

group	specimen's title	Aspect ratio (A_{SPR})	(H)	External retrofitting: Details No. / type		Failure load (KN): P_{EXP} (KN)	Failure load (KN): P_{FEA} (KN)	Key
group (1)	C-1a	1	1800mm	1 ply steel wire mesh lower+ spiral stirrupsϕ6mm /80 mm + 2 plies of steel wire mesh upper		293.57	300.91	
	C-1b	1.5				425.44	449.61	
	C-1c	2				577.46	591.79	
	C-1d (local repair)	2.5				688.07	696.59	
	C-1e	3				825.64	831.87	
group (2)	C-2a	1	1800mm	1 ply steel wire mesh lower+ Spiral stirrupsϕ6mm /80 mm	2ϕ6	336.04	362.86	
	C-2b	1.5			4ϕ6	444.44	462.09	
	C-2c	2			6ϕ6	617.54	643.74	
	C-2d (local repair)	2.5			4ϕ8	704.38	715.54	
	C-2e	3			4ϕ8+2ϕ6	860	862.31	
group (3)	C-3a	1	1800mm	1 ply steel wire mesh lower+ spiral stirrupsϕ6mm /120 mm + 2 plies of steel wire mesh upper		281.69	285.2	
	C-3b	1.5				391.89	401.49	
	C-3c	2				559.87	580.39	
	C-3d (local repair)	2.5				693.74	702.4	
	C-3e	3				803.32	805.05	
group (4) (short specimens)	C-4a	1	900mm	1 ply steel wire mesh lower+ spiral stirrupsϕ6mm /80 mm + 2 plies of steel wire mesh upper		329	362.56	
	C-4b	1.5				475	491.86	
	C-4c	2		1 ply steel wire mesh lower+ spiral stirrups ϕ6mm /80 mm+6ϕ6		671	688.1	
	C-4d	2.5		1 ply steel wire mesh lower+ spiral stirrupsϕ6mm /120 mm + 2 plies of steel wire mesh upper		685	693.44	
	C-4e	3				720	757.34	

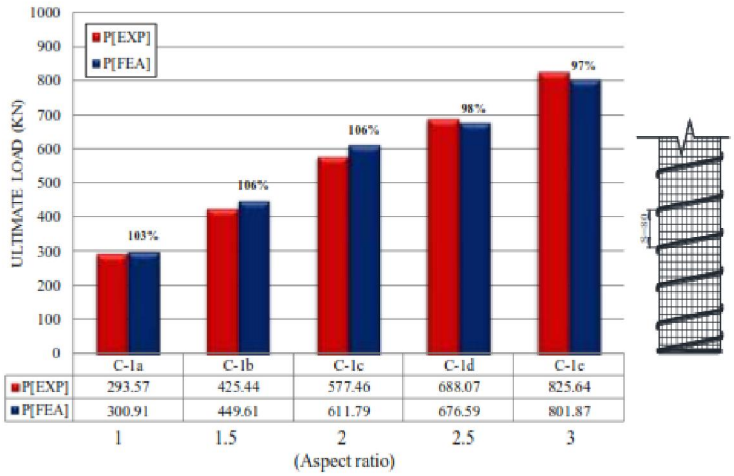


Figure [26] Comparison between experimental and analytical models loads capacity for retrofitted specimens of the group (1) Retrofitted by (spiral stirrupsϕ6/80mm+3 plies of steel wire mesh)

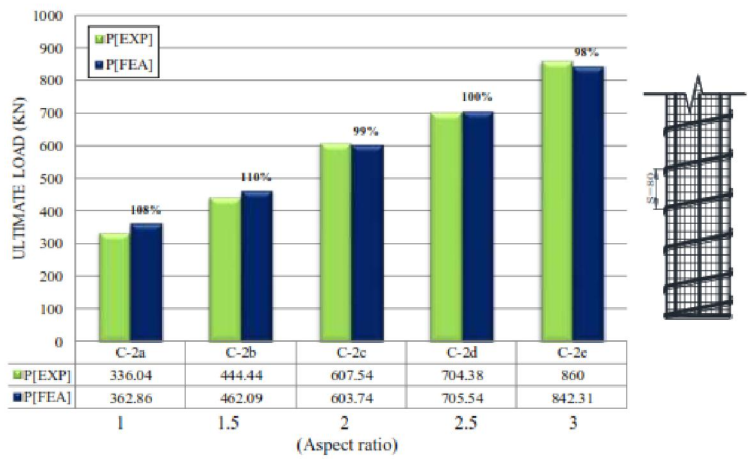


Figure [27] Comparison between experimental and analytical models loads capacity for retrofitted specimens of the group (2) retrofitted by (1 ply of steel wire mesh + longitudinal steel bars +spiral stirrupsϕ6/80mm)

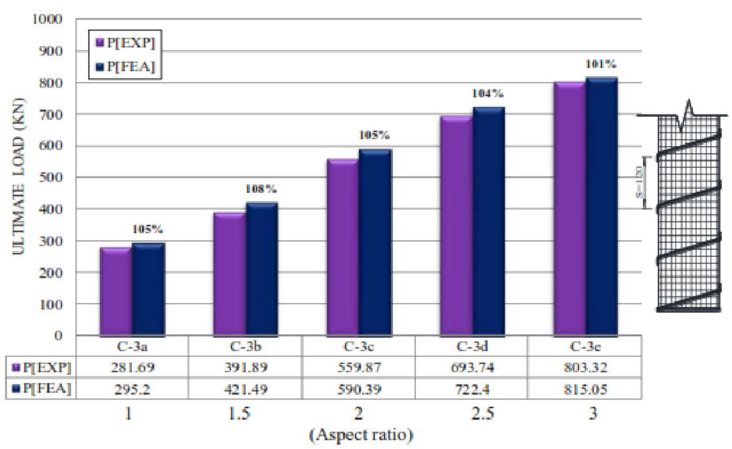


Figure [28] Comparison between experimental and analytical models loads capacity for retrofitted specimens of the group (3) Retrofitted by (spiral stirrupsϕ6/120mm+3 plies of steel wire mesh)

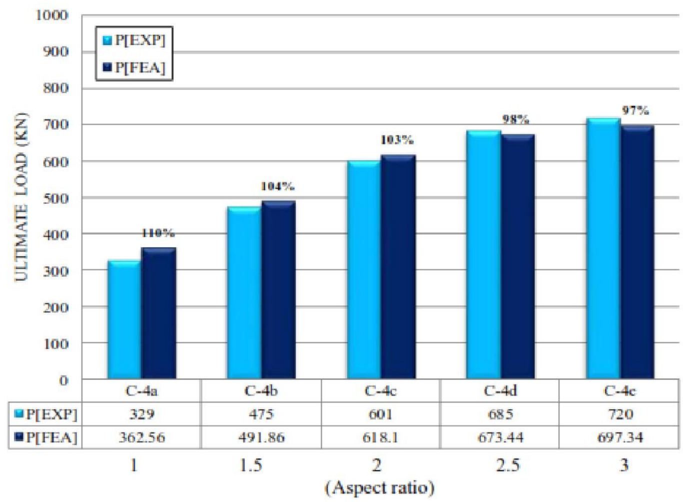
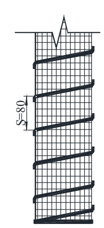
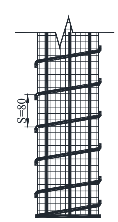
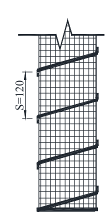


Figure [29] Comparison between experimental and analytical models loads capacity for different techniques used for retrofitting of damaged RC column specimens of the group (4)

Table [6] the recorded horizontal displacement (δ) at middle height of long specimens for all models obtained from (FEA) analysis and (EXP) test results.

Groups	Column's title	Aspect ratio (A_{SPR})	External retrofitting	failure load P_u (KN)		Horizontal displacement (δ) at middle height (mm)		Key
				P_{EXP}	P_{FEA}	δ_{EXP}	δ_{FEA}	
Group(1)	C-1a	1	1 ply steel wire mesh lower+ spiral stirrupsϕ6mm /80 mm + 2 plies of steel wire mesh upper	293.57	300.91	2.64	2.58	
	C-1b	1.5		425.44	449.61	1.99	2.12	
	C-1c	2		577.46	591.79	1.75	1.75	
	C-1d	2.5		688.07	696.59	1.66	1.61	
	C-1e	3		825.64	831.87	1.55	1.51	
Group(2)	C-2a	1	1 ply steel wire mesh lower+ Spiral stirrupsϕ6mm /80 mm 2ϕ6	336.04	362.86	2.25	2.02	
	C-2b	1.5	4ϕ6	444.44	462.09	1.95	1.77	
	C-2c	2	6ϕ6	617.54	643.74	1.66	1.46	
	C-2d	2.5	4ϕ8	704.38	715.54	1.56	1.35	
	C-2e	3	4ϕ8+2ϕ6	860	862.31	1.5	1.26	
Group(3)	C-3a	1	1 ply steel wire mesh lower+ spiral stirrupsϕ6mm /120 mm + 2 plies of steel wire mesh upper	281.69	285.2	4.8	4.60	
	C-3b	1.5		391.89	401.49	3.99	3.97	
	C-3c	2		559.87	580.39	3.19	3.26	
	C-3d	2.5		693.74	702.4	2.29	2.65	
	C-3e	3		803.32	805.05	1.92	2.10	

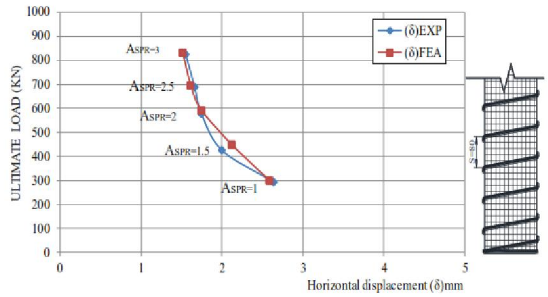


Figure [30] Comparison between results of maximum horizontal displacements at mid-height of retrofitted columns obtained from experimental (EXP) and finite element model (FEA) for retrofitted of damaged RC columns of the group (1)

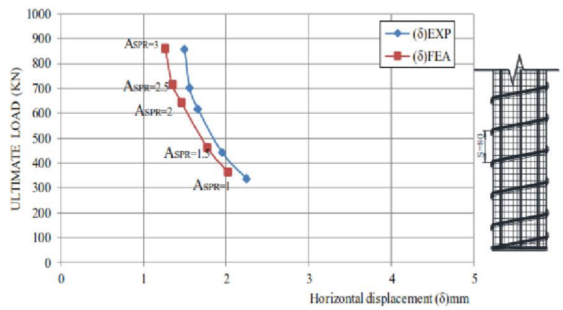


Figure [31] Comparison between results of maximum horizontal displacement at mid-height of retrofitted columns obtained from experimental (EXP) and finite element model (FEA) for retrofitted of damaged RC columns of the group (2)

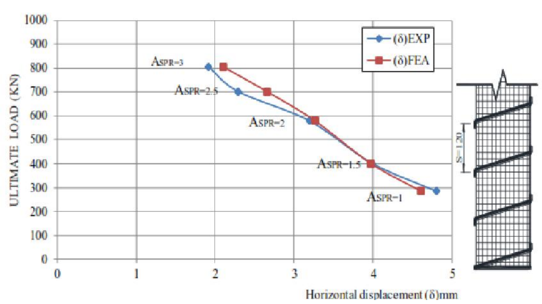


Figure [32] Comparison between results of maximum horizontal displacement at mid-height of retrofitted columns obtained from experimental (EXP) and finite element model (FEA) for retrofitted of damaged RC columns of the group (3)

7.2. Comparison Between Carrying Capacities And Horizontal Displacements At Mid-Height Of Tested Long Columns Obtained From (Exp) And (Fea) Results

Table [6] shows the maximum failure load and maximum horizontal displacement at the middle height of retrofitted specimens with different aspect ratios (1, 1.5, 2, 2.5 and 3) obtained from the experimental test (EXP) and finite element model (FEA).

Figure [30] shows a comparison between the results of maximum horizontal displacement at mid-height of retrofitted columns obtained from the experimental test (EXP) and finite element model (FEA) for group one retrofitted specimens.

Figure [31] shows a comparison between the results of maximum horizontal displacement at mid-height of retrofitted columns obtained from the experimental test (EXP) and finite element model (FEA) for group two retrofitted specimens.

Figure [32] shows a comparison between the results of maximum horizontal displacement at mid-height of retrofitted columns obtained from the experimental test (EXP) and finite element model (FEA) for group three retrofitted specimens.

7.3. Comparison Between Modes Of Failure Obtained From (Exp) And (Fea) Results

Figures [33 to 37] show a comparison between failure modes between [EXP] and [FEA] for retrofitted of damaged RC columns of the group [1] as follows;

Figure [33] Comparison between modes of failure obtained from (FEA) and (EXP) for retrofitted column [C-1a] of group [1]

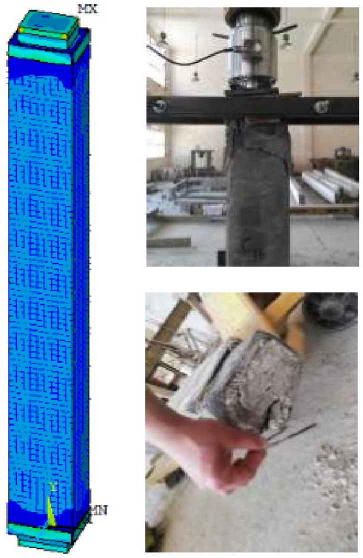


Figure [34] Comparison between modes of failure obtained from (FEA) and (EXP) for retrofitted column [C-1b] of group [1]

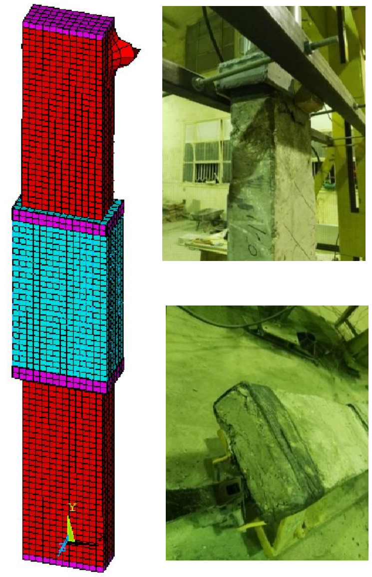


Figure [36] Comparison between modes of failure obtained from (FEA) and (EXP) for retrofitted column [C-1d] of group [1]

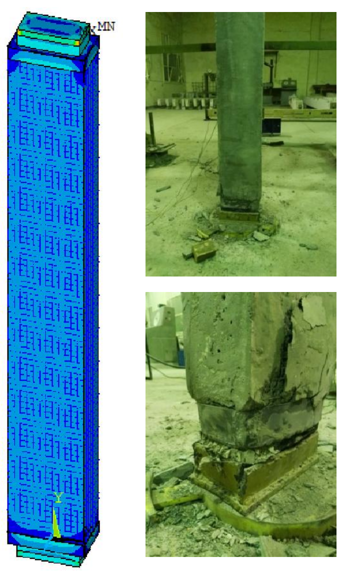


Figure [35] Comparison between modes of failure obtained from (FEA) and (EXP) for retrofitted column [C-1c] of group [1]

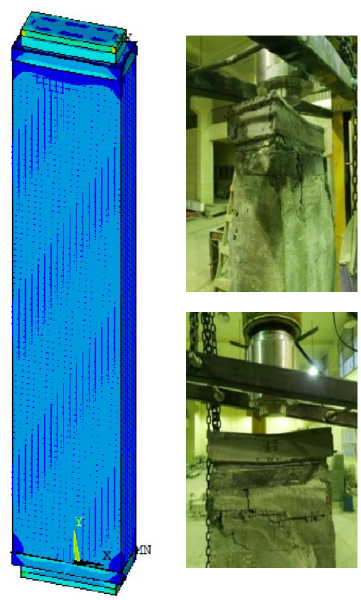


Figure [37] Comparison between modes of failure obtained from (FEA) and (EXP) for retrofitted column [C-1e] of group [1]

It can be shown from Figures [33 to 37] for retrofitted damaged RC columns of group [1] that the obtained failure modes from (EXP) have the same shape of (FEA). From figures; it has been noticed that the failure for retrofitted columns occurred in the head and/or base or both for the tested specimen.

The obtained failure modes showed fair agreement between finite element (FEA) results and experimental (EXP) results.

8. Conclusions

From the present study, the following conclusions are obtained:-

i. A new jacketing technique was presented including spiral stirrups, steel wire mesh and grout mortar that cheap material and easy to apply that make satisfying results give an increase in the load carrying-capacity up to (82%) from the control ultimate capacity under axial loading.

ii. Jacketing presented by spiral stirrups techniques proved to be an easy, inexpensive in retrofitting of damaged (RC) columns.

iii. The column carrying capacity increases by decreasing spiral pitching from 120 to 80 mm up to 151%, 145%, 143%, 135%, and 139% respectively.

iv. The column carrying capacity increases by using longitudinal steel bars tied by spiral stirrups more than using spiral stirrups wrapped by steel wire mesh up to 182%, 167%, 160%, 146%, and 153% respectively.

v. The failure mode for columns before retrofitting located in the middle zone. While the failure mode for columns after retrofitting occurred in the head and/or base or both for the tested specimen.

vi. Faire agreement was found between finite element (FEA) results and experimental (EXP) results. However, the FEA models can identify the structural behavior of tested columns and can be an alternative to a destructive laboratory test.

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2/25/2020