Efficiency of Corrugated Steel Jackets for Strengthening or Repairing Square Section Concrete Columns

Majid Matouq Assas

Civil Engineering Department, College of Engineering & Islamic Architecture, Umm al Qura University, Makkak, KSA
mmassas@uqu.edu.sa

Abstract: The steel jacket technique is used to strengthen or repair RC columns all over the world, as it has been shown to be effective, economical and easy to apply. Most studies carried out to date on this strengthening technique have focused on isolated sections of columns strengthened or repaired by angles or batten plates. In this study a new technique for strengthening or repairing reinforced concrete columns was introduced; this was achieved by using corrugated steel jacket. The behavior of the strengthened or repaired square columns was investigated experimentally on twenty seven real concrete column models. Response of the columns before and after being strengthened or repaired with steel jackets was examined. Four variables were considered in this experimental study; the surface treatment of the original column, the grade of the filled concrete, the steel jacket type, and the thickness of the corrugated steel jacket. Test results suggest that square steel jackets can considerably improve the performance of columns with adequate strength. The steel jackets can significantly enhance the response of concrete columns with adequate ductility, when corrugated steel jacket was used. Also corrugated steel jacket give a better result compared to flat steel jacket.

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1.Introduction

One of the most widely methods used to strengthen or repair reinforced concrete columns is the construction a reinforced concrete jacket around the original one. The concept of this method of strengthening or repairing is that the jacket improves the ability of the original column to carry additional load, depending mainly on the roughness of the contact surface between the jacket and the original column, and on the confining action of the jacket and transverse reinforcement in it [1,2]. Other factors affect the strengthened or repaired columns such as, area and arrangement of transverse reinforcement, shear key of the contact surface between the column and the jacket, applied load, shape and dimensions of the original column [3,4].

The use of steel jacket as a retrofitting technique has several advantages such as the lightweight, the saving of construction time and it can be prefabricated, besides that the steel jacket of short column prevents shear failure and avoids column buckling where the jacket is deliberately deboned from the existing column, thus insuring that the jacket acts only as hoop reinforcement. Many factors affect the use of steel jacket in strengthening of reinforced concrete column such as the method of bonding of steel jacket with the original column and the type of steel jacket (flat or corrugated)[5,6].

An experimental research program describes the use of rectangular steel jackets for seismic retrofit of non-ductile reinforced concrete frame columns with inadequate shear strength. Eleven large-scale columns were tested to examine the effectiveness of various types of steel jackets for improving the ductility and strength of columns with inadequate shear resistance. Several types of steel jackets were investigated, including rectangular solid steel jackets and partial steel jackets. The test results indicate that a thin rectangular steel jacket can be a highly effective retrofit measure for reinforced concrete columns with inadequate shear resistance [7].

Two different, additional methods presented in an experimental work. In one of this methods the steeljacket is formed by two bent plates I, shaped welded longitudinally in the two common corners, leaving a small clearance with respect to the original column surface that is injected with a polymeric grout afterwards. In the other, 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 has been assumed, in centered compression, and a method of calculation for load transfer between column and jacket in the smallest length possible will be presented. A good experimental behavior and correspondence between calculation and results has been obtained for the welded and injected jacket but these results have been 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 have been made.[8,9&10]

The method of fixation between the steel jacket and column was studied. Three different methods were investigated; Hilti anchors epoxy and Hilti anchors in addition to epoxy. It was found that some considerations must be satisfied if the steel jacket is fixed to the concrete core by mechanical anchor only, such as: i) cubic strength of concrete must be greater than 30 MPa at 28 days. ii) the allowable shearing force for the used anchors should be greater than or equal to the bearing force of the used sheet. iii). The local buckling between the regions of anchoring must be checked. Also it was noticed that the use of the epoxy as bonding material between the steel jacket and the original column assures the full contact. The confining effect depends on the thickness of epoxy layer. One of the disadvantages of using the epoxy in bonding is the expected film of cement which forms on the interface and prevents the bond. Also it is noticed that the using of epoxy, in addition to the mechanical anchors, has better ductility and resilience compared with the other method used anchors only[11]**.**

In addition the shear failure of reinforced concrete columns and the effectiveness of full-height flat steel jacket for enhancing the seismic shear strength were studied. Rectangular columns were retrofitted by elliptical steel jacket with larger gaps that were filled with concrete rather than grout. It can be concluded that the use of steel jacket increased the elastic stiffness of the columns by 30 and 64 percent for circular and rectangular columns respectively. The steel jacket is extremely effective in enhancing shear strength and flexural ductility of columns[12-14].

The results of a research program aimed at investigating the effectiveness of simultaneous application of carbon fiber-reinforced polymer (CFRP) sheets and steeljacket to upgrade corrosion-damaged reinforced concrete (RC) columns was presented. A total of 14 RC columns were tested under combined lateral cyclic displacement excursions and constant axial load. The variables studied in this program included effectiveness of different strengthening techniques, as well as effects of degree of rebar corrosion, axial load, CFRP sheets and steeljacket. It was showed that strengthening corroded RC columns with combined CFRP sheets and steeljacket was effective in enhancing the seismic performance of the columns and resulted in more stable hysteresis curves with lower strength degradations as compared with the un-strengthened ones. Additionally, it was also found that the corroded RC columns strengthened with combined CFRP sheets and steeljacket behaved better than those strengthened only with the single material [15].

The failure modes for existing beam-column joint and the effectiveness of using corrugated steel jacket for enhancing its seismic shear strength and ductility was studied [16, 17s]. The main studied parameters were; the amount of transverse reinforcement with column and jacket of column only or column beamjoint. The gap between the concrete and the jacket was filled with grout were taken into consideration. The study stated that, the corrugated steel jacket has high out of plane stiffness which resists out of plane buckling. The corrugated steel jacket acted as extremely efficient form of lateral confinement and enhancing the concrete ultimate compression strain. Also the corrugated steel jacket was effective in reducing joint distortion.

The aim of the present investigation is to study the efficiency of the corrugated steel jackets in repairing and/or strengthening the reinforced concrete columns. To cover the variables that affect the behavior of corrugated steel jacket of columns, four different variables were taken into consideration in this work. These variables are: i) surface treatment of the original columns; ii) the compressive strength of the filled concrete between the original columns and the jacket; iii) type of steel jackets; iv) the thickness of the steel jacket.

2. Experimental work

Columns physical models were conducted from reinforced concrete material for the purpose of this study. The cross section of the all tested models was square (150×150mm), as shown in Table 1.

Three different methods of surface treatment were adopted in the present work, the first one was surface roughness where the original column surface was moderately roughened by cavities of dimensions one cm diameter and one cm depth with distance between cavities of about 10cm. The second method was cement light blast sand where the surface was roughened by light sand blasting with a ratio of cement: s and: water equals to1:1: 0.5, respectively**.** The last one was epoxy resin, where epoxy resin was used to offer the bond between new (filled concrete) and old concrete of column.

The gap between the original column and the steel jacket was filled by concrete to provide continuity between the original column and the jacket. Three grades of filled concrete were used in this study. The compressive strength of filled concrete was 300 kg/cm^2, 600 kg/cm^2 and 750kg $/cm^2$.

Two types of steel jackets were used (flat and corrugated). The thickness of the steel jackets, for each type of the used steel were 1mm, 1.5mm and 2.0mm.

2.1 Models and groups

Twenty seven reinforced concrete column models divided into nine groups were tested. One of these groups (group S_0) is left without any strengthening or repairing to represent the original column and to be as a reference specimens. Each group (eight groups) consists of three models ; two of them were repaired and the third was strengthened except the group S_2 in which the three models were strengthened. The groups S_1,S_2, and S_3 were used to study the effect of surface treatment of the original columns and to check the bond between the original columns and filled concrete in the jacket, where the compressive strength of the filled concrete was kept constant (300kg/cm^2) and the thickness of the corrugated steel jacket was 1.0mm.

The groups, S_3, S_4, and S_5 were used to investigate the effect of grade of filled concrete. The tested grades were 300,600,and 750kg/cm^2. The surface treatment and the thickness of the corrugated steel jacket (1.0 mm) were constant.

The groups S_3, S_7, and S_8were used to study the effect of different thickness of the corrugated steel jacket (1.0, 1.5, and 2.0mm) when the surface treatment and compressive strength of the filled concrete in the jacket were constant. The group S_6 was referred to flat steel jacket and was used to study the effect of steel jacket type.

2.2 Materials

Fine clean sand free from any impurities such that silt, learn, clay and organic compounds was used. Natural gravel with 14 mm M.N.S, free from any undesired impurities, was washed and dried before batching and mixing.

Ordinary Portland cement and clean fresh water free from any impurities was used. Silica fume having specific surface 18 m^2/gm and specific gravity 2.2 was used. Silica fume was added to concrete in a dry powder form. Silica fume were added by about 7.5% as an addition of cement weight.

Deformed round bars of high grade steel (40/60) were used as the main reinforcing of the original columns (10mm in diameter). Plain round bars of normal mild steel were used in the transverse direction as ties (stirrups, 6-mm in diameter).

Flat steel plates and pre-fabricated corrugated steel plates of different thickness (1mm, 1.5mm, and 2mm) and grade 24/37 were used. Figure1 shows the corrugated steel plate dimensions.

One type of admixture was used in concrete mixes, which is classified as high rang water reducer (HRWR) meeting the requirements of ASTM. C494-81 type F. Epoxy-resin for bonding old to fresh concrete was used.

2.3 Models preparation and testing

The dimensions and reinforcement of the original column models were constant. The model height in the study was 750mm. The main reinforcement of the original columns was 4-10 for square columns. For all columns the stirrups were 6, 6 mmas shown in Fig. 1. The gaps between the steel jackets and original columns were kept constant in all groups and equal to 40mm.The compressive strength of the concrete used in the original columns was250-300 kg/cm^2.

The wooden forms were prepared for the desired dimensions in the vertical position. The main steel reinforcement were tied by transverse reinforcement which were anchored by 90° bend around the main reinforcement in the corners and extended of at least eight times the bar diameter.

Concrete was cast immediately after mixing around the steel reinforcement of the column in the wooden forms in the vertical direction and then the models were vibrated mechanically to ensure full compaction. Forms were stripped after 24 hours and columns were cured at 20°c for 28 days. Three cubes (150×150×150 mm) were also cast simultaneously with each column and cured in the same conditions to measure the concrete compressive strength.

After 28 days the column models (which will be repaired) were painted with plastic to facilitate cracks detecting. Small copper plugs (demic points) were adhered carefully at positions on the surface of the columns. The columns models were tested in a universal hydraulic testing machine with capacity 2500 kN.

To facilitate leveling, the column models were placed on a thin bed of plaster on the bottom platen of the testing machine and on the top level of the models. The load was applied at a constant rate and hold constant every 100 or 200 KN increment. The reading of the lateral and longitudinal strains at the surface of the columns by mechanical extensometer with gauge length 50mm and accuracy of 0.001mm were recorded.

In the cases of repaired models, the loose concrete and white paint of the tested column models were removed. The surface of the models were cleaned and treated to achieve good bond action. In the case of corrugated and flat steel jackets of columns, four steel sheets slightly oversized for easy installation were welded in the corners in situ up the vertical seams. The inner surfaces of the steel jackets were cleaned from any undesired materials, which may be attached during the fabrication stage.

The steel jackets were constructed around the models in the vertical positions. The concrete constituents were prepared and mixed as the desired proportional to reach the required compressive strength of the concrete and then placed on the gap between the steel jackets and the original columns and carefully handily compacted to reach the desired compressive strengths of the concrete.

After 28 days from casting the filled concrete between the steel jackets and the original columns, the copper plugs (demic points) were adhered carefully at positions on the surface of the columns as shown in Fig.1. The top and the bottom levels of the columns were facilitated as described in the first testing. The models were tested in the testing machine as described in the first test, where the lateral, longitudinal strains, and the ultimate capacity loads were recorded.

3. Results and Discussions

The horizontal and vertical strains along the column height were plotted for different load increments. The ultimate loads for each group are tabulated, and crack pattern and shape of failures are also illustrated.

The effect of all parameters taken into consideration on the behavior of the repaired or strengthened columns (method of surface treatment, grade of the filled concrete, type of the steel jacket and the thickness of corrugated steel jacket) was investigated and compared with the original columns.

3.1 Original column

The distribution of lateral and longitudinal strain along the column height at different load levels for the original column is illustrated in Fig.2. It is clear that, at any load level the lateral strain shows the maximum values at the column ends due to the stress concentration at the contact surface with the testing machine. Away from these ends the lateral strain decreases to attain its minimum value approximately at 0.6 of the column height.

It was noticed that, by increasing the load level the lateral strain increases along the column height but the rate of lateral strain development is more pronounced at the mid height of the column than that at the column ends. For a given load level the longitudinal strain shows its highest value at the column ends, and the minimum value of the longitudinal strain is monitored at approximately mid height of the column. It was found that the average ultimate load was500 KN as reported in Table2. This value is almost equal to the theoretical ultimate capacity of the column.

3.2 Effect of surface treatment methods

Three different methods of surface treatment were considered in this work. In all cases the thickness of corrugated steel jacket was 1.0mm and the grade of filled concrete was 300 kg/cm^{2}for all groups S_1, S_2, and S_3.

Nearly similar behavior was observed for all models representing different types of surface treatment. The minimum value of the lateral strain is recorded approximately at midsection of the column height. By increasing the applied load, the lateral strain increases along the column height but the rate of lateral strain development is more pronounced at the mid height of the column. The maximum value of the longitudinal strain is monitored at a distance of approximately two times the breadth of the original column below column top, as shown in Figs.3 and 4.

The values of lateral strain for repaired and strengthened columns were decreased by about 96%, 77% and 77% for epoxy bond, surface roughness and light sand blast surface respectively. The corresponding values of longitudinal strain for repaired column were 97%, 85%, and 85%.

The corresponding values of strengthened columns were 140%, 85% and 85%. All the above percentages values were relative to the results of original columns (group S_0). It is clear that there is no significant effect of surface treatment on the behavior of jacketed columns as illustrated in Fig.5.

3.3 Effect of Grade of Filled Concrete

The effect of compressive strength of filled concrete on the behavior of strengthened and repaired columns was studied through the groups S_3, S_4, andS_5. All the other parameters were considered to be constant where the steel jacket was corrugated of 1.00mm thickness, and the surface treated with light sandblast for square column cross section.

Similar results for lateral and longitudinal strainare detected for strengthened and repaired columns at the different compressive strength of filled concrete (300,600, and 750 kg/cm^2). At any load level the lateral strain shows its maximum values at the jacket top, but away from the top the lateral strain decreases to attain its minimum value approximately at 0.50 and 0.75 of the height of the strengthened and repaired columns, respectively. It is clear that, by increasing the load level, the lateral strain increases along the column height but the rate of lateral strain development is more pronounced at the mid height of the column than that at the column ends. Comparing these results with the original group results, it could be found that the lateral strain is decreased by about 75% for strengthened and repaired columns.

The longitudinal strain at the jacket ends is lower than the other values, and the maximum value of the longitudinal strain is noticed at a distance of approximately two times the breadth of the original column below the column top. The longitudinal strain is decreased by a ratio equals 85% for strengthened and repaired columns as compared with the original one. The increase of the ultimate load is nearly equals to 85% for both strengthened and repaired columns as compared with the original columns.

Finally, it can be concluded that there is no significant effect of the grade of filled concrete on the behavior of steel column jacket as shown in Fig.3.

3.4 Effect of Steel Jacket Types

The effect of the steel jacket types (corrugated and flat) on the behavior of tested models was investigated through the group $S_4$and S_6.The steel jackets thickness was 1.00mm, the surface treated was light sandblast, and the grade of the filled concrete was 300 kg/cm^2.

The variation of lateral strain along the column height at different load levels was measured for strengthened and repaired square specimens. It was found that, at any load level the lateral strain shows its maximum values at the jacket top, but away from the top the lateral strain decreases to attain its minimum value approximately at 0.6and 0.5 of the column height for flat and corrugated steel jacket respectively. It was observed that, by increasing the load level, the lateral strain increases along the column height but the rate of lateral strain development is more pronounced at the mid height of the column than the column ends.

Moreover, lateral strain decreases by a ratio equals 70% and 77% for flat and corrugated steel jacket respectively, for both strengthened and repaired columns as compared with the original one as shown in Fig.4.

The variation of the longitudinal strain along the column height at different load levels was recorded. For a given load the longitudinal strain at the jacket ends is lower than the other values, and the maximum value of the longitudinal strain is shown at a distance of approximately two times the breadth of the original column below the column top. Compared with the original group, it could be found that the longitudinal strain decreases by a ratio equals 85% for strengthened and repaired columns.

From Table 2, the ultimate load increases by 60% and 90% for flat and corrugated steel jacket respectively, for both strengthened and repaired columns as compared with the original one.

Finally it was observed that, the ultimate capacity of the corrugated steel jacket increases by a ratio of 30% than that of the flat steel jacket as shown in Fig. 4.

3.5 Effect of Corrugated Steel Jacket Thickness

In the case of corrugated steel jacket the surface was treated with light sandblast, and the grade of the filled concrete was 300 kg/cm^2. The effect of steel jacket thickness on lateral and longitudinal strain distribution, and ultimate load capacity is reported in Table 2. Three thickness were considered (1.0, 1.5, and 2.0mm).

The thickness of the corrugated steel jacket affects the behavior of the strengthened or repaired columns, as follows:

- When the thickness is 1.5mm the lateral strain decreases by ratios equal to 32% and 7% for strengthened or repaired columns respectively. Also the longitudinal strain decreases by a ratio nearly equal 9%. The ultimate load increases by a ratio equal to 4% for both strengthened and repaired as compared with the thickness of 1.0mm.
- When the thickness is 2.0mm the lateral strain decreases by ratios equal to 48% and 14% for strengthened or repaired columns respectively. Also the longitudinal strain decreases by a ratio nearly equal 28%. The ultimate load increases by a ratio equal to 25% for both strengthened and repaired as compared with the thickness of 1.0mm.
- When the thickness is 2.0mm the longitudinal strain decreases by ratios equal 20% and 6% for strengthened or repaired columns respectively. Also the longitudinal strain decreases by a ratio nearly equal 23%. The ultimate load increases by a ratio equal to 20% for both strengthened and repaired as compared with the thickness of 1.5mm.

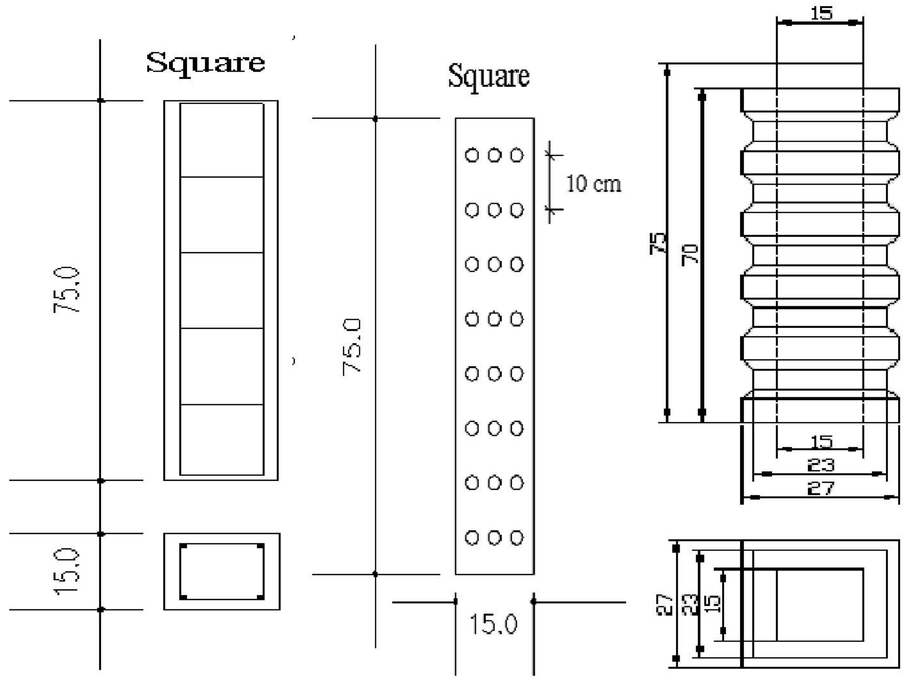
Table 1. properties and dimensions of square test models.

Group	Original Columns				Steel jacket				
	Concrete		Reinforcement		Dimensions [cm]	Filled Concrete strength	Surface Treat. Method	Type	Thickness [mm]
	Dimensions [cm]	F_c Kg\cm^2	Main	Stirrup					
S0	15×15×75	200-250	4Ø10	6 Ø 6	-	-	-	-	-
S1	15×15×75	200-250	4Ø10	6 Ø 6	23×23×70	250	Epoxy	corrugated	1.00
S2	15×15×75	200-250	4Ø10	6 Ø 6	23×23×70	250	Surface roughness	corrugated	1.00
S3	15×15×75	200-250	4Ø10	6 Ø 6	23×23×70	250	Sand blast	corrugated	1.00
S4	15×15×75	200-250	4Ø10	6 Ø 6	23×23×70	750	Sand blast	corrugated	1.00
S5	15×15×75	200-250	4Ø10	6 Ø 6	23×23×70	600	Sand blast	corrugated	1.00
S6	15×15×75	200-250	4Ø10	6 Ø 6	23×23×70	250	Sand blast	flat	1.00
S7	15×15×75	200-250	4Ø10	6 Ø 6	23×23×70	250	Sand blast	corrugated	1.50
S8	15×15×75	200-250	4Ø10	6 Ø 6	23×23×70	250	Sand blast	corrugated	2.00

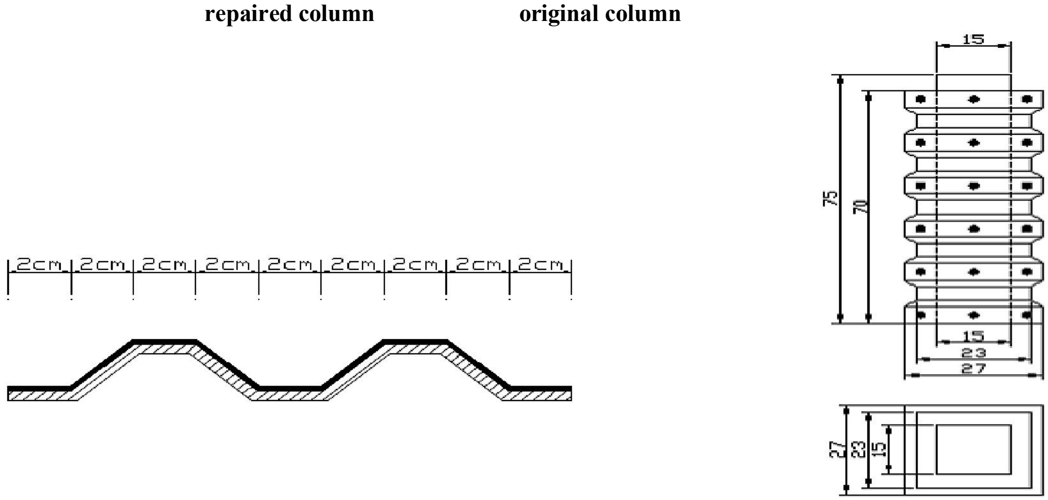
Table 2. Comparison of test results of square columns.

Group	Pu1t (KN)		Pu1t/po		[(Pu1t –Po) / Po](%)	
	strengthened	Repaired	strengthened	Repaired	strengthened	Repaired
S0	500	500	1	1	-	-
S1	945	927	1.89	1.854	89	85.4
S2	952	-	1.904	-	90.4	-
S3	944	946	1.888	1.892	88.8	89.2
S4	940	937	1.88	1.874	88	87.4
S5	941	939	1.882	1.878	88.2	87.4
S6	790	800	1.58	1.6	58	60
S7	975	965	1.95	1.93	95	93
S8	1175	1160	2.35	2.32	135	132

P_o : Ultimate load of the original square column.P_{ult} : Ultimate load of strengthened or repaired square column.

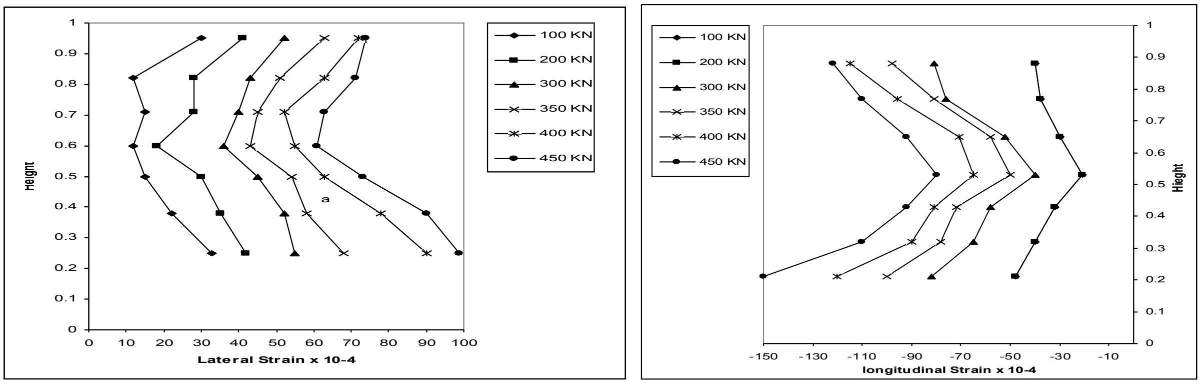


(a) Strengthened and repaired column **(b) Location of dimic original column** **(c) Dimension**



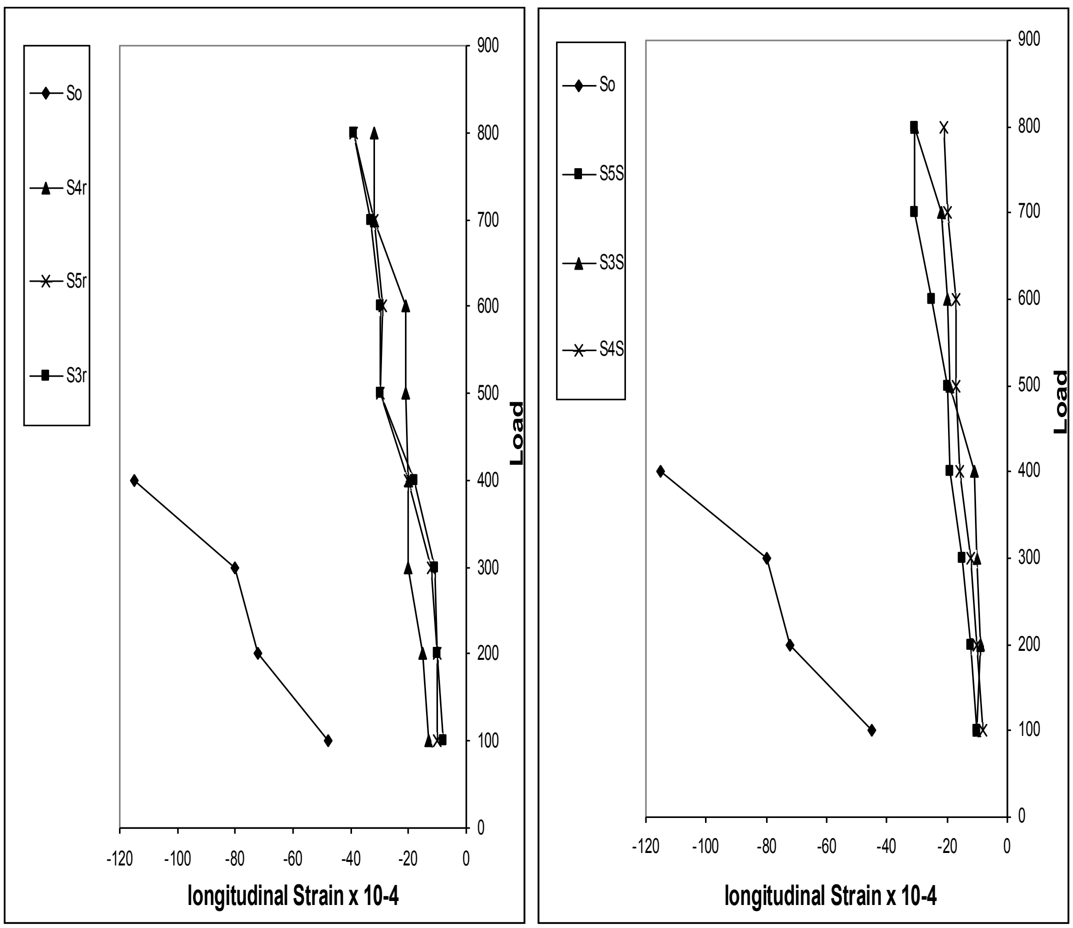
(d) Dimensions of corrugated steel(e) Location of dimic

Fig. 1. Details of tested columns.



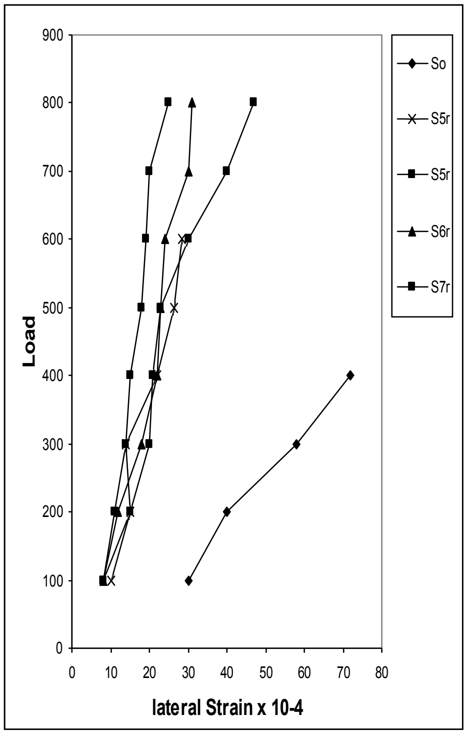
a. Lateral strain. b. Longitudinal strain.

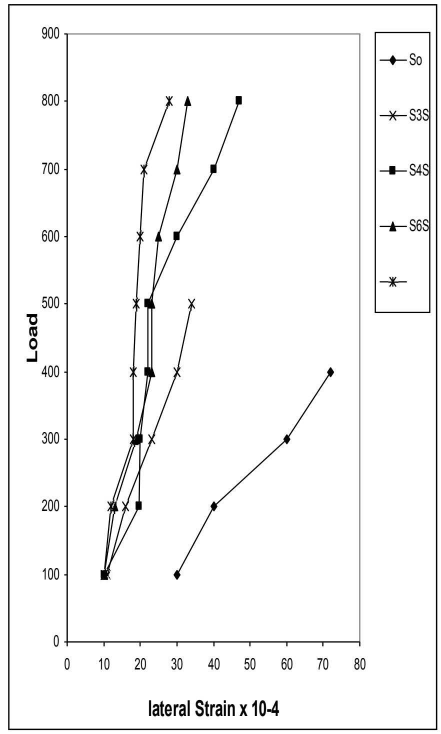
Fig 2. Distribution of lateral and longitudinal strain along the original column height.



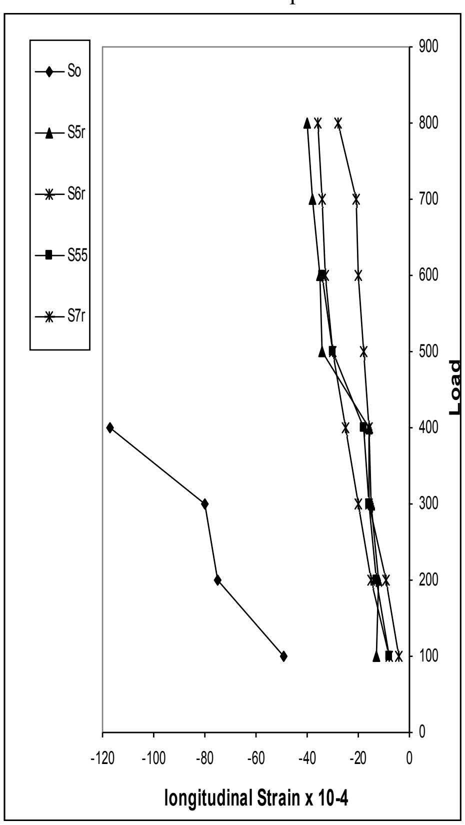
a. Repaired column b. strengthened column

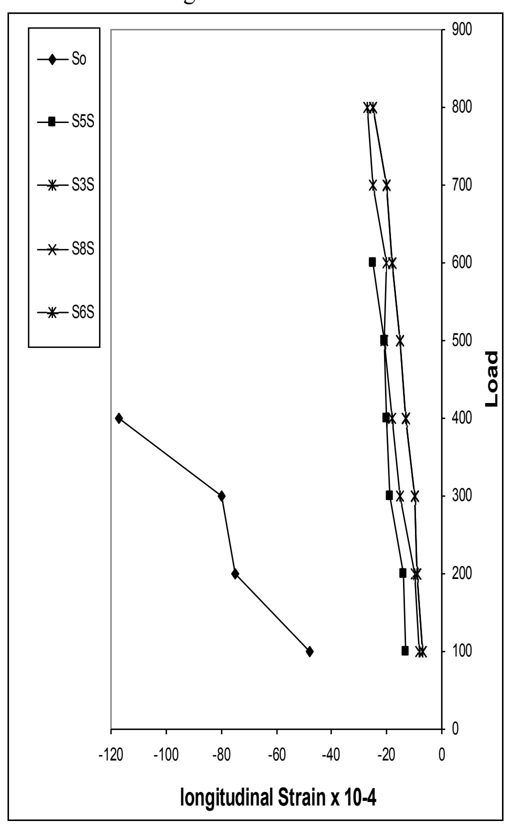
Fig. 3. Effect of grade of filled concrete on lateral and longitudinal strain.





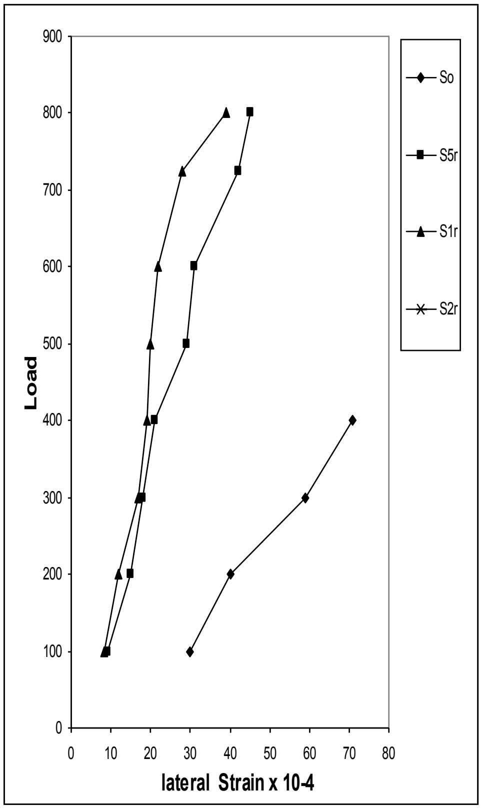
a. Repaired column. b. strengthened column.



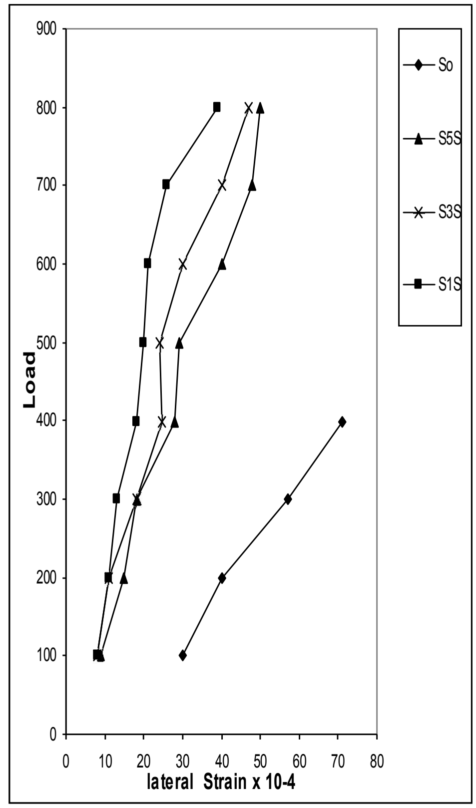


c. Repaired columnd d. strengthened column

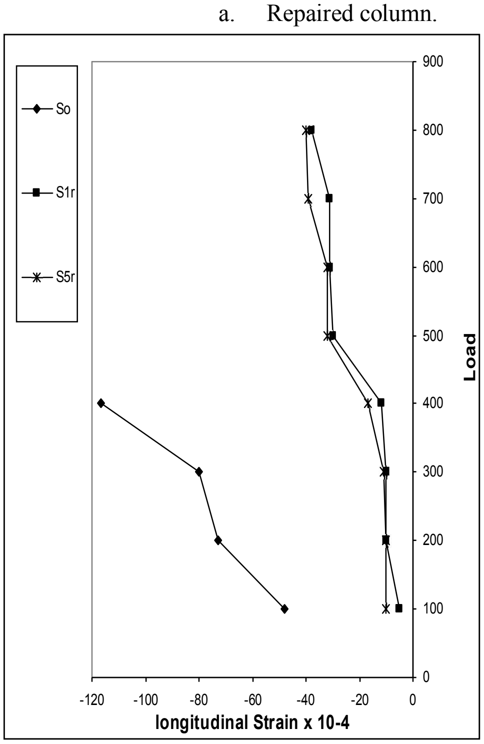
Fig. 4. Effect of steel jacket type on lateral and longitudinal strain



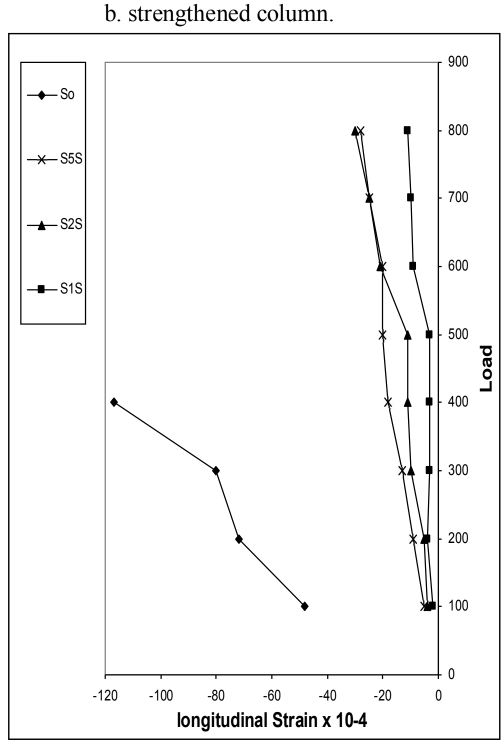
a. Repaired column.



b. strengthened column.



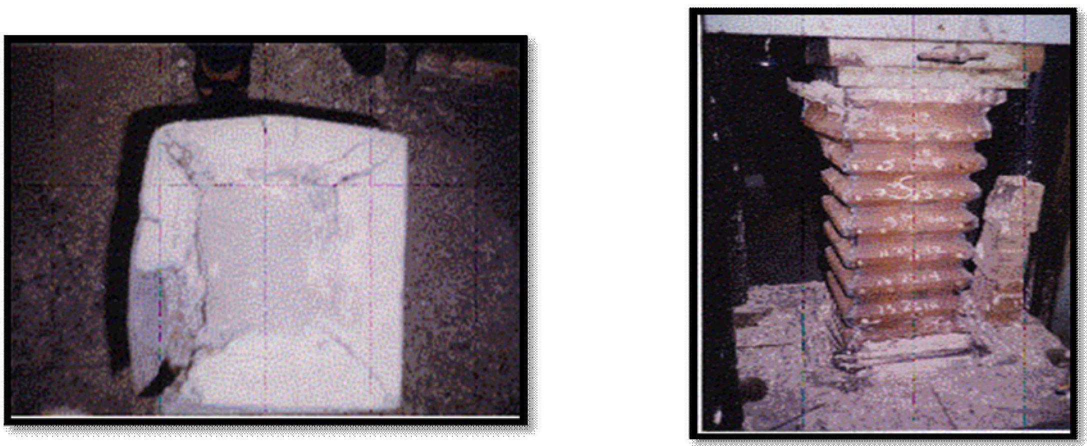
a. Repaired columnd



d. strengthened column

Fig. 5. Effect of surface treatment on lateral and longitudinal strain.

Photo 1. Original Square Column.



a. Plan b. Elevation

Photo 2. Mode of failure for Strengthened and Repaired Square Column (Corrugated).

a. Plan b. Elevation

Photo 3. Mode of failure for Strengthened and Repaired Square Column (Flat).

4. Mode of failure and crack pattern

The crack pattern for the models were carefully observed, marked and recorded. Photo 1 shows the crack pattern for the original column. The first crack is observed at a load equals 87% of the ultimate load. The failure occurred due to crushing and shearing at inclined planes at the ultimate load.

Very little damage could be observed during the tests and some crushing of concrete with gaps at the top of the jacketed columns. For corrugated and flat steel column jackets. Photo 2 and Photo 3 show the final failure of corrugated and flat jackets respectively. The first crack was initiated and propagated in the diagonal direction from the corners of the original columns in the filled concrete to the steel jacket. With increasing the applied load the crack is widened in the same direction until the ultimate load is recorded. After that the load is decreased. The unjacketed portion of the column is compressed inside the jacketed column. The welded part of the jacket (corners) is failed and cracking of the top part of the jacketed columns occur.

5. Conclusions

The following major conclusions can be drawn from the above investigations:

i. Using corrugated steel jackets to strengthen or repair undamaged or damaged square columns increases the ultimate load by a ratio of about 135%.

ii. The method of surface treatment and the grade of the filled concrete are not significant factors when using corrugated steel jacket.

iii. Using corrugated steel jacket in strengthening or repairing square columns increases the ultimate capacity by a ratio of about 46% compared with the case of using the flat steel jacket.

iv. The ultimate load increases by increasing the thickness of corrugated steel jacket; the rate of increasing increases with the increase of the considered thickness.

v. The welded part of the jacket (corners) is considered a weak point; it is failed and cracked at the top part of the jacketed columns. It can be strengthened using additional steel angles.

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