EFFECT OF STIRRUPS DENSIFICATION AND REHABILITATION ON BEHAVIOR OF RECTANGULAR (RC) COLUMNS

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ABSTRACT

The present study deals with an experimental (EXP) and finite element (FEA) investigation for studying internal confinement during construction by using stirrups densification at top and bottom of columns and the regular stirrups distribution along length of columns with different slenderness ratio (λ). Also, it deals with the effect of external confinement for damaged (RC) columns by using steel jacketing technique with a various percentage of covered steel surface area to column surface area (36,42,50,57 and 64). A total of twenty reinforced concrete columns specimens having a cross section of 125 x 250 mm and a different slenderness 6, 8, 10 and 12 have been tested. Columns were divided in two stages; First stage tested four columns to studying internal confinement during construction. It consists of four column specimens with a different slenderness ratio 6, 8, 10 and 12 tested. The results in first stage; give a decrease in the load carrying by increasing the slenderness ratio.

The increase in internal stirrups volumetric ratio by using densification of stirrups along of column resulted in higher ultimate load. The failure of columns caused due to spall off concrete after stirrups densification zone, thus signifying the large stress concentration after densification directly. Second stage tested twenty columns until failure to study the internal and external confinement for damaged (RC) columns. All damaged concrete parts were removed and replaced the loose concrete part with grout mortar and retrofitted by using steel straps jacketing technique. The steel jacket consists of four vertical steel angles placed at each corner of column and connected together with horizontal steel straps. The results in second stage; gives an increases in the column carrying capacity by increasing percentage of covered steel surface area to column surface area and decrease by increasing slenderness ratio.

The optimum percentages of covered steel surface area to column surface area are 25, 28, 32 and 36 % for different slenderness ratio 6, 8, 10 and 12 for the rehabilitation of damaged (RC) columns so that the column reaches the original. Faire agreement was found between finite element (FEA) results and experimental (EXP) results. However, the (FEA) models can identify the structure behavior of tested columns and can be excellent alternative of destructive laboratory test.

KEYWORDS : **(RC) Columns; Capacity; Axially Loaded; Slenderness Ratio; Stirrups; Densification; Rehabilitation; Failure Load; Straps; Experimental (EXP); Finite   Element (FEA)**

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تأثير تكثيف الكانات وإعادة التأهيل على سلوك الأعمدة الخرسانية المستطيلة المسلحة

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الملخص

تتناول الدراسة تاثير تكثيف الكانات اسفل واعلى الاعمدة الخرسانية المسلحة وكذلك التوزيع المنتظم على كامل طول العمود مع تغير نسبة النحافة كما تتناول ايضا اعادة تاهيل الاعمدة الخرسانة التالفة حيث تم ازالة جميع الاجزاء الخرسانية التالفة واستبدالها بمونه الجراوت. تم استخدام اربعة زوايا رأسية فى الاركان مع خوص افقية بعرض مختلف. قد بينت النتائج ان زيادة نسبة النحافة تؤدى الى انخفاض حمل الانهيار. التوزيع المنتظم للكانات على كامل طول العمود اكثر فاعلية من التكثيف اعلى واسفل العمود. ايضا انهيار الاعمدة يقع مباشره بعد منطقة تكثيف الكانات مباشره مما يدل على تركيز الاجهاد بعد منطقة التكثيف.زيادة نسبة حديد التغطية يؤدى الى زيادة حمل الانهيار.النسبة المؤية المثلى لحديد التغطية هى٢٥ – ٢٨ – ٣٢ – ٣٦ % المقابلة لنسبة النحافة ٦ – ٨ – ١٠ – ١٢.

الكلمات المفتاحية : أعمده خرسانيه مسلحة : تحميل : ؛تحميل محورى؛نسبه نحافة؛كانات؛تكثيف ؛ أعاده تأهيل ؛ حمل الانهيار؛خوصة؛عملى؛عناصرمحددة .

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1. INTRODUCTION

The most critical structure elements used to resist several loads in the building which play a significant role are the columns. Numbers of reinforced concrete columns may be damaged by earthquakes or due to the deficiencies in the design. The columns can deteriorate for several reasons such as the evolution and changing habits of the loads. In addition, the columns during construction may be subjected to several problems. When those problems occur, the columns exhibit damage and the columns cannot reach their ultimate load carrying capacity. Therefore, rehabilitation of columns is necessary. Engineers have used different methods and techniques to strengthen columns by providing internal confining stresses during construction and external confining stresses after construction.

Internal confinement means that the internal configuration of transverse reinforcement should be made in a way to increase the lateral resistance of reinforced concrete columns and consequently increasing the ultimate compressive capacity of column. Many researchers investigated the internal confinement of reinforced concrete columns. Only a few studies involved the effect of stirrups densification at top and bottom of (RC) columns and regular densification along of (RC) columns with different slenderness ratio.

External confinement means that the external configuration of steel detailing combined with new concrete jacket or configuration of techniques of steel jacket are used to enhance the performance of original reinforcement concrete members. When the RC columns are subjected to large deformation due to seismic motion, the ability to resist the acting loads will be based on the internal confinement while the column core is weak and can't resist such deformation, additional external confinement should be applied. Many researchers investigated the strengthening of reinforced concrete columns .Only a few studies involved rehabilitation of damaged reinforced concrete columns. So, the purpose of the present study is investigated the effect of stirrups densification at top and bottom of (RC) columns and regular densification along of (RC) columns as well as rehabilitation damaged reinforced concrete columns with different slenderness ratio .

Etman, E. (2010) [1] presented an experimental program consisted of twenty seven specimens to investigate the behavior of reinforced concrete (RC) columns with slenderness ratio (λ=20) for the un-braced rectangular columns under the effect of eccentric loads. The program contained three groups each have 9 specimens. The first group was considered as a control group tested without confinement and the second group was confined by using near surface mounted (NSM) longitudinal steel bars while the third group was confined by using NSM longitudinal steel bars partially wrapped with one ply of carbon fibers reinforced polymers (CFRP) sheets. In addition to the strengthening schemes, the test parameters included the investigation on the change in the ratio of the internal longitudinal steel bars as well as the

stirrups' volumetric ratio. All specimens were tested by eccentric loading with eccentricity-to section height e/h equals 0.25. The results shown that the strengthening columns for third group showed better improvement in load capacity at the same value of lateral buckling than columns strengthened by second group. Increasing the longitudinal internal reinforcement for the strengthened columns did not show the same increase in ultimate load as in reference columns.

Soliman, A. E. K. S. (2011) [2] investigated the behavior of long concrete columns confined by means of proper plastic tube including failure mechanisms with theoretical model for calculation of the column capacity. The influence of column slenderness ratio on their axial load capacity, axial strains, and radial strains were also investigated. The experimental program was classified into three different groups with slenderness ratios from 9 to 18. Test results showed that, utilizing plastic tube for confinement significantly influences the failure mechanisms of concrete columns. Results also showed that the stiffness of the tested long confined concrete columns specimens increases as slenderness ratio decreases.

Malhotra, et al. (2013) [3] investigated (R.C) columns with three different slenderness ratios 3, 7 and 15. These specimens were further divided in to three categories. First category consisted of three unconfined control columns from each size group, second category consisted of three column confined with ferrocement using one layer of wire mesh and third category consisted of three columns confined with ferrocement using two layers of wire mesh. All the columns were tested under monotonic uniaxial compression loading. The results showed that ferrocement confinement increases the load carrying capacity and decreases the lateral deflection. The increase in slenderness ratio results in a decrease of strength of the ferrocement confinement.

Hales, T. A., et al. (2016) [4] studied the behavior of slender high-strength concrete columns reinforced with glass fiber-reinforced polymer (GFRP) bars and spirals subjected to concentric and eccentric axial loads. Large-scale tests were conducted for nine circular concrete columns (three short and six slender) reinforced with internal GFRP-spirals and either steel, GFRP, or a combination of steel and GFRP longitudinal bars. The short and slender columns have slenderness ratios equal to 10 and 49, respectively. Axial load tests were conducted with loads placed concentrically (short columns) and at two eccentricities (slender columns) to observe the general behavior associated with different geometric and loading conditions. The behavior of slender columns with small eccentricity (8.3% of the column size) was governed by material failure, while that of slender columns with large eccentricity (33% of column size) was governed by a buckling failure. The research shows that GFRP spirals and GFRP longitudinal bars are a viable method of reinforcement for slender concrete columns subjected to eccentric axial loads.

Sheikh, T. R., et al. (2017) [5] investigated the confinement of (RC) short square columns with ferrocement jacketing. A total of six RC short square columns were casted and three of them were taken as control specimens. The specimens were tested to failure after 28 days under pure axial concentric loading in order to investigate the effect of strengthening with ferrocement jacket as an alternative technique to classical RC Jacketing. The observed experimental ultimate axial load carrying capacity of retrofitted columns was compared with the calculated theoretical values. Moreover, the effect of jacketing on the slenderness ratio of column was also studied and initial cracking load as well as ultimate load carrying capacity were recorded and discussed for future scope. From the result analysis, it was observed that the retrofitted column showed an increase of 62% in the ultimate load carrying capacity.

The objective of the presented study is to determine the effect of stirrups densification and rehabilitation on behavior of rectangular (RC) columns as follows:-
   i. Studying the effect of internal confinement by using stirrups densification at top and bottom of columns and the regular distribution along length of columns with different slenderness ratio.
  ii. Studying the effect of external confinement by using steel jacketing technique with various percentage of covered steel surface area to column surface area on the behavior of damaged (RC) columns.
 iii. Determination of optimum percentages of covered steel surface area to column surface area to rehabilitation damaged (RC) columns.

iv. Obtain of failure modes before and after rehabilitation of damage columns for (RC) columns.

v. Presenting finite element model to simulate the studying the effect of internal confinement by using stirrups densification at top and bottom of columns as well as the regular stirrups distribution along of columns.

vi. Presenting finite element model to simulate studying effect of external confinement by using steel jacketing technique with various percentage of covered steel surface area to column surface area on the behavior of damaged (RC) columns.

2. EXPERIMENTAL PROGRAM

A total of twenty reinforced concrete column specimens having a cross section of 125 x 250 mm and a different slenderness 6,8,10 and 12.All columns contained six longitudinal reinforcement normal mild steel bars 8mm diameter and stirrups 6mm diameter bars . The longitudinal reinforcement was 8mm diameter with yield strength 280MPa, providing a steel content of 1% of the cross section.

2.1. COLUMNS CHARACTERISTICS
2.1.1. USED MATERIALS

i. Fine aggregates having sizes in the range of (0.075 - 0.3 mm) was used as a fine aggregate in the mix.

ii. Crushed stone has a maximum nominal size of (0.07-20.0 mm) was used as a coarse aggregate in the mix.

iii. Ordinary Portland cement obtained from Siena factory was used in all the experimental work. The usual chemical and physical properties are in compliance with the Egyptian Standard Specification (BS EN) 197-1/2011.

iv. Clean fresh water is used for mixing and curing the specimens. Percentage of water cement ratio 50%.

v. Normal mild steel bars St24/37 of diameter 8.0 and 6 mm were used.

vi. The concrete mix used in all specimens was designed according to the Egyptian code of practice. The concrete mix was designed to obtain target strength of 20 MPa at the age of 28 days. The mix proportions of the concrete are shown in Table [1].

vii. Using cementations mix (Cetorex grout mortar) that needs only the addition of water achieving a high strength non-shrink mortar.

viii. The steel angles used in rehabilitation have a yield stress of 325 MPa and tensile strength of 420 MPa.

ix. Kemapoxy 165 an adhesive mortar is pre-filled medium viscosity and solvent free. It contains two components product on the basis of modified epoxy resin giving an appropriate hardening system.

2.2. INTERNAL CONFINEMENT BY USING DENSIFICATION OF STIRRUPS DURING CONSTRUCTION

The work carried out has been planned to investigate effect of internal confinement by using stirrups densification at top and bottom of columns with different slenderness ratio as shown in Table [2]. Details of group-1 as follows:-

Group -1:- Consists of four column specimens with a different slenderness ratio 6, 8, 10 and 12 tested under axial load which have a different percentage of stirrups densification height to total column height [Δ/H] are 33,25, 20, and 17 % and the stirrups volumetric ratio [ρ t %] are 0.93,0.82, 0.76 and 0.72 % respectively as shown in Figure [1] and Figure [2].The spacing between stirrups in densification zone is 41.67 mm, While the spacing between stirrups in out of densification zone is 125 mm according to code limits (The maximum vertical spacing for stirrups is $15x$ the smallest longitudinal bar diameter or width of column but not more than 200 mm).The minimum stirrups volumetric ratio is 0.25% according to ECP 203.

2.3. STRAIN GAUGES

Strain Gauges have been mounted inside all specimens on the two longitudinal reinforcement bars and two strain gauges were also mounted externally on the rehabilitated columns. The location of strain gauges mounted inside and outside all specimens as follows:-

2.3.1. INTERNAL STRAIN

Two strain gauges have been located at the mid height on the longitudinal reinforcement bars. One of these gauges was firmly fixed on the vertical corner steel bar (Strain I); while the other was firmly fixed on the middle vertical steel bar (Strain II).

2.3.2. EXTERNAL STRAIN

One of these gauges was firmly fixed at the second steel strap from column top (Strain III); while the other was mounted on the fourth steel strap from column top (strain IV).

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 $2.13 \pm 1.0\%$. Figure (3) the location of strain gauges.

2.4. CASTING AND CURING OF COLOUMNS

The tested columns were casted in wooden forms and a mechanical vibrator was used. Figure [4] shows the wooden forms. Columns forms were removed and columns specimens were cured. Figure [5] and Figure [6] show casting and curing columns respectively.

2.5. TESTING SETUP AND PROCEDURE

2.5.1. TESTING SETUP

All column specimens were tested under static axially loads at the material laboratory of Al-Azhar University. Loading frame was manufactured to resist the expected maximum load. The loading frame and test setup is shown in Figure [7].All columns were tested until failure after 28 days from casting.

2.5.2. LOAD JACK, LOAD CELL AND DATA ACQUISITION SYSTEM

The testing load was applied using hydraulic jack with manual pump as shown in Figure [7]. Data acquisition system connected to load cell consisted of a computer and the lab tech notebook software.

2.6. EXTERNAL CONFINEMENT FOR DAMAGED (RC) COLUMNS

All columns were tested until damage after 28 days from casting then rehabilitated it to reach to original before damage. The rehabilitation was carried out in two phases; local and general rehabilitation.

2.6.1. LOCAL REHABILITATION TECHNIQUE FOR DAMAGED COLUMNS

For damaged concrete areas, loose concrete is removed and the surface is roughened and dust is removed. Temporary cast form is constructed. After one day, the form can be removed and fresh concrete can be chipped away. Figure [8] shows a localized removal and replacement of a damaged part of a concrete column.

2.6.1.1. REMOVAL OF DAMAGE CONCRETE AREAS

Damaged concrete areas and loose concrete were removed, the surface is roughened and dust is removed as shows in Figure [9].

2.6.1.2. REPLACEMENT OF DAMAGE CONCRETE AREAS BY CASTING GROUT MORTAR

The damaged columns were placed in their own forms then the surface of the old concrete are painted by adhesive material to ensure adhesion of the concrete surface of the old concrete with grout mortar as shows in Figure [10]. CETOREX grout mortar with high-strength, non-shrink was used for replacing the damaged concrete part and restore specimens dimension.

2.6.2. GENERAL REHABILITATION TECHNIQUE FOR DAMAGED COLUMNS

Steel jacketing technique used for rehabilitation damaged (RC) column by using four external vertical steel angles (25x25x3) mm connected with horizontal steel straps. Figure [11] shows general rehabilitation technique for damaged columns.

2.6.2.1. FIXING OF VERTICAL STEEL ANGLE

A non-shrinkable material (KEMAPOXY 165) was used to fix the vertical steel angle in corner of columns as shown in Figure [12].

2.6.2.2. WRAPING THE HORIZONTAL STRAPS AND FIXATION BY WELDED IN THE VERTICAL ANGLES

The horizontal straps were wrapped on the column. Straps and angles were fixed by welding as shown in Figure [13].

2.6.2.3. FIXING OF HORIZONTAL STEEL STRAPS

Figure [14] shows applying epoxy adhesive mortar to ensure full contact between straps and surface of concrete columns.

The experimental program for external confinement for damaged (RC) columns is shown in Table [3] contains of four groups as following:-

Group -1R:-Consists of five column specimens with a same slenderness ratio 6 tested under axial load which have a percentage of stirrups densification height to total column height [Δ/H= 33%] and the stirrups volumetric ratio [ρ_t %=0.93%]. Also it was rehabilitated by using four external vertical steel angles (25x25x3) mm connected with horizontal steel 7 straps with a variable width 20,30,40,50 and 60 mm [percentage of covered steel surface area to column surface area 36,42,50,57 and 64%] welded to the angles as shown in Figure [15] as example.

Group -2R:-Consists of five column specimens with a same slenderness ratio 8 tested under axial load which have a percentage of stirrups densification height to total column height [Δ/H=25%] and the stirrups volumetric ratio [ρ_t %] (0.82 %). Also it was rehabilitated by using four external vertical steel angles (25x25x3) mm connected with horizontal steel 9 straps with a variable width 20,30,40,50 and 60 mm [percentage of covered steel surface area to column surface area 36,42,50,57 and 64%] welded to the angles.

Group -3R:-Consists of five column specimens with a same slenderness ratio10 tested under axial load which have a percentage of stirrups densification height to total column height [Δ/H =20 %] and the stirrups volumetric ratio [ρ_t %] (0.76 %).Also it was rehabilitated by using four external vertical steel angles (25x25x3) mm connected with horizontal steel 11 straps with a variable width 20,30,40,50 and 60 mm [percentage of covered steel surface area to column surface area 36,42,50,57 and 64%] welded to the angles.

Group -4R:-Consists of five column specimens with a same slenderness ratio12 tested under axial load which have a percentage of stirrups densification height to total column height [Δ/H =17 %] and the stirrups volumetric ratio [ρ_t %] (0.72 %).Also it was rehabilitated by using four external vertical steel angles (25x25x3) mm connected with horizontal steel 13 straps with a variable width 20,30,40,50 and 60 mm [percentage of covered steel surface area to column surface area 36,42,50,57 and 64%] welded to the angles**.**

Figure [16] shows details of rehabilitated damage (RC) columns with a different slenderness ratio (6, 8, 10 and 12) and percentage of covered steel surface area to column surface area 36% as example.

3. EXPERIMENTAL TEST RESULTS
3.1. EXPERIMENTAL TEST RESULTS FOR INTERNAL CONFINEMENT FOR (RC) DURING CONSTRUCTION

Table [2] shows the ultimate loads obtained from (EXP) results for columns with internal confinement.

3.1.1. ULTIMATE LOADS

Figure [17] shows the effect of slenderness ratio on the ultimate loads for columns with internal confinement by using densification of stirrups during construction [Δ/H] (33, 25, 20, and 17 %).

From Figure [17], it can be shown that the use of internal confinement by using densification of stirrups during construction gives a decrease in the load carrying by increasing the slenderness.

3.1.2. MODES OF FAILURE

For group-1 with internal confinement by using densification of stirrups at top + bottom of columns as increasing load inclined cracks started to appear on surface of column. The cracks increased with the increasing load the column. The concrete cover spall off and a visible buckling of longitudinal reinforcement with outside buckling in the stirrups occurred from one side. When the load reached failure load, crushing was observed and total collapse of specimens occurred as shown in Figure [18].It was found from Figure [18] that the failure of columns caused due to spall off concrete after the stirrups densification zone.

3.2. EXPERIMENTAL TEST RESULTS FOR EXTERNAL CONFINEMENT FOR DAMAGED (RC) COLUMNS

Table [3] shows the ultimate loads obtained from (EXP) results for columns with external confinement.

3.2.1. ULTIMATE LOADS

Figure [19] shows the relationship between slenderness ratio (λ) and ultimate load with different percentage of covered steel surface area to column surface area (A_{SS}) 36,42,50,57 and 64 % and control columns. It can be shown from Figure [19] that the used internal and external confinement by using densification of stirrups and different parentage of covered steel surface area to column surface area gives a decrease in the load carrying by increasing the slenderness.

Figure [20] shows the relationship between slenderness ratio (λ) and percentage of columns carrying capacity with different percentage of covered steel surface area to column surface area (A_{SS}) 36,42,50,57 and 64 % and control columns. It can be shown from Figure [20] that the column carrying capacity decreases by increasing the slenderness ratio.

Figure [21] shows the relationship between percentage of column carrying capacity and percentage of covered steel surface area to column surface area for columns with a different slenderness ratio 6,8,10 and 12. It can be shown from Figure [21] that the column carrying capacity increases by increasing percentage of covered steel surface area to column surface area for damaged (RC) columns.

3.2.2. LOAD AND STRAIN IN INTERNAL REINFORCEMENT AND EXTERNAL STEEL STRAPS

Figure [22] shows the relationship between load and strain at corner and middle steel bars for vertical internal reinforcement as well as strain at second and fourth steel straps for group -1R with slenderness ratio (λ=6) and percentage of covered steel surface area to column surface area (A_{SS} = 36%) for example . Table (3) shows load and recorded strain at external steel straps. It was found that the recorded strain increases by increasing percentage of covered steel surface area to column surface area and ductility increase.

3.2.3. MODES OF FAILURE

Figure [23] shows modes of failure for rehabilitated columns. It was found that the failure occurred in the top third of the column height. The position of failure is after to the second strap.

4. FINITE ELEMENT ANALYSIS

The finite element package ANSYS 15.0 was used in order to simulate the obtained experimental testing by introducing a numerical model. The tested columns in the experimental work were modeled to determine the failure loads and strains to simulate the effect internal confinement by using densification of stirrups and external confinement by using four external vertical steel angles connected with horizontal steel straps (Steel jacketing technique).

4.1. STAGES OF FINITE ELEMENT MODEL

There are five main stages to model columns specimen:-

  i.   Defining element types, real constants, and material properties.
 ii.   Modeling the geometry of column specimens.
iii.   Meshing the specimen geometry.
 iv.   Applying boundary conditions and loads on specimen.
  v.   Loading procedure and analysis of the results.

4.1.1. MODEL OF CONCRETE

The concrete is modeled using hexahedral elements (SOLID 65) type with eight corner nodes having three translation degrees of freedom at each node. The Young's modulus for concrete was taken 19677 MPa and Poisson's ratio was taken to be (0.2). The stress- strain curve was defined for concrete element in "ANSYS" program with f_{cu}= 20 MPa as shown in Figure [24]. Figure [25] shows concrete elements.

4.1.2. MODEL OF LONGITUDINAL AND TRANSVERSE REINFORCEMENT STEEL ELEMENTS

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

be (0.3). The idealized stress-strain curve for the internal vertical and horizontal reinforcement was used in the finite element model as shown in [26]. Figure [27] shows create longitudinal and transverse reinforcement elements.

4.1.3. MODEL OF LOADING PLATE

The loading plate is modeled using (SOLID 45) element type. This element is defined by eight nodes which three degrees of freedom. The Young's modulus for internal steel was taken 2.0×10^5 MPa and Poisson's ratio was assumed to be (0.3).

4.1.4. MODEL OF STEEL JACKET [ANGLES AND STRAPS]

The proposed rehabilitation technique consists of four vertical steel angles connected together by using with horizontal steel straps with different dimension. The steel jacket is modeled using quadrilateral shell elements SHELL181, with four nodes each of six degree of freedom of yield stress, $F_y = 325$ MPa. The Young's modulus for reinforcement was taken 2.0×10^5 MPa and Poisson's ratio was taken to be (0.3). Figure [28] shows the modeling of steel jacket.

4.1.5. APPLYING BOUNDARY CONDITIONS AND LOADS ON SPECIMEN

Boundary conditions were applied accordingly to simulate the experimental conditions at the base joints of specimen in horizontal translations and rotations in three directions as shown in Figure [29].

5. COMPARISON BETWEEN EXPERIMENTAL AND ANALYTICAL FINITE ELEMENTS RESULTS

5.1. ULTIMATE LOADS

Table [4] shows comparison between ultimate loads obtained from (EXP) and (FEA) analysis for (RC) columns with internal confinement during construction.

Table [5] shows comparison between ultimate loads obtained from (EXP) and (FEA) analysis for (RC) columns with external confinement for damaged (RC) columns.

Figure [30] shows comparison between slenderness ratio (λ) and ultimate load obtained from (FEA) and (EXP) results for columns with internal confinement by using different percentage of stirrups densification (Δ/h) 33, 25, 20 and 17% and different slenderness ratio (λ) 6,8,10 and 12 respectively.

Figure [31] shows comparison between slenderness ratio (λ) and ultimate load obtained from (FEA) and (EXP) results for external confinement for damaged (RC) columns with different slenderness ratio (λ) 6,8,10 and 12 and percentage of covered steel surface area to column surface area (A_{SS}) 36%.

Figure [32] shows comparison between slenderness ratio (λ) and percentage of column carrying capacity obtained from (FEA) and (EXP) results external confinement for damaged (RC) columns with different slenderness ratio (λ) 6,8,10 and 12 and percentage of covered steel surface area to column surface area (A_{SS}) 36%.

Figure [33] shows comparison between percentage of columns carrying capacity and percentage of covered steel area to column surface area (A_{SS}) obtained from (FEA) and (EXP) results external confinement for damaged (RC) columns.

The obtained results showed Faire agreement between finite element (FEA) results and experimental (EXP) results and the results obtained from (FEA) is greater than results obtained from (EXP).

5.2. MODES OF FAILURE

Figures [34 to 37] show comparison between modes of failure obtained from (FEA) and (EXP) model for columns with internal confinement by using stirrups densification at top and bottom of columns [Δ/H] 33%, 25.20.17 reactively. From the figures; it has been seen generally that, the failure of columns are due to spall off concrete between stirrups densification zones, thus signifying large stress concentration after densification directly. Faire agreement is obtained between finite element (FEA) results and experimental (EXP) results.

Figure [38] show comparison between modes of failure obtained from (EXP.) and (FEA) for rehabilitated columns by 4 angles 25 x 3 and straps 60 x3 mm. It can be shown from Figure [38] that the obtained failure modes from (EXP) have the same shape of (FEA). From figure; it has been noticed that the failure for rehabilitated columns occurred in the top third of the column height. \

6. PARAMETRIC STUDY AND ANALYTICAL RESULTS TO STUDY EFFECT OF STIRRUPS DENSIFICATION

As illustrated in previous, finite element models performed with numerical analysis using ANSYS15.0 predict truly the analysis and discussion of the effect of stirrups densification and rehabilitation of reinforced concrete columns. Thus, it is possible to perform a parametric study with numerical finite element model followed by indications as illustrated previously. Table [6] shows parametric study by using (FEA) for regular stirrups distribution.

Figure [39] shows concrete dimension and reinforcement for group -2 consists of four columns with a different slenderness ratio ($\lambda = 6,8,10$ and 12) and regular stirrups distribution each 41.67 mm as well as stirrups volumetric ratio equal 1.58%.The spacing between stirrups according to code limits (The maximum vertical spacing for stirrups is $15x$ the smallest longitudinal bar diameter or width of column but not more than 200 mm).The minimum stirrups volumetric ratio is 0.25% according to ECP 203.

Figure [40] shows comparison between slenderness ratio (λ) and ultimate load obtained from (FEA) results for columns with internal confinement by using stirrups densification at top and bottom of columns and regular stirrups distribution. It can be shown from Figure [40] that the effect of the slenderness ratio on the load carrying capacity of columns with internal confinement by using distribution of stirrups along of column during construction is more significant than that of columns with internal confinement by using densification of stirrups at top + bottom of columns.

Finite element models performed with numerical analysis using ANSYS15.0 predict truly the analysis and discussion of the optimum percentage of covered steel surface area to column surface area .Figure [41] shows the relationship between slenderness ratio (λ) and the optimum percentage of covered steel surface area to column surface area (A_{ss}) for rehabilitated columns. It can be shown from Figure [41] that the optimum percentages of covered steel surface area to column surface area are 25, 28, 32 and 36% for different slenderness ratio 6,8,10 and 12 respectively for the rehabilitation of damaged (RC) columns so that the column reaches the original.

CONCLUSIONS

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

i. The increase in internal stirrups volumetric ratio by using densification of stirrups along of column during construction resulted in higher ultimate load.

ii. The failures of columns are due to spall off concrete between stirrups densification zones, thus signifying the large stress concentration after densification directly.

iii. Steel jacketing technique proved to be an easy, inexpensive in rehabilitation of damaged (RC) columns.

iv. The column carrying capacity increases by increasing percentage of covered steel surface area to column surface area and decreases by increasing slenderness ratio.

v. The optimum percentages of covered steel surface area to column surface area are 25, 28, 32 and 36% for columns with different slenderness ratio 6,8,10 and 12 for the rehabilitation of damaged (RC) columns so that the column reaches the original.

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

REFERENCES

1. Etman, E. (2010). Experimental Study on The Behavior of Slender Rectangular Columns Under Eccentric Loading. Concrete Research Letters, 1(2), 45-59.

2. Soliman, A. E. K. S. (2011). Behavior of long confined concrete column. Ain Shams Engineering Journal, 2(3-4), 141-148.

3. Malhotra, J., Bansal, P. G. (2013), "Behavior of RCC columns confined with ferrocement". Journal of Composites for Construction Vol.17, Issus 4, PP. 443-453.

4. Hales, T. A., Pantelides, C. P., & Reaveley, L. D. (2016). Experimental evaluation of slender high-strength concrete columns with GFRP and hybrid reinforcement. Journal of Composites for Construction, 20(6), 04016050.

5. Sheikh, T. R., Khan, M. K. and Izhar, T. (2017) , "Strengthening of RC short square columns subjected to concentric axial loading by Ferrocement Jacketing". International Research Journal of Engineering and Technology (IRJET) Vol. 4 ,Issue4, PP. 3490-3495.

Table [1] Concrete mix design

Constituents	Mix proportions by weight for m^3
Crushed stone	1108 Kg
Gradate sand	640 Kg
Water	135 Liter
Cement	270 Kg
Water cement ratio (w/c)	50 %

Table [2] Internal confinement during construction for (RC) columns

Groups	Columns No	Stirrups distribution method	Columns dimension; (mm)			Slenderness ratio [λ]	Height of stirrups densification zones at top + bottom of columns; mm[Δ]	Number of stirrups at densification zones	Total No. of stirrups	Stirrups volumetric ratio;% [ρ]	% of stirrups densification at top + bottom of columns;% (ΔH)	Long.steel ratio;[μ]	Ultimate loads (EXP) (KN)
			b	t	h								
Group-1	C11	stirrups densification at top + bottom of columns	125	250	750	6	250	8	11	0.93%	33%	1%	660
	C12				1000	8			13	0.82%	25%		626
	C13				1250	10			15	0.76%	20%		614
	C14				1500	12			17	0.72%	17%		600

Table [3] External confinement for damaged (RC) columns

Groups	Columns No	Stirrups distribution method	Columns dimension; (mm)			Slenderness ratio [λ]	[Δ] mm	Number of stirrups at densification zones	Total No. of stirrups	Stirrups volumetric ratio;% [ρ]	(Δ/H) %	Jacket		(Ass) %	Ultimate loads form (EXP) (KN)		column carrying capacity %	Strain in steel straps (%)	
			b	t	h							Vertical steel angles	Horizontal steel straps		Internal confinement (Control)	Internal and external confinement		at second steel strap from column top (III)	at fourth steel strap from column top (IV)
Group-1R	C11R	stirrups densification at top + bottom of columns	125	250	750	6	250	8	11	0.93%	33%	4L (25×3) mm	7-straps 20×3mm	36%	660	940	142%	0.029%	0.022%
	C12R												7-straps 30×3mm	42%		1020	100%	0.035%	0.027%
	C13R												7-straps 40×3mm	50%		1039	157%	0.040%	0.030%
	C14R												7-straps 50×3mm	57%		1061	161%	0.048%	0.033%
	C15R												7-straps 60×3mm	64%		1097	166%	0.049%	0.045%
Group-2R	C21R	stirrups densification at top + bottom of columns	125	250	1000	8	250	8	13	0.82%	25%	4L (25×3) mm	9-straps 20×3mm	36%	626	820	131%	0.028%	0.021%
	C22R												9-straps 30×3mm	42%		845	135%	0.034%	0.025%
	C23R												9-straps 40×3mm	50%		867	139%	0.039%	0.029%
	C24R												9-straps 50×3mm	57%		879	140%	0.045%	0.032%
	C25R												9-straps 60×3mm	64%		895	143%	0.049%	0.038%
Group-3R	C31R	stirrups densification at top + bottom of columns	125	250	1250	10	250	8	15	0.76%	20%	4L (25×3) mm	11-straps 20×3mm	36%	614	691	113%	0.028%	0.019%
	C32R												11-straps 30×3mm	42%		711	116%	0.030%	0.023%
	C33R												11-straps 40×3mm	50%		745	121%	0.036%	0.027%
	C34R												11-straps 50×3mm	57%		781	127%	0.041%	0.030%
	C35R												11-straps 60×3mm	64%		800	130%	0.047%	0.036%
Group-4R	C41R	stirrups densification at top + bottom of columns	125	250	1500	12	250	8	17	0.72%	17%	4L (25×3) mm	13-straps 20×3mm	36%	600	616	103%	0.022%	0.017%
	C42R												13-straps 30×3mm	42%		626	105%	0.030%	0.021%
	C43R												13-straps 40×3mm	50%		646	108%	0.035%	0.026%
	C44R												13-straps 50×3mm	57%		683	114%	0.041%	0.029%
	C45R												13-straps 60×3mm	64%		700	117%	0.044%	0.032%

R: : Rehabilitated columns.
Δ: : Height of stirrups densification zones at top + bottom of columns; mm [Δ]
(Δ/H) : Parentage of stirrups densification at top + bottom of columns; %
A ss: : Parentage of covered steel surface area to column surface area

Table [4] Comparison between ultimate loads obtained from experimental and finite element analysis for (RC) columns with internal confinement during construction

Groups	Columns No.	Stirrups distribution method	Columns dimension; (mm)			Slenderness ratio [λ]	Height of stirrups densification zones at top+bottom of columns; mm[Δ]	Number of stirrups at densification zones	Total No. of stirrups	Stirrups volumetric ratio; % [ρ t]	% of stirrups densification at top + bottom of columns; % (Δ/H)	Long. steel ratio; [μ]	Ultimate loads (KN)	
			b	t	h								(EXP)	(FEA)
Group-1	C 11	stirrups densification at top + bottom of columns	125	250	750	6	250	8	11	0.93 %	33 %	1 %	660	665
	C 12				1000	8			13	0.82 %	25 %		626	629
	C 13				1250	10			15	0.76 %	20 %		614	620
	C 14				1500	12			17	0.72 %	17 %		600	603

Table [5] Comparison between ultimate loads obtained from experimental and finite element analysis for (RC) columns with external confinement for damaged (RC) columns

Groups	Columns No.	Stirrups distribution method	Columns dimension; (mm)			Slenderness ratio [λ]	[Δ] mm	Number of stirrups densification zones	Total No. of stirrups	Stirrups volumetric ratio; %[ρt]	(Δ/H) %	Jacket		(Ass) %	Ultimate loads form (KN)		column carrying capacity %	
			b	t	h							Vertical steel angles	Horizontal steel straps		(EXP)	(FEA)	(EXP)	(FEA)
Group-1R	C11R	stirrups densification at top+bottom of columns	125	250	750	6	250	8	11	0.93%	33%	4L(25x3) mm	7-straps20x3mm	36%	940	986	142%	148%
	C12R												7-straps30x3mm	42%	1020	1084	١٥٥%	163%
	C13R												7-straps40x3mm	50%	1039	1117	157%	168%
	C14R												7-straps50x3mm	57%	1061	1139	161%	171%
	C15R												7-straps60x3mm	64%	1097	1162	166%	175%
Group-2R	C21R	stirrups densification at top+bottom of columns	125	250	1000	8	250	8	13	0.82%	25%	4L(25x3) mm	9-straps20x3mm	36%	820	836	131%	133%
	C22R												9-straps30x3mm	42%	845	861	135%	137%
	C23R												9-straps40x3mm	50%	867	887	139%	141%
	C24R												9-straps50x3mm	57%	879	914	140%	145%
	C25R												9-straps60x3mm	64%	895	941	143%	150%
Group-3R	C31R	stirrups densification at top+bottom of columns	125	250	1250	10	250	8	15	0.76%	20%	4L(25x3) mm	11-straps20x3mm	36%	691	714	113%	115%
	C32R												11-straps30x3mm	42%	711	743	116%	120%
	C33R												11-straps40x3mm	50%	745	788	121%	127%
	C34R												11-straps50x3mm	57%	781	803	127%	130%
	C35R												11-straps60x3mm	64%	800	843	130%	136%
Group-4R	C41R	stirrups densification at top+bottom of columns	125	250	1500	12	250	8	17	0.72%	17%	4L(25x3) mm	13-straps20x3mm	36%	616	631	103%	105%
	C42R												13-straps30x3mm	42%	626	663	105%	110%
	C43R												13-straps40x3mm	50%	646	682	108%	113%
	C44R												13-straps50x3mm	57%	683	703	114%	117%
	C45R												13-straps60x3mm	64%	700	731	117%	121%

R: : Rehabilitated columns.
Δ: : Height of stirrups densification zones at top + bottom of columns; mm [Δ]
(Δ/H) : Parentage of stirrups densification at top + bottom of columns; %
L   : Equal steel angle
A $_{ss}$: : Parentage of covered steel surface area to column surface area

Table [6] Parametric study by using (FEA) for internal confinement during construction for (RC) columns

Groups	Columns No.	Stirrups distribution method	Columns dimension; (mm)			Slenderness ratio [λ]	Total No. of stirrups	Stirrups volumetric ratio; % [ρt]	% of stirrups densification at top + bottom of columns; % (Δ/H)	Long. steel ratio; [μ]	Ultimate loads (KN) (FEA)
			b	t	h						
Group -2	C 21	Regular distribution @ 41 mm (Δ/H=100%)	125	250	750	6	19	1.58 %	100 %	1 %	805
	C 22				1000	8	25				770
	C 23				1250	10	31				749
	C 24				1500	12	37				715

Slenderness ratio (λ le / b)	6	8	10	12
Total stirrups number at top and bottom of column (Constant number)	8			
Top stirrups densification height	125 mm			
Bottom stirrups densification height	125 mm			
Total stirrups densification height	250 mm			
percentage of stirrups densification at top and bottom of column (η = Δ / H)	250/750=33%	250/1000=25%	250/1250=20%	250/1500=17%
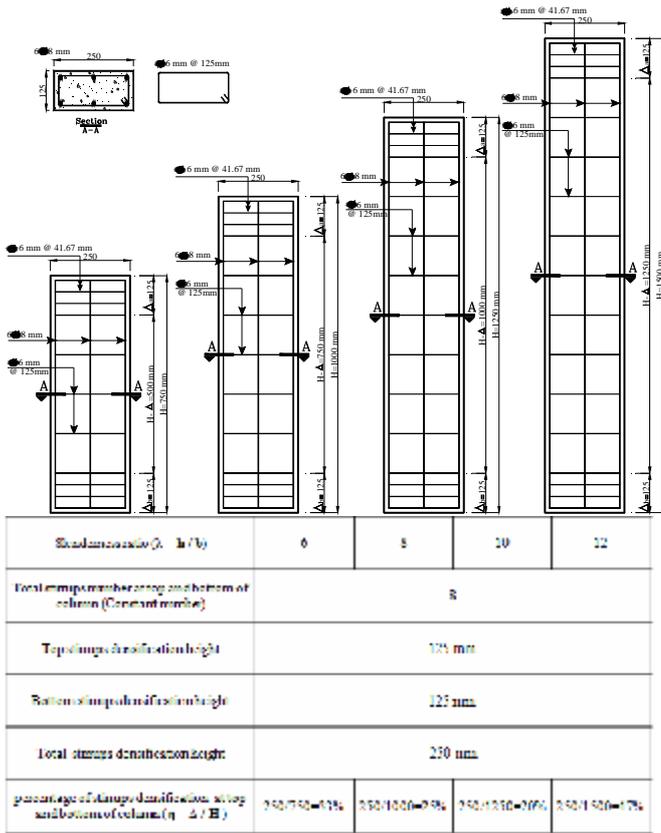
Figure [1] Concrete dimension and stirrups densification details for group -1 with different percentage of stirrups densification (Δh) 33, 25, 20 and 17% and different slenderness ratio (λ) 6,8,10 and 12 respectively

Figure [2] Reinforcement for group -1 with different percentage of stirrups densification (Δh) 33, 25, 20 and 17% and different slenderness ratio (λ) 6,8,10 and 12 respectively
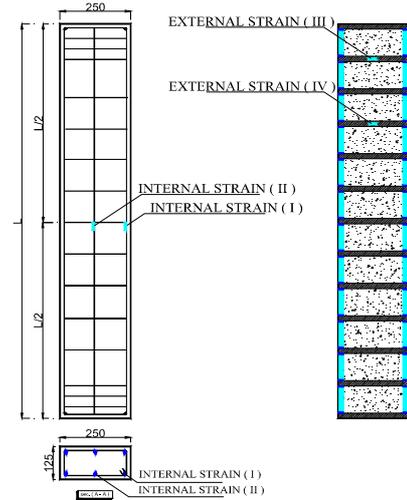
Figure [3] Location of strain gauges

Figure [4] Wooden forms for columns casting

Figure [5] Columns casting

Figure [6] Columns curing

Figure [7] loading frame and test setup

Figure [8] Localized removal and replacement of damaged concrete

Figure [9] Removal of damage concrete

Figure [10] Replacement of damaged concrete by grout mortar
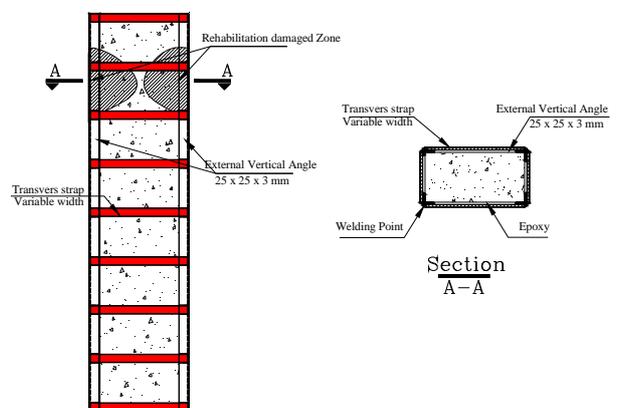
Figure [11] general rehabilitation technique for damaged columns

Figure [12] Using epoxy adhesive mortar to ensure full contact between angles and concrete columns

Figure [13] Warping the horizontal straps around the column and fixation of straps and angles by welding

Figure [14] Applying epoxy adhesive mortar to ensure full contact between straps and concrete columns

Ass=36%   Ass=42%   Ass=50%   Ass=57%   Ass=64%

Figure [15] Details of steel jacketing for general rehabilitation of columns with slenderness ratio 6 for group -1R with a variable of percentage of covered steel surface area to column surface area 36,42,50,57 and 64% respectively
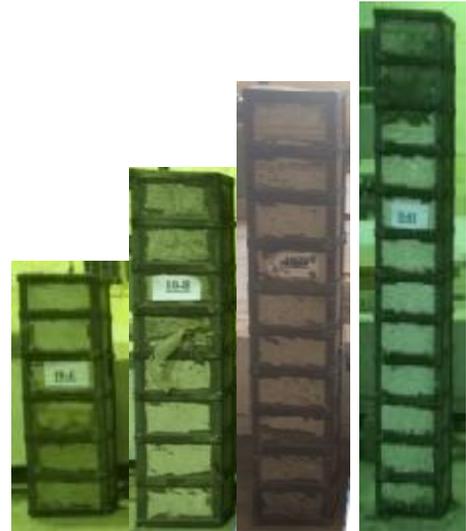
Figure [16] Details of steel jacketing for general rehabilitation by using four external vertical steel angles (25x25x3) mm connected with variable number of horizontal steel straps (7, 9, 11 and 13), different slenderness ratio (6, 8, 10 and 12) and percentage of covered steel surface area to column surface area 36 %
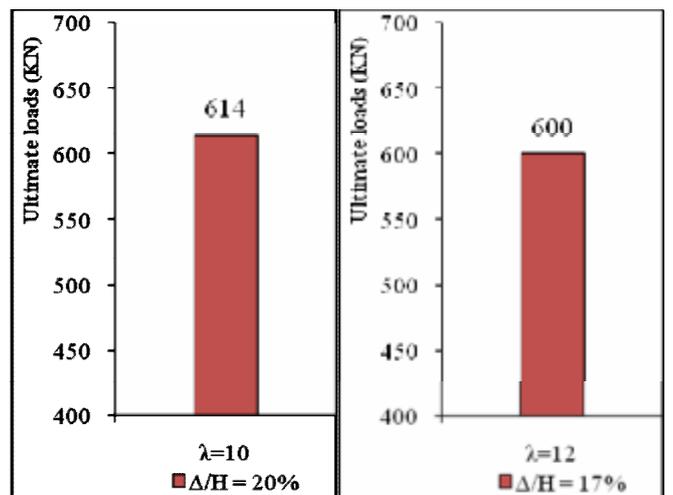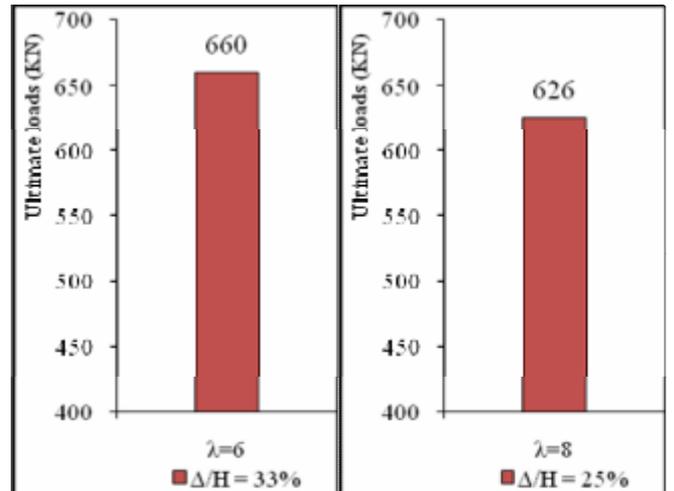
Figure [17] Relationship between slenderness ratio (λ) and ultimate load for columns with internal confinement by using different percentage of stirrups densification (Δ/h) 33, 25, 20 and 17% and different slenderness ratio (λ) 6,8,10 and 12 respectively
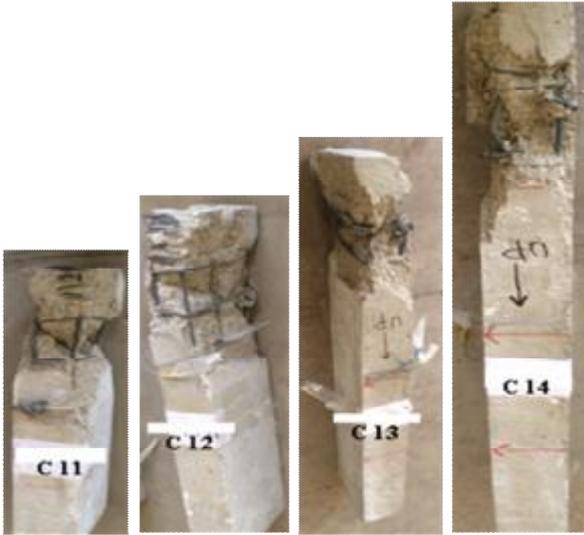
Figure [18] Failure mode of column for group-1 with internal confinement by using different percentage of stirrups densification (Δh) 33, 25, 20 and 17% and different slenderness ratio (λ) 6,8,10 and 12 respectively
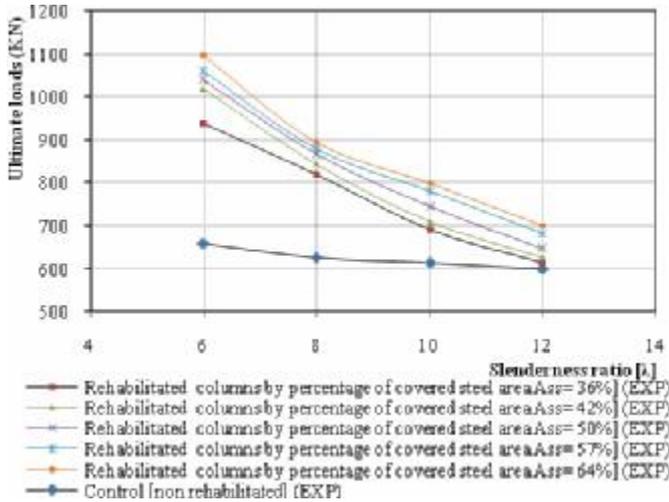

Figure [19] Relationship between slenderness ratio (λ) and ultimate load with different percentage of covered steel surface area to column surface area (Ass) 36,42,50,57 and 64 % and control columns
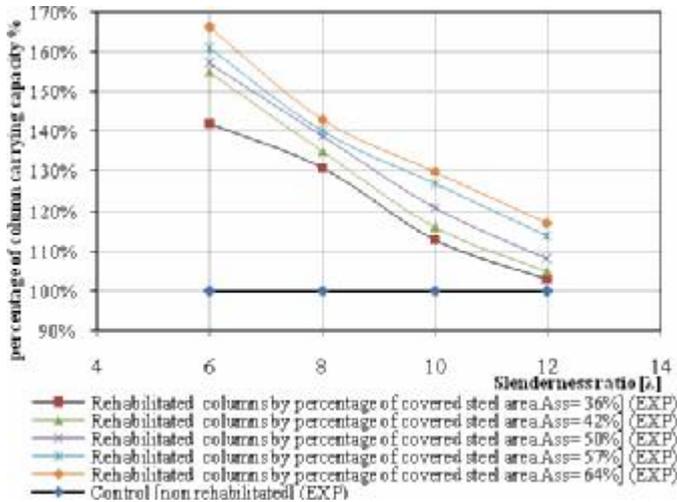
Figure [20] Relationship between slenderness ratio (λ) and percentage of column carrying capacity with a different percentage of covered steel surface area to column surface area (Ass) 36,42,50,57 and 64 % and control columns
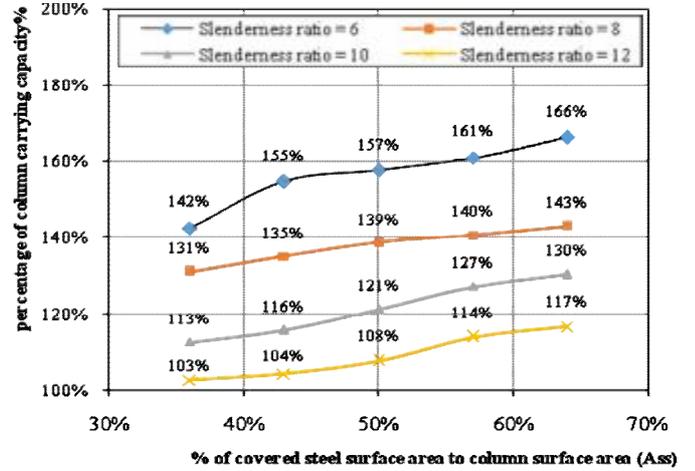
Figure [21] Relationship between percentage of columns carrying capacity and percentage of covered steel area to column surface area (Ass) with a different slenderness ratio (λ=6, 8, 10 and 12) for rehabilitated columns
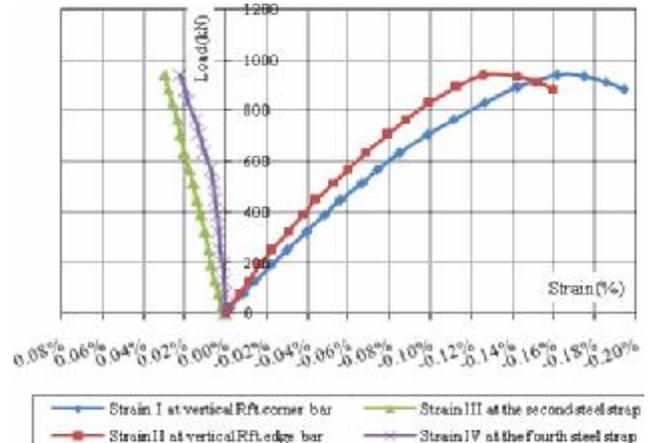
Figure [22] Relationship between loads and strain at corner and middle steel bars for vertical internal reinforcement as well as strain at second and fourth steel straps for group - 1R with slenderness ratio (λ=6) and percentage of covered steel surface area to column surface area (Ass= 36%)


Figure [23] Failure modes of the rehabilitated columns.
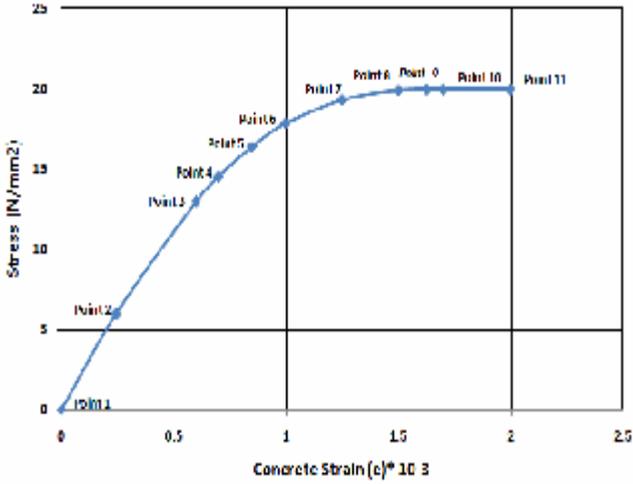
Figure [24] Concrete stress strain curve (f_{cu}=20 MPa)

Figure [27] Modeling longitudinal and stirrups

Figure [25] Modeling of concrete elements

Ass 36%   Ass 42%   Ass 50%   Ass 57%   Ass 64%
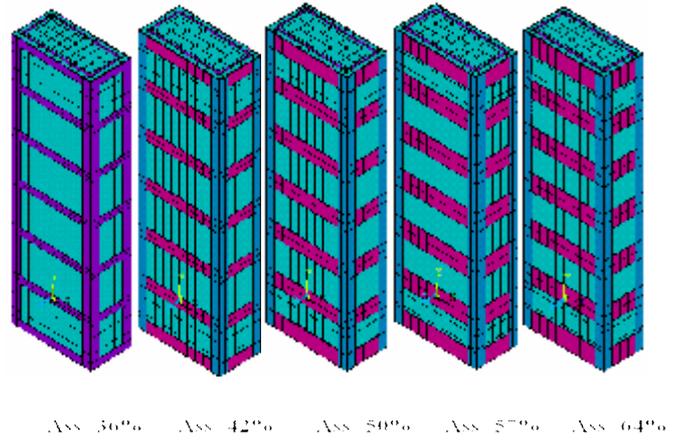
Figure [28] Modeling of steel jacketing technique
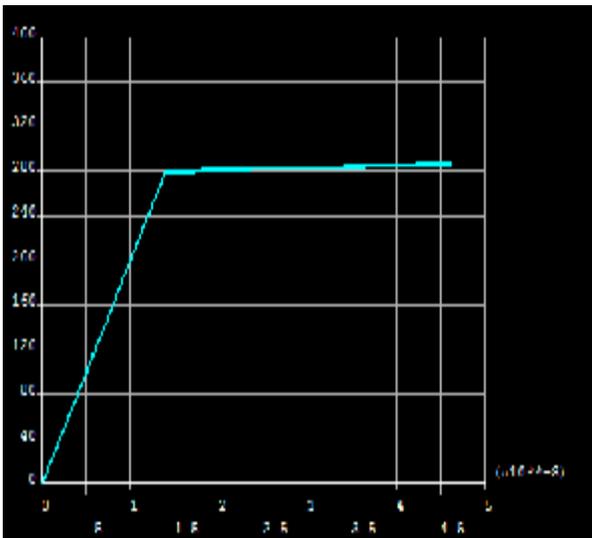
Figure [26] Idealized stress-strain for reinforcing steel bars (f_y=280 MPa)

Loading Method

Boundary condition
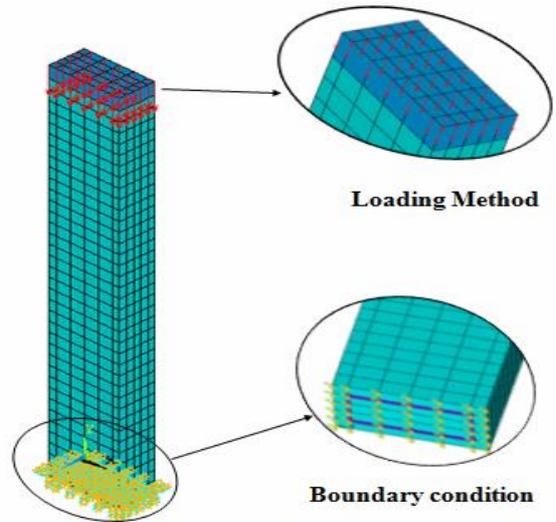
Figure [29] Boundary condition and Loading method of column specimen
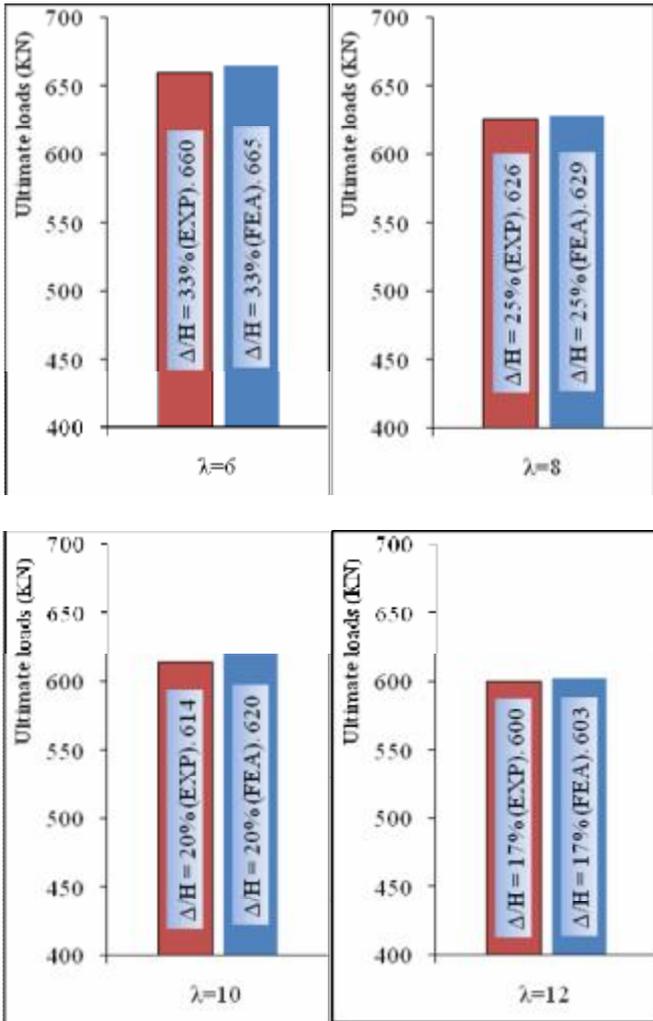
Figure [30] Comparison between slenderness ratio (λ) and ultimate load obtained from (FEA) and (EXP) results for columns with internal confinement by using different percentage of stirrups densification (Δh) 33, 25, 20 and 17% and different slenderness ratio (λ) 6,8,10 and 12 respectively
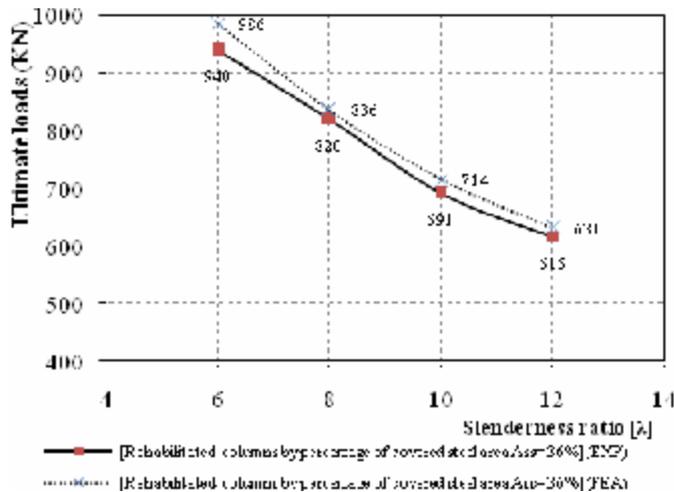
Figure [31] Comparison between slenderness ratio (λ) and ultimate load obtained from (FEA) and (EXP) results for external confinement for damaged (RC) columns group-1R

with different slenderness ratio (λ) 6,8,10 and 12 and percentage of covered steel surface area to column surface area (A_{SS}) 36%
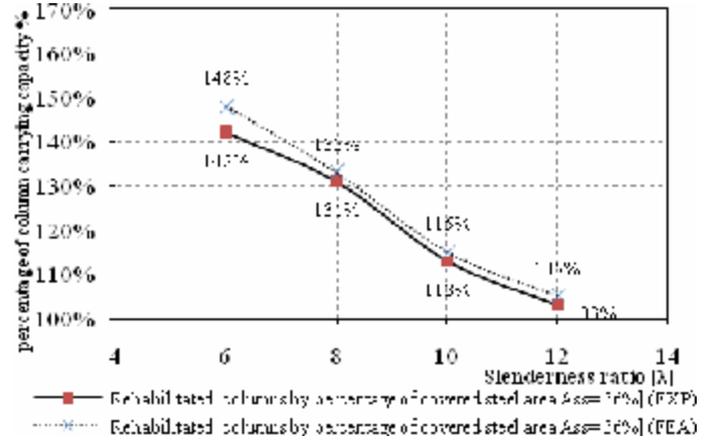
Figure [32] Comparison between slenderness ratio (λ) and percentage of column carrying capacity obtained from (FEA) and (EXP) results external confinement for damaged (RC) columns with different slenderness ratio (λ) 6,8,10 and 12 and percentage of covered steel surface area to column surface area (A_{SS}) 36%
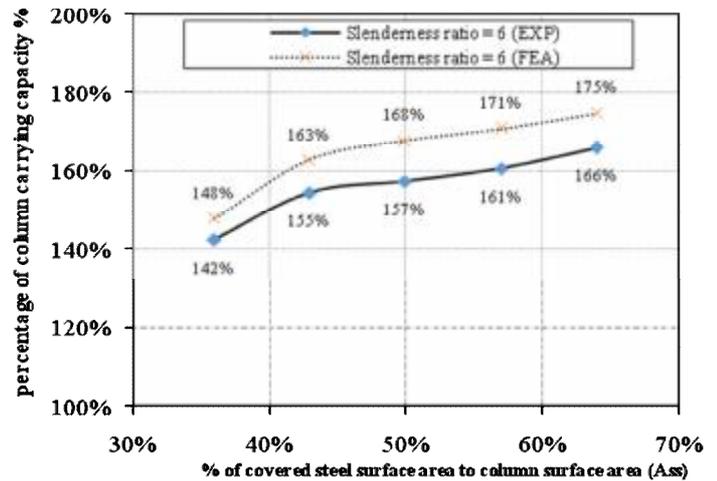
Figure [33] Comparison between percentage of columns carrying capacity and percentage of covered steel area to column surface area (A_{SS}) obtained from (FEA) and (EXP) results external confinement for damaged (RC) columns
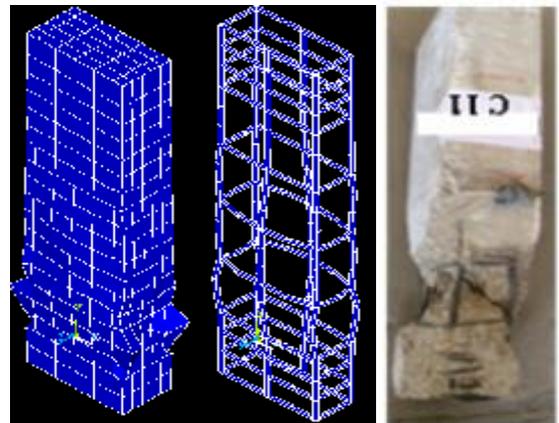
Figure [34] Comparison between modes of failure obtained from (FEA) and (EXP) for columns with internal confinement by using stirrups densification at top and bottom of columns [Δ/H] 33%
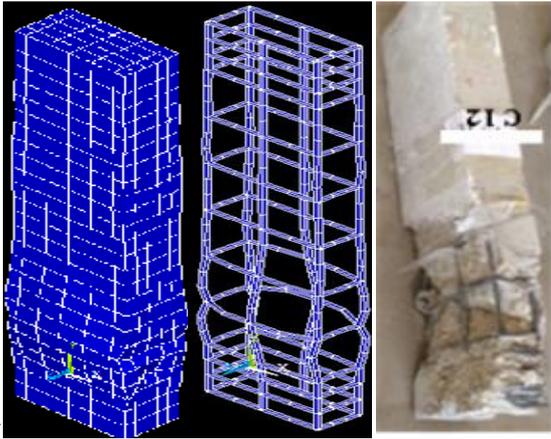
Figure [35] Comparison between modes of failure obtained from (FEA) and (EXP) for columns with internal confinement by using stirrups densification at top and bottom of columns [ΔH] 25 %

**Figure [38]** Comparison between modes of failure obtained from (EXP.) and (FEA) for Columns rehabilitated by 4 angles 25 x 3 and straps 60 x 3 mm
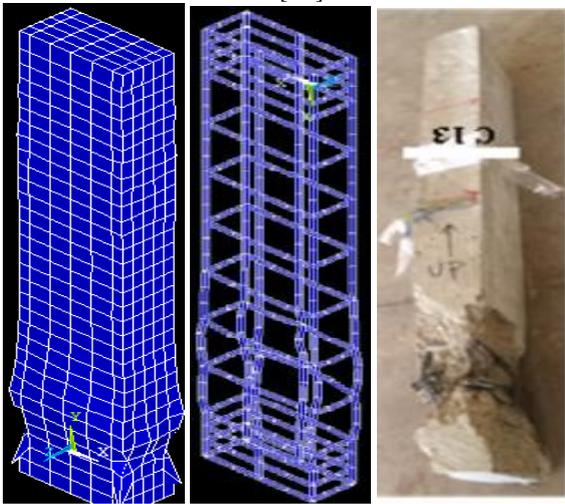

Figure [36] Comparison between modes of failure obtained from (FEA) and (EXP) for columns with internal confinement by using stirrups densification at top and bottom of columns [ΔH] 20 %
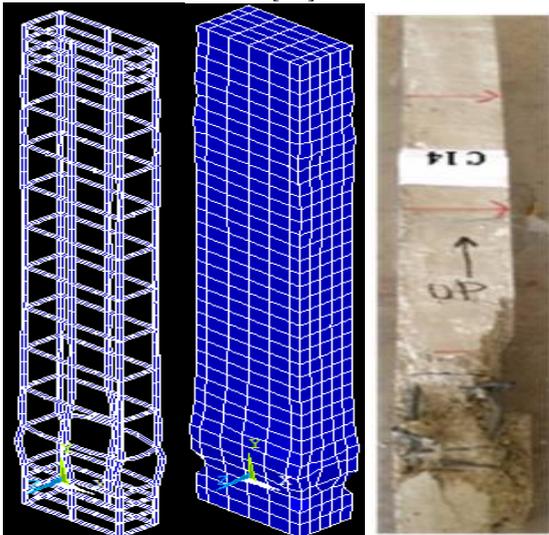
Figure [37] Comparison between modes of failure obtained from (FEA) and (EXP) for columns with internal confinement by using stirrups densification at top and bottom of columns [ΔH] 17 %
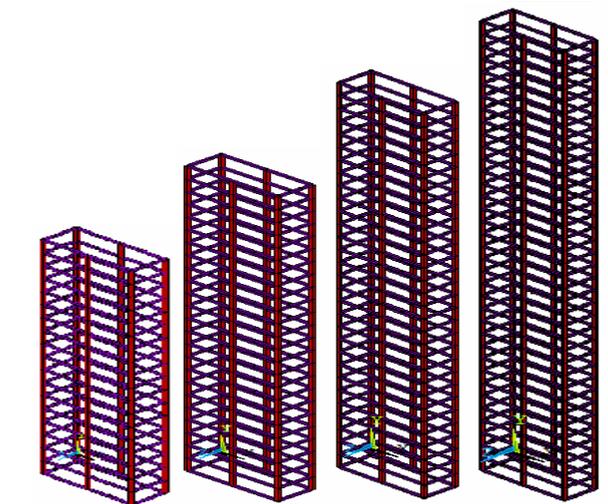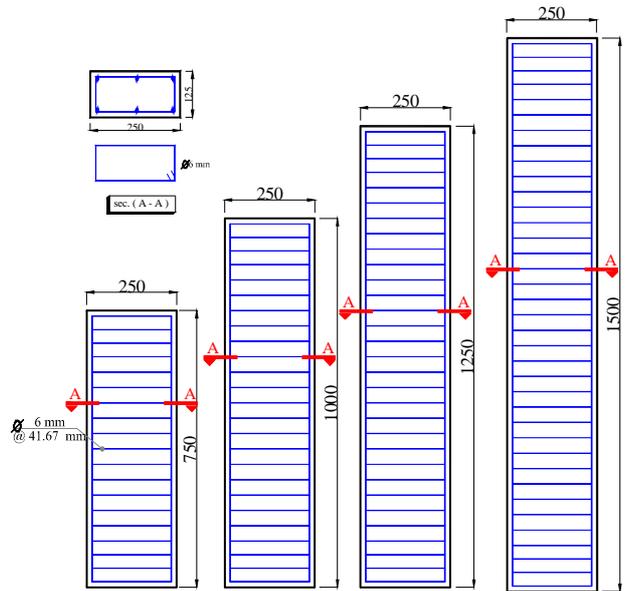
Figure [39] Details of reinforcement for group -2 with different slenderness ratio (λ = 6,8,10 and 12) and regular distribution of stirrups each 41.67 mm [ΔH] 100%
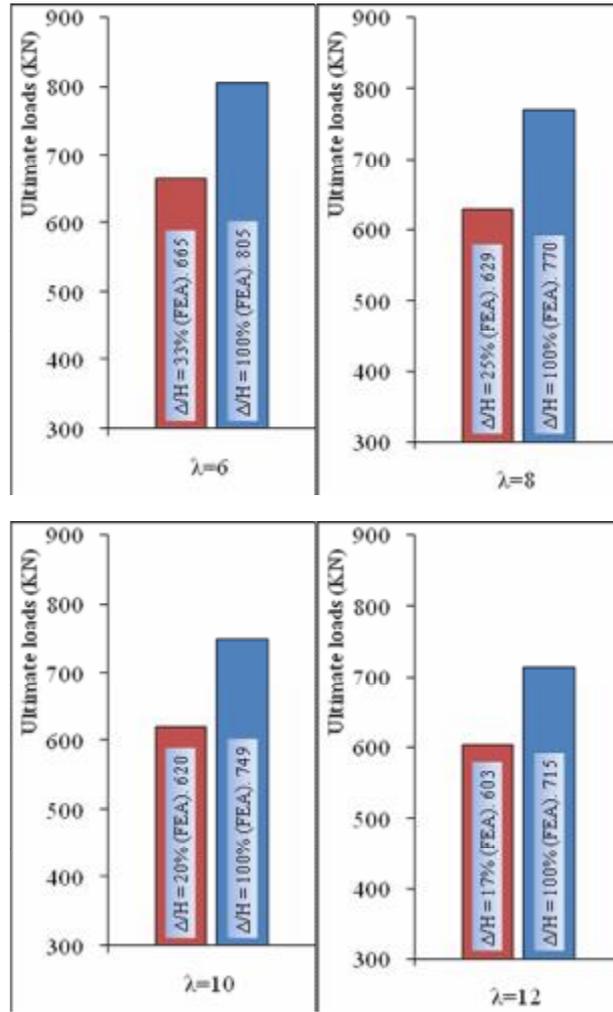
Figure [40] Comparison between slenderness ratio (λ) and ultimate load obtained from (FEA) results for columns with internal confinement by using different percentage of stirrups densification at top and bottom of columns [Δ/H] 33, 25, 20 and 17 % and regular stirrups distribution each 41.67 mm [Δ/H] 100%
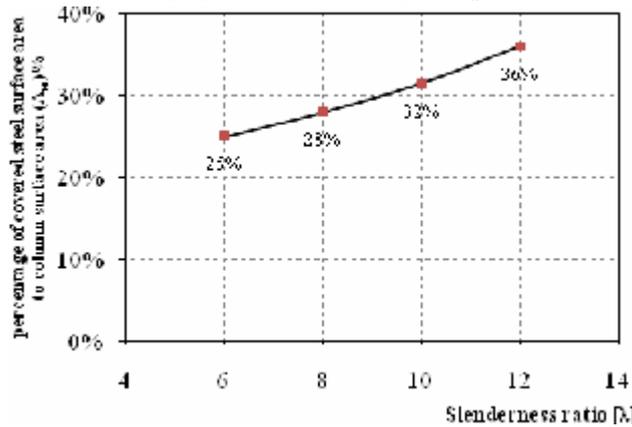

Figure [41] Relationship between slenderness ratio (λ) and the optimum percentage of covered steel surface area to column surface area (A_{ss}) for rehabilitated columns