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Experimental and Theoretical Behaviors of Edge and Corner Jacketed R.C. Columns Subjected to Combined Axial and Lateral Loads

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ABSTRACT

In this paper an experimental and numerical investigations were performed to study the performance of partially jacketed R.C. columns subjected to both axial and lateral loads. The current research also investigates the effect of the lateral load direction, with respect to jacket's direction during constant axial load, on the structural response of strengthened columns. The experimental study consists of seven square columns of 100 x 100 mm^2 cross-section dimensions and total length of 1000 mm. The columns were strengthened from different sides with 50 mm concrete jackets. The strengthened columns were tested under constant axial load with an increasing lateral force up to column failure. Columns capacities and modes of failure were illustrated and discussed. Going deep into the investigation, a finite element analysis was performed on the experimented columns. A satisfactory agreement was found when the experimental and numerical data were compared together. The ultimate lateral loads of the strengthened columns from two, three, and four sides increased up to 5.83, 8.43, and 11.03 times the lateral load capacity of control columns, respectively. The study also concluded that the loading direction has a significant effect on column lateral capacity.

Keywords: Lateral loads, Concrete jacket, RC columns, Strengthening, Partial strengthening.

1. INTRODUCTION

Strengthening of edge or corner columns from all sides of the perimeter may be not applicable due to neighboring buildings or to reserve the building's facade from distortion. Therefore, partial strengthening from two or three sides could be used. A group of research work have been carried out to investigate the efficiency of full jacket strengthening under the effect of combined loads [1]. K. M. Mahmoud et al. [2] studied experimentally and theoretically the concrete jacketing, the steel cage and the factors affecting steel cage column capacity. From their results, some modifications were implemented on jackets to improve the efficiency of them. H. Rodrigues et al. [3] wrote a book contains case studies of full strengthening columns and explains the various methods of repairing and strengthening. Ahmed et al. [4] studied the effectiveness of jacketed RC columns after cracking investigated at the models' accuracy while considering the influence of the column's size, the quantity of reinforcement, and cracked and uncracked columns. In order for the strengthened columns to reach the safety limit, they concluded that a reduction coefficient with values of 94% and 76% for the strengthened columns before and after cracking, respectively, must be used. Additionally, compared to strengthening before crack, strengthening after cracking decreases the column's ultimate load capacity by 15.7%, 14.1%, and 13.5% for square, rectangular, and circular columns, respectively. Arafa et al. [5] illustrated the performance of restoration of deteriorated reinforced concrete columns using thin concrete jacketing by increasing the contact between the interfaces of the core and jacket and found that using shear studs were the most effective among all used techniques. While, Bakhsh, Ortega, Krainskyi, and et al. [6-8] found that the behavior of repaired columns is unaffected by using bonding agents. Eduardo et al. [9] found that using sandblasting is the best surface treatment between the core and jacket. Dritsos [10] illustrated that the resistance capacity factor, Kr, rises with increasing interface roughness, falling axial load, and rising cross-sectional area ratio of the original concrete to the jacket. It is obvious that using steel connectors at the interface is necessary when adding more concrete layers due to the benefits of the bend down bars. Zaiter and Tze [11] studied the partially strengthening of columns according to jacket's height and found that the column's stiffness was enhanced by increasing the jacket height and strengthening, and Over the jacket, a short column shear failure was caused by the stiffness irregularity. Thermou et al. [12] studied of the behavior of jacketed structural elements. Reinforced concrete jacketing was conducted to analyze the behavior under reversed cyclic stress. To evaluate the bending response to cyclic loading, a computing approach that takes slip at the interfaces into consideration is also developed. Previous studies disregard the strengthening of edge and corner columns and instead place more emphasis on strengthened columns by full jacket. The authors have previously investigated the performance of RC columns strengthened by RC jackets from two, three, and four sides of the perimeter subjected to axial loads [13]. The study examined the effects of using various column and strengthening jacket interactions, including friction, dowels, and welding. According to the study, welding jacket stirrups to the existing column's stirrups is the most effective stirrup arrangement for partially jacketed columns.

There are a few research efforts on partially jacketed, either corner and edge, columns subjected to both axial and lateral loads. Moreover, it was noticed that there is a research gap should be filled in studying the effect of lateral load direction on the structural efficiency of the jacketed concrete columns.

2. EXPERIMENTAL WORK

2.1. Specimens Configurations

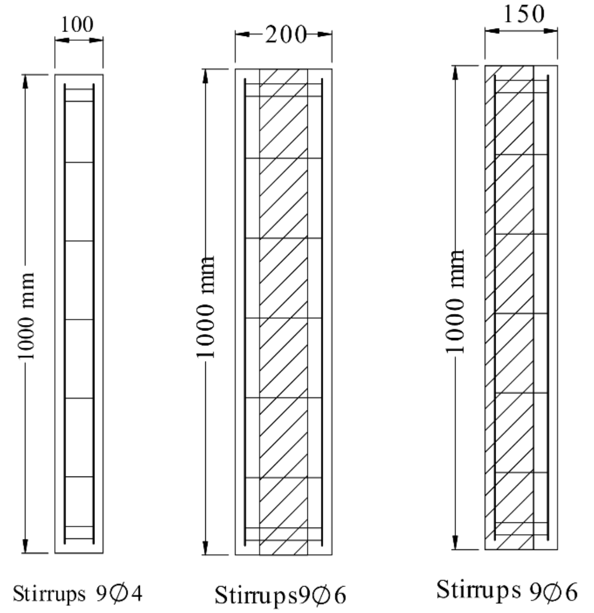
The experimental program consists of seven case studies: The first case is the reference column before strengthening, second case is full strengthened reinforced concrete column, cases 3-5 are strengthened reinforced concrete columns by concrete jackets from three sides, cases 6 and 7 are strengthened reinforced concrete columns by concrete jackets from two sides. Details of specimens are indicated in Fig. 1. Tables 1 and 2 describe the studied cases.

Table 1. Control column parameters

Column	Column dimensions	Main reinforcement	Stirrups	Remark
C0	100x100 mm	4Ø10	9Ø4	Control column

Table 2. Jacketed columns parameters

Specimen No.	Strengthened column dimensions (mm)	Jacket main reinfor-cement	Jacket stirrups	Remark.
CA	200x200	4Ø10	9Ø6	Full jacketed column
CC	200x150			Jacketed columns from three sides
CD				
CE				
CB	150x150	3Ø10		Jacketed columns from two sides
CBB				



(a) Control column elevation

(b) Strengthened columns elevations

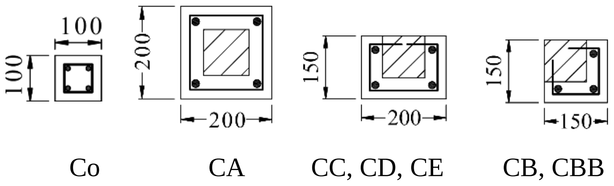


Figure 1: Specimens details; a) Control column b) Strengthened columns

2.2. Materials Properties

Concrete with strength 14 MPa was cast for control columns and 26 MPa for jackets. Concrete was cast using materials from the local market. Specimen preparation was done in a manner that was similar to that should be followed in the site. For control columns, OPC type 1 cement with a grade of 42.5 is used; for jackets, OPC type 1 cement with a grade of 52.5 is used.

Crushed dolomite is utilized as the coarse aggregate, while sand is used as the fine aggregate. In the mixing and curing process, potable water was used. High grade steel with an ultimate strength of 550 MPa and yield strength of 445 MPa was used for main longitudinal reinforcement for both the core and the jackets. Mild steel with ultimate and yield strength 390, 280 MPa, respectively, is used in the stirrups of the column and Mild steel with ultimate and yield strength 410, 320 MPa respectively is used in the jacket. Standard specifications were applied to test the materials' properties according to ASTM D638.

2.3. Specimens Preparation

A rotating mixer was used to mix the concrete components, then Concrete was poured into the formwork in a vertical direction and vibrated on the inside and outside. Cubes 150x150x150 mm were also cast to determine the compressive strength of the concrete. After pouring and according to ASTM number C31, the formwork was removed after two days and the specimens were cured in water for a week [14].

2.4. Strengthening Procedures of RC Jacket

28 days after casting, the specimens were ready for strengthening. The control column (C0) before strengthening as well as specimens (CA, CB, CBB, CC, CD, CE) of strengthened RC columns by using the concrete jackets from various directions were included in the research work. The surfaces of control columns were prepared by grinding. On the surfaces of the control column, there were loose crusts that were removed with a wire brush. To place the dowels, holes had to be drilled through the specimens' prepared surfaces. Dowel grout was used to fix the dowels. Due to the specifics of each specimen, the longitudinal reinforced steel and stirrups of the concrete jacket were inserted into the formwork and attached to the original column (core). Before putting the new concrete, the core's concrete surfaces were moist. To increase the cohesiveness of the old and new concrete, an epoxy-based bonding agent "kemapoxy 104 with bond strength 114kg/cm2 (ASTM C882) " was applied to the contact surfaces of the core and jacket. A vertical pour of concrete was prepared in the formwork, and it was then compacted. Additionally, 150x150x150 mm cubes were created to evaluate the concrete jacket's compressive strength. After the pour, the formwork was removed after two days, and the specimens were water-cured for a further week.

2.5. Instrumentation and Testing Procedure

The main objective of the test is to investigate the response of the strengthened columns subjected to both axial and bending moment. The bending moment could be generated either by frame action at column top or by applying lateral force considering column as a beam. Before testing, all specimens were instrumented as shown in Fig. 2. A load frame was used to apply lateral load on specimens and special preparation, to apply constant axial load on specimen, consisted from hydraulic piston and load cell to allow axial forces measurement. The columns were placed and adjusted between the heads of the loading machine as shown in Fig. 2. Columns were subjected to constant axial load and a gradually increasing lateral loads. The axial load value was chosen to represent service load of reference column before strengthening. The lateral displacements were measured using LDVT equipment. When the load reached a small amount of the maximum load measurement, tests were stopped.

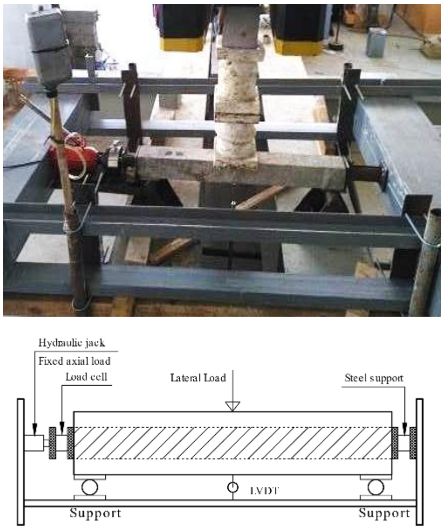


Figure 2: Loads frame and the system of loading

2.6. Loading Direction

All specimens subjected to axial load as a compression constant load. At the same time, specimens were subjected to lateral from various sides. Some specimens subjected to lateral load at the core column's side, some specimens subjected to lateral load at the jacket's side. These cases were investigated to simulate various loading conditions as shown in Fig. 3.

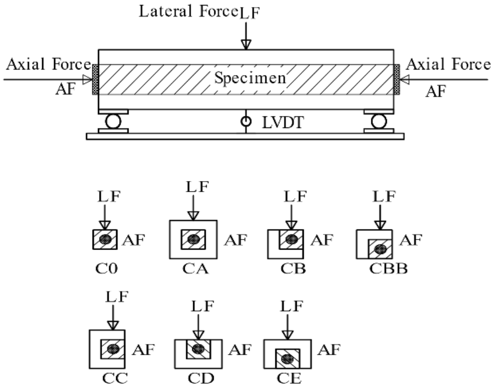


Figure 3: Load direction of each column specimen

3. THEORETICAL FORMULATION

In the current work, 3D finite element model was created using the finite element software ANSYS to model the geometric and material nonlinear behavior of control, fully jacketed, and partially jacketed columns. Fig. 4 presents 3D finite element models of the examined columns.

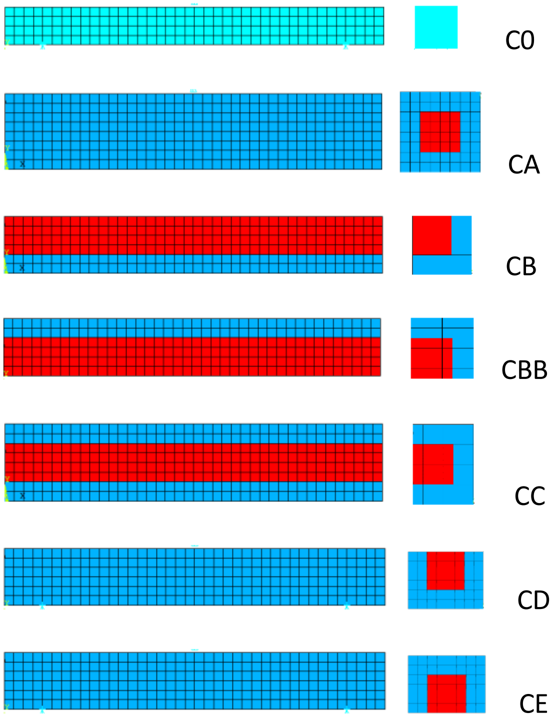


Figure 4: Models of columns specimens

3.1. Element Modeling

The solid element (SOLID65) is used to model concrete, the element has capability of cracking and crushing. Drager and Bruker failure criteria was used for concrete, the tensile and compressive strengths was used as inputs for this failure criteria. The reinforcement was modeled using beam element (BEAM188), this element is accepting bilinear material model as shown in Figure (6), full bond is assumed between steel and concrete, this is achieved by maintaining same nodes for concrete and reinforcement. The interface between core column and jacked is modeled using three springs in x, y and z directions using spring element (COMBIN39). The nonlinear spring element can be provided with nonlinear force-displacement relationship to simulate interface slip between the adjacent surfaces. Due to the uncertainty for the bond strength characteristics between column core and concrete jacket, the authors provided the interface spring elements with large stiffness and capacity to simulate in somehow minimal slipping and separation between the interface surfaces which is similar to full bond assumption.

3.2. Material modeling

The cores' and the jackets' concrete strengths were 14 and 26 MPa respectively. The multi-linear stress-strain curve shown in Fig. 5 was determined using the following equations to produce the compressive uniaxial stress-strain relationship for the concrete model:

$$f = E_c * \varepsilon / [1 + (\varepsilon / \varepsilon_c)^2] \qquad (1)$$

$$\varepsilon_c = f_c / E_c \qquad (2)$$

$$E_c = f_c / \varepsilon_c \qquad (3)$$

Where

f stress at strain ε

ε strain at stress f

ε_c strain at the ultimate compressive strength f_c

E_c concrete's modulus of elasticity

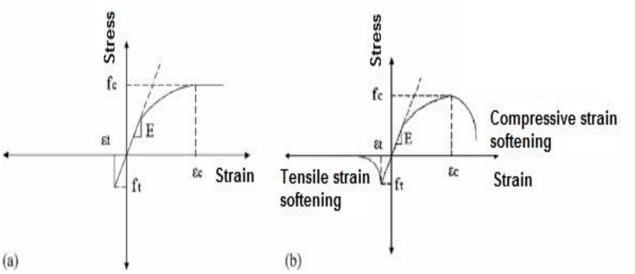


Figure 5: Concrete stress-strain curve
a) without softening branches in tension and compression
b) with softening branches in tension and compression

The concrete uniaxial tensile strength was 2.6 MPa in the finite element analysis. Because reinforcing bars are often long and slender, they are only capable of transmitting axial forces. Finite element models idealize the steel uniaxial stress-strain relationship as a bilinear curve to illustrate elastic-plastic behavior with strain hardening. It is thought that this relationship holds true for both compression and tension. The optimum stress-strain relationships for steel are shown in Figure 6.

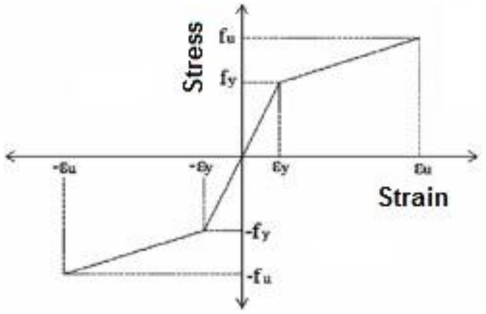


Figure 6: Stress against strain model for steel

4. RESULTS AND DISCUSSION

4.1. Failure Modes

Figures (7-13) illustrate the failure modes of the RC columns that were strengthened from two, three, and four sides compared to the reference columns. For the reference column (specimen C0) and full strengthened column (CA), the cracks started at the tension side in the middle of the column span, then the cracks increased in the middle area of tension side, followed by inclined cracks occurred at the two sides of the column near supporting locations. The failure occurred near the supports of the column, as shown in Figs. 7,8.

For all jacketed columns from two sides (CB, CBB) and three sides (CC, CD, CE), the cracks began at the tension side in the middle of the column span then the cracks increased at the middle area of tension side. Inclined cracks appeared at the two sides of the column near the supports then more inclined cracks parallel to the main diagonal crack was noticed. The number and locations of the inclined cracks were different for each group. The failure mode was flexure-shear mode with cracks starting near column supports as shown in Figs. 9-13.

Figure 7: Failure of (C0)

Figure 8: Failure of (CA)

Figure 9: Failure of (CC)

Figure 10: Failure of (CD)

Figure 11: Failure of (CE)

Figure 12: Failure of (CB)

Figure 13: Failure of (CBB)

Cracks patterns for all specimens from ANSYS were shown in fig. 14.

4.2. Load Capacity of Strengthened Columns

All specimens were subjected to a constant axial load of 45 kN for all columns, in addition to a gradually increasing lateral load. It is obvious that the lateral load capabilities of fully or partially strengthened columns were increased from the testing results of strengthened columns that are shown in Table 4. Column (CA) showed the best gained capacity by full strengthening. Columns (CC) and (CE) (external columns) showed the most efficient partial strengthening in terms of lateral load capacity. Corner columns that were partially strengthened (columns CB and CBB) gained good lateral load capacities as well.

The ultimate lateral load of the control column was 14.5 kN. The full strengthened column gained lateral load capacity as 403% of the control column. The lateral load capacity of the jacketed columns from three sides for specimens CC, CD, and CE is 843%, 536%, and 607% higher than that of the control column, respectively. Jacketed columns on both sides of specimens CB and CBB gained capacities against lateral loads equal to 583% and 428%, respectively, of the capacity of the control column.

Table 4. Jackets' experimental results

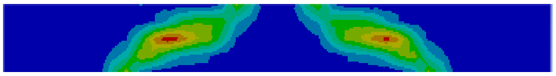
Type of strengthening	Specimen	Maximum experimental capacity due to lateral load (kN) under 45 kN constant axial load	capacity gain %
Reference column	CO	14.5	NA
Strengthened column from all sides	CA	174.5	1103
Strengthened column from three sides	CC	136.75	843
	CD	92.25	536
	CE	102.5	607
Strengthened column from two sides	CB	99	583
	CBB	76.5	428

Table 5 presents experimental and theoretical results about strengthened columns. It is clear that every ANSYS model produced a higher failure load than the results of the laboratory test; additionally, the average failure load ratio between ANSYS models and experimental data is 82%.

The difference between experimental and finite element results could be referred to:

a. The author assumed full bond interaction between reinforcing bars and concrete at FE software which appears in FE model's stiffness.

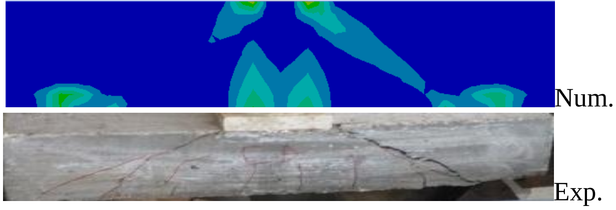
b. FE model is ideal at everything but in fact at the experiments, there are a lot of factors affecting on results such as compaction at casting, curing, the loading rate and method of loading, friction between core and jacket, stiffness of test rig, …etc. so at any theoretical equations, factor of safety should be applied.



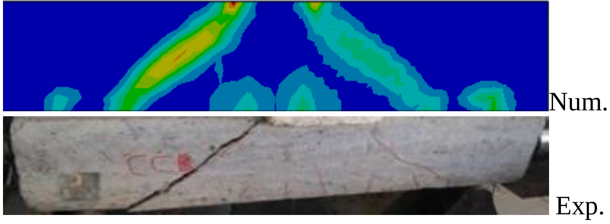
Numerical cracks pattern (Num.)

Experimental cracks pattern (Exp.)

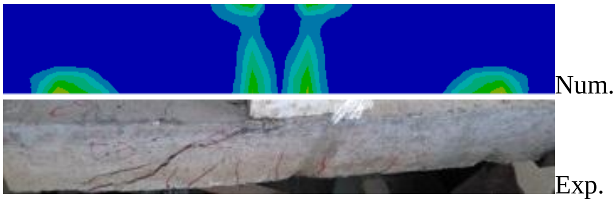
a) Specimen C0



b) Specimen CA

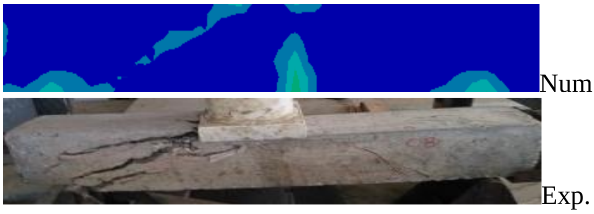


c) Specimen CC

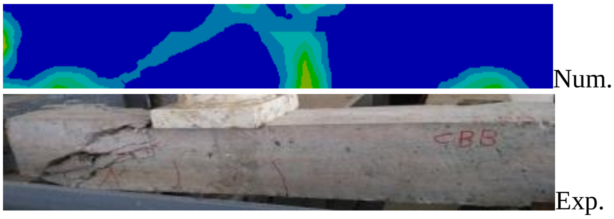


d) Specimen CD

e) Specimen CE



f) Specimen CB



g) Specimen CBB

Figure 14: Plastic strain distribution indicating crack locations due to ANSYS program

Table 5. Jackets' experimental and theoretical results

Type of strengthening	**Group**	**Laboratory capacity due to lateral load (kN) under constant axial load (45 kN)**	**Analytical capacity due to lateral load (kN) under constant axial load (45 kN)**	$\frac{P_{u\ \text{exprimental}}}{P_{u\ \text{analytical}}}$
Control column (core)	C0	14.5	20	0.73
Strengthened column from all sides	CA	174.5	184	0.95
Strengthened column from three sides	CC	136.75	183	0.75
	CD	92.25	106	0.87
	CE	102.5	135	0.76
Strengthened column from two sides	CB	99	112	0.88
	CBB	76.5	101	0.76

4.3. Lateral Deformations for the Tested Columns

According to experimental research, the control column's max. lateral displacement was 4.18 mm. The full jacketed column's max. lateral displacement was 2.79 mm. The jacketed columns' maximum lateral displacement from the three sides of columns CC, CD, and CE were 2.61, 2.40, and 3.45 mm, respectively. According to Fig. 15, the greatest lateral displacements of the jacketed columns from the two sides of specimens CB and CBB were 3.23 and 2.70 mm, respectively.

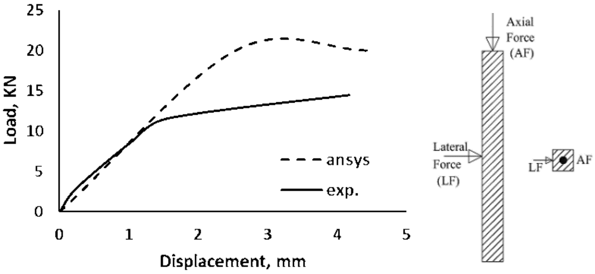


Figure 15a: Lateral Load–displacement curve for specimen C0

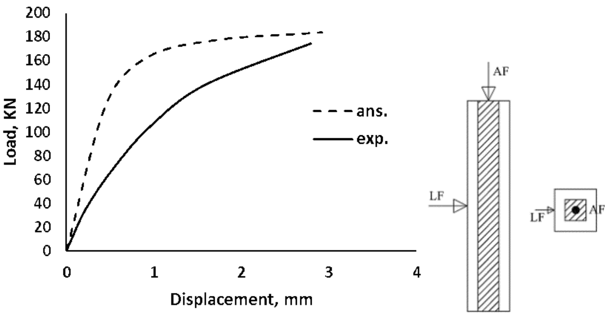


Figure 15b: Lateral Load–displacement curve for specimen CA

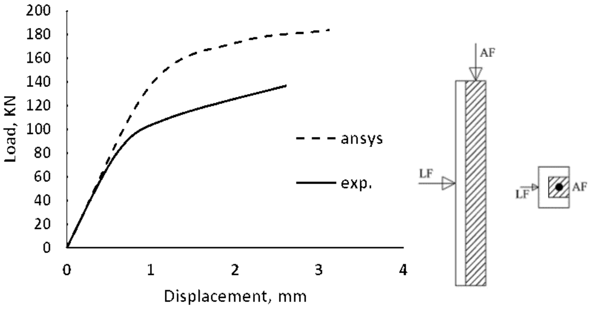


Figure 15c: Lateral Load–displacement curve for specimen CC

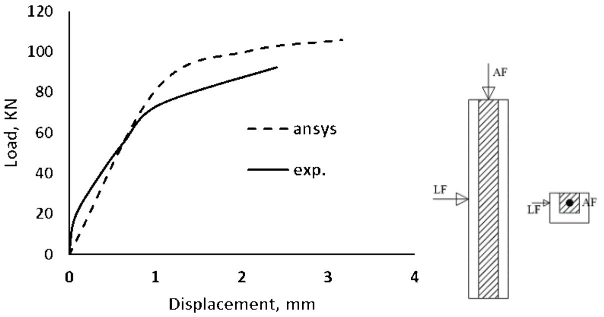


Figure 15d: Lateral Load–displacement curve for specimen CD

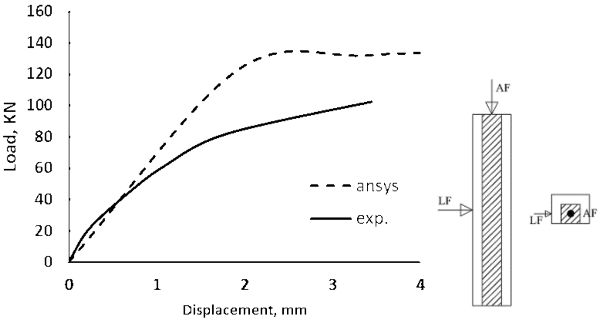


Figure 15e: Lateral Load–displacement curve for specimen CE

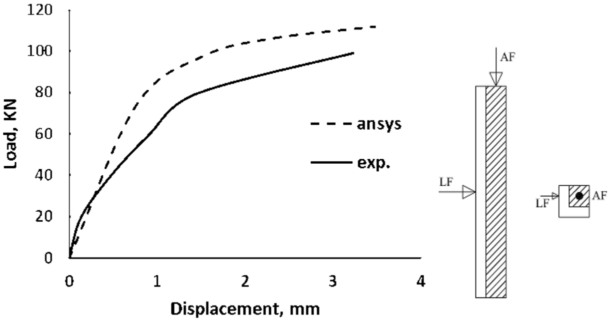


Figure 15f: Lateral Load–displacement curve for specimen CB

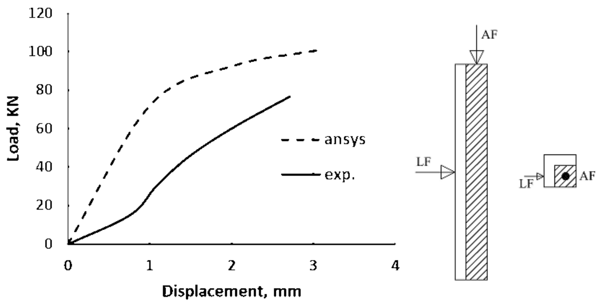


Figure 15g: Lateral Load–displacement curve for specimen CBB

Figure 15: Deformed shapes for specimens from ANSYS

4.4. Effect of Loading Direction

For two sides jacket, the maximum gained capacity was in the specimen (CB). This may be referred to the surface of jacketed column, which is subjected to the tensile stresses resulting from the bending moment that generated as a result of the effect of lateral loads, consists of the jacket concrete of the higher strength. While the minimum gained capacity was in the specimen (CBB), because the surface of jacketed column which subjected to tension forces consists of two types of concrete of different strengths (core and jacket). So, the resistance of the jacketed column against this force depends mainly on the shear friction between the surfaces of the core and jacket. It was noticed that the position of the constant axial load on the core does not have a significant effect on the resistance of the jacketed column to the lateral loads, due to the lack of symmetry in the section of the strengthened column.

For three sides jacket, it was noticed that the position of the constant axial force on the core affects directly on the resistance of the strengthened column against lateral loads due to the symmetry in the jacketed column's section, specimen (CC). Whereas, if the position of the core is at the bottom, specimen (CE), this led to an increase in the resistance of the jacketed column, as the axial constant compressive force reduces the effect of the tensile force resulting from the bending moment generated as a result of the lateral loads. In the case that the position of the core is at the top, specimen (CD), the resistance of the jacketed column decreases as the constant axial compression force is added to the value of the compression force resulting from the bending moment generated as a result of the lateral loads.

4.5. Stiffness and Ductility

The concrete jacket's major function is to decrease the lateral deformation of the concrete section, which will keep it confined. The strengthened specimens' initial stiffness is higher than that of the control column, as shown in Fig. 16, which also demonstrates a noticeable increase in the ductility of the strengthened columns. This shows that using concrete jackets increases ductility. In general, larger shortenings than those of the reference columns were achieved by all the strengthened columns.

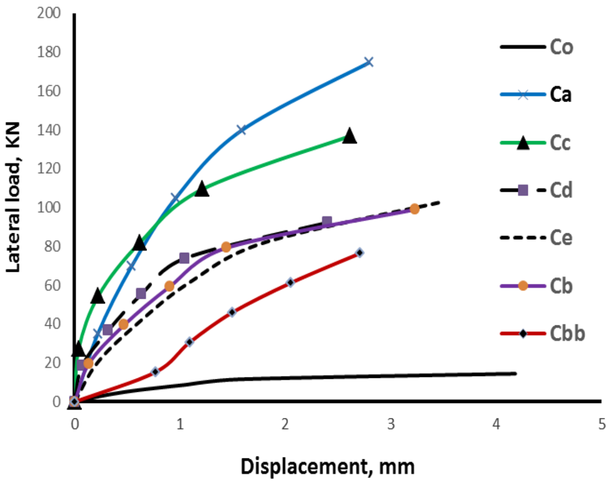


Figure 16: Lateral Load – displacement curves

5. CONCLUSIONS

Reinforced concrete columns strengthened using concrete jackets were experimentally studied in the conducted research. The columns were subjected to both axial and lateral loads. Based on the experimental and theoretical investigations conducted in this research, the following could be concluded:

- Increasing number of strengthening sides increases column gained capacity for columns subjected to both axial and lateral loadings. It was noticed that the gained capacity depends on loading direction with respect to jacket location.
- The lateral load capacity of columns strengthened from two sides increased by 583 % and 428% when column core being in compression and tension side, respectively. When the column core is located in tension side of bending moment, the lateral load capacity of strengthened column is less than columns with core in compression side.
- In the case of three sides jacket: columns with concrete jackets located in compression and tension fibers have the largest gained lateral capacity of 843% from control specimen. When column core is located in compression or tension fibers of the strengthened column, the gained lateral capacity was 536% and 607%, respectively. It could be concluded from this point, when the strengthening jacket can serve as an independent section from the column core against the compression and tension forces of lateral load's bending moment the column lateral capacity is increased.
- The results of the finite element models agree with an acceptable margin to the experimental results and it achieved an accuracy of 82 %.

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