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COMBINED EFFECT OF STIRRUP VOLUMETRIC RATIO WITH VERTICAL STEEL BARS ON THE BEHAVIOR OF R.C. COLUMNS UNDER AXIAL LOADS

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ABSTRACT:
Most international codes in the design of R.C. columns use only the vertical steel bar effect in determining ultimate load capacity. No combination effect of stirrup volumetric ratio with vertical steel bar has been taken in design of the R.C. column. The present study deals with an experimental and analytical analysis of the behavior of reinforced concrete columns with different percentage of vertical steel bars (μ) and stirrups volumetric ratio (ρ v). A total of sixteen R.C. columns with cross-section (250x250x1000) mm were tested and divided into four groups and tested until failure under axial load. Group 1 consisted of four columns with vertical steel bars with (μ) = 0.18% and stirrups (ρ v) = (0.27%, 0.48%, 0.75 and 1.09%). Group 2, 3 and 4 having same stirrups (ρ v) % with vertical bars (μ) = (0.32%, 0.50%, 0.75%) respectively. The test results showed that increasing in the percentage of vertical steel bars (μ) = (0.18% up to 0.73%) give an increase of the ultimate failure load up to 9.7%. Also, increasing percentage of stirrups volumetric ratio (ρ v) = (0.27% up to 1.09 %) gives an increase of the ultimate failure load up to 12.3% and enhancement in ductility of columns Thus, the increase in the ultimate load of columns due to stirrups effect should be taken into consideration in the design of R.C columns. The analytical analysis (FEA) models can be simulate the experimental behavior of tested columns and can be suitable to reduce time and cost.

KEYWORDS: Einforced Concrete Column, Ultimate Load Capacity, Finite Element, Axially Loaded, Vertical Bar, Stirrups.

التأثير المشترك لتغيير نسبة الكانات الأفقية مع الأسياخ الرأسية علي سلوك الأعمدة الخرسانية تحت تأثير القوي المحورية

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الملخص:
تدخل معظم الأكواد العالمية عند تصميم الأعمدة الخرسانية المسلحة تأثير الحديد الرأسي فقط عند حساب الحمل الأقصي ولا يدخل في تصميم الأعمدة التأثير المشترك بين حدود الكانات والحديد الرأسي.
هذه الدراسة تناولت عمل تجارب عملية ونظرية لدراسة تأثير تغيير نسب الحديد الرأسي والكانات الأفقية.وتم اختبار ستة عشر عمود خرساني بقطاع ٢٥* ٢٥* ١ متر وتم تقسيمهم إلي أربع مجموعات :المجموعة الأولي: تحتوي علي أربع

أعمدة بنسب حديد ٠.١٨% ونسب الكانات (١.٠٩% و٠.٧٥%و ٠.٤٨%و ٠.٢٧%) المجموعة الثانية والثالثة والرابعة : لهم نفس نسب حديد الكانات الأفقية مع تغيير في الحديد الرأسي بنسبة (٣٢%و ٥٠%و ٧٥ %) علي الترتيب. وأظهرت نتائج الاختبارات كالتالي :
زيادة نسبة الحديد الرأسي أدت إلي زيادة الحمل الأقصى للأعمدة حتي ٩.٧% . زيادة نسبة الكانات الأفقية أدت إلي زيادة الحمل الأقصى للأعمدة حتي ١٢.٣ % مع وجود تحسن ملحوظ في الممطولية. ولذلك فإن الزيادة في الحمل الأقصى نتيجة التغيير في نسب حديد الكانات يجب أن يؤخذ بعين الاعتبار في أعمال تصميم الأعمدة.

الكلمات المفتاحية: الأعمدة الخرسانيه المسلحة، سعة التحميل القصوي، العناصر المحدودة، القوي المحورية، الأسياخ الرأسية، الكانات .

1.1. INTRODUCTION

One of the most significant construction components in the building which play an important role are the columns. The columns are the main structural element needed to resist several loads. In spite of many researchers investigated the different parameters that affect columns ultimate capacity were dependent on a percentage of vertical steel bars, stirrup volumetric ratio, stirrup spacing and cross-section of columns. However, most international codes neglect the contribution of stirrups effect on the ultimate capacity of RC columns. The present study deals with an experimental and analytical analysis to determine the combined effect different vertical steel bars and stirrups volumetric ratio percentage on the behavior of RC columns. Cusson, D., & Paultre, P. (1994) [1] presented an experimental study to investigate number of variables that affect RC columns behavior, such as the transverse reinforcement ratio, the tie spacing and the longitudinal reinforcement ratio. Twenty-seven large-scale columns (235x235x1400mm) were tested under concentric loading. The test results showed that the transverse reinforcement ratio has the most important beneficial effect on the stress-strain behavior of concrete. In addition, the lateral confining pressure imposed on the concrete core is directly related to the amount of lateral reinforcement. When the ratio of the lateral reinforcement is increased about 50%, increases in strength is gained between 10 and 16% was obtained and enhancements in toughness is gained between 55 and 136%. However, when the lateral reinforcement ratio is increased from 2.0 to 2.8%, increases in strength is gained by 10% and a low enhancement in toughness 17% is obtained.

Li Bing, R. Park, and H. Tanaka (2001) [2] studied the effect of volumetric ratio and spacing of stirrups reinforcement on the behavior of RC columns. The spacing used started from 1.66 up to 5.83 diameter of longitudinal bar. The results showed that the behavior of R.C. become less ductile with increasing stirrups spacing.

Yehia A. Daou and EyadSeifeddinc (2001) [3] tested twenty-four square tied columns with cross section 12 x 12 cm and height 56 cm under concentric load to explore the influence of the diameter and spacing of stirrups on the strength and behavior of reinforced concrete columns. The diameter of stirrups used were 2, 4 and 6mm and stirrups spacing ranged between 6.25 cm and 25 cm. The experimental test results showed that full capacities of columns were achieved when the ratio of the stirrups area / (spacing x column dimension) $A_{sv}/(S_v.b) \cong 0.1\%$ and the volume of the stirrups / volume of concrete $V_{st} / V_c \cong 3\%$.

J. Němečekand at el (2004) [4] tested six reinforced concrete columns with a square cross section 50×150 mm and length1150 mm. Three different densities of stirrups were chosen. The test results showed that the ductility and ultimate load of the columns increases as the distance between stirrups becomes smaller.

Hong, K. N., et al. (2006) [5] presented an experimental study to investigate the behavior of high-strength concrete (HSC) columns with a tie volumetric ratio smaller than 2.0%.All columns were tested under concentric loading. The test variables included measurements of concrete compressive strength; measurements of tie yield strength; and the tie volumetric ratio. The results showed that the tie volumetric ratio is more effective and performed is better in case normal strength concrete.

Khaleek, A., et al. (2012) [6] studied the effect of different spacing of stirrups on the compressive strength of concrete columns. Cylindrical and square test columns having height to diameter (or width) ratio as 2 were used. The longitudinal distance between the stirrups at the middle part of the columns was ranged from 25 up to 150 mm and the distance of stirrups at the ends of columns was denser to prevent damage in this region. The test results showed that increasing ratio of volume of stirrups to the volume of core, the peak strength of concrete substantially increases.

Wasan Ismail Khalil and at el (2012) [7] investigated the effect of variation lateral confined stirrups spacing on the behavior square short concrete columns. The test results showed that with the increases in volumetric ratio (decrease spacing between stirrups) increase the confinement efficiency of concrete and decrease the lateral buckling of the longitudinal bars also, the volumetric ratios of longitudinal reinforcement is slightly affected the peak strength of columns. Radnic, J., et al (2013) [8] studied the impact of adding stirrups on both the compressive strength and ductility of axially loaded confined reinforced concrete columns having rectangular cross-section. The influence of varying concrete strengths and the difference of both stirrup bar diameters and spacing were studied on the column's ultimate capacity and ductility. It was shown that stirrups spacing greatly have more effect than the stirrup bar diameter .Columns with smaller stirrup spacing will gain greater strength capacity and greater ductility when the same quantity of transversal reinforcement per column length unit is used. Smaller stirrup bar diameter at smaller spacing is more favorable than greater stirrup bar diameter at greater spacing. Xiang Zeng (2016) [9] developed a Finite Element model to evaluate the behavior of concrete confined by stirrups in square RC columns. Xiang Zeng proposed a new uniaxial compression stress-strain relation of concrete considering the confinement effect of stirrups. Three volumetric stirrup ratios (0.8%, 1.6% and 2.39%) were used. The study showed that increasing the value of stirrup ratios has little effect on the strength of confined concrete, but it improves the ductility of the confined concrete.

Min Du and at el (2017) [10] tested twenty four stocky reinforced concrete columns confined by stirrups ratios from 1.26% up to 2.89%. The test results observed indicate that increasing the stirrup ratio could make the enhancement of the nominal strength and makes a less brittle failure behavior of RC columns.

Liu Jin and at el (2018) [11] tested twelve square reinforced concrete columns with two different stirrups ratios (i.e., 0% and 0.66%) under small-eccentric compressive loading. The specimens were divided into two series to explore the influences of stirrup confinement on the size effect of RC columns under the small eccentric compressive loading. Series one: without stirrups in the middle part of the RC columns and series two: having middle stirrups with the stirrup ratio of 0.66%.The test results showed that the RC columns without middle stirrups failed by compression-shear mode. While, the other RC columns with middle stirrups failed by localized at the middle part where a wedge-shaped pattern developed. In addition, the presence of stirrups improves the nominal strengths and makes the failure of columns less brittle.

M.K. Abd-Elhamed and M.E. Owida (2019) [12] studied the effect of stirrups densification at top and bottom of columns and along of height of columns on ultimate load capacity. The results showed that the failure load increases by increasing the percentage of stirrups densification height at top and bottom of column / total column height.

The present study deals with an experimental (EXP) and analytical analysis by Finite element (FEA) to investigate the combined effect of vertical steel bars and stirrups volumetric ratio percentage on the behavior of reinforcement concrete columns.

2.EXPERIMENTAL PROGRAM

2.1 Detailed model

A total of sixteen RC columns models have a typical cross section of 250 mm × 250 mm with the height of 1000 mm is shown in Figure 1. All specimens contained four vertical steel bars with a deferent diameter 6, 8, 10 and 12 mm corresponding to vertical steel bars percentage (μ) = (0.18, 0.32, 0.50and 0.73 %) respectively. The stirrups diameters are 6,8,10 and 12 corresponding to stirrups volumetric ratio percentage (ρ v) = (0.27, 0.48, 0.75 and 1.09 %) respectively .The concrete cover was 25 mm. The columns were divided into four groups as shown in Table [1].

2.2 COLUMNS CHARACTERISTICS

2.2.1 Used material

- Crushed stone has a maximum nominal size of (0.07-20.0 mm) was used as the coarse aggregate in the mix.
- Graded sand having sizes in the range of (0.075 - 0.3 mm) was used as the fine aggregate in the mix.
- Ordinary Portland cement was used.
- Clean fresh water is used for mixing and curing the specimens. Percentage of water cement ratio 50%.
- 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 N/mm2 at the age of 28 days as shown in Table [2]. The test specimens were casted in steel forms shown in Fig. [2].

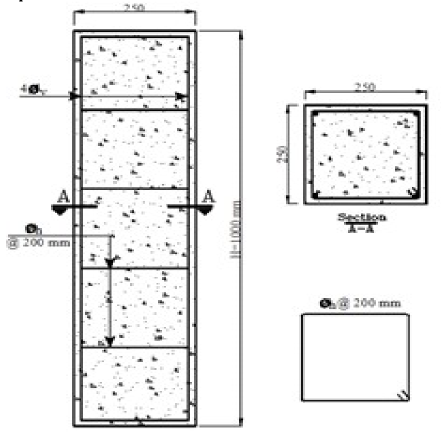

Fig. 1 Geometrical properties of column specimens

Table 1. Geometrical and properties of the column specimens

	Columns name	Columns dimension	Internal reinforcement bars diameter (mm)		Vertical steel bar (μ) " % "	Stirrups volumetric ratio (ρ v) %
			Vertical bar	Stirrups		
	C1-1	Control Column			0.18 %	0.27 %
Group 1	C1-1	250 x 250 x 1000 (mm)	4 Φ 6	5 Φ 6	0.18 %	0.27 %
	C1-2			5 Φ 8		0.48 %
	C1-3			5 Φ 10		0.75 %
	C1-4			5 Φ 12		1.09 %
Group 2	C2-1		4 Φ 8	5 Φ 6	0.32 %	0.27 %
	C2-2			5 Φ 8		0.48 %
	C2-3			5 Φ 10		0.75 %
	C2-4			5 Φ 12		1.09 %
Group 3	C31		4 Φ 10	5 Φ 6	0.50 %	0.27 %
	C32			5 Φ 8		0.48 %
	C33			5 Φ 10		0.75 %
	C34			5 Φ 12		1.09 %
Group 4	C41		4 Φ 12	5 Φ 6	0.73 %	0.27 %
	C52			5 Φ 8		0.48 %
	C43			5 Φ 10		0.75 %
	C44			5 Φ 12		1.09

Table 2. Concrete mix design

Constituents	Mix proportions by weight for m3
Crushed stone	1108 kg
Gradate sand	640 kg
Water	135 lit
Cement	270 kg
Water/cement ratio (w/c)	50 %

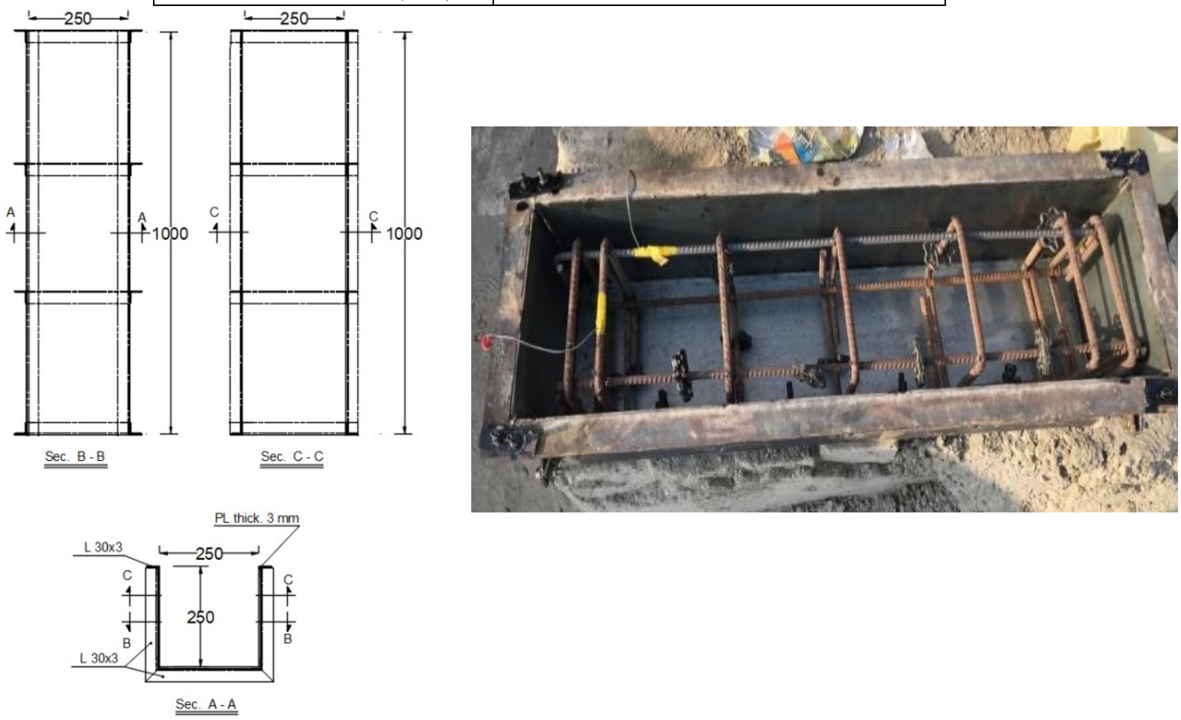

Fig. 2 Steel forms for casting

2.2.2 Strain gauges locations

- Tow strain gauges have been mounted on the vertical reinforcement bars and steel stirrups. One was mounted on the corner vertical steel bars, while another one was mounted on the steel stirrups as shown in Fig. [3].The strain gauges used were manufactured by TOKYO SOKKI KENKYUJO CO. LYD. The strain gauges type used was PFL-30-11-3L, having resistance of 120.4 ± 0.5nd % Ohms at 11ºC.The gauge factor ranges 2.13 ± 1.0%.

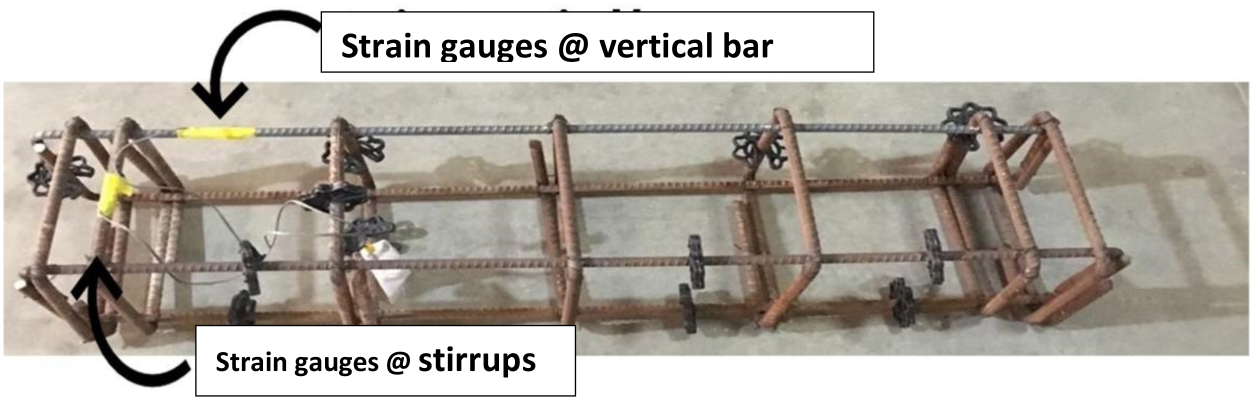

Fig. 3 Location of strain gauges

2.2.3 Casting of columns

- All specimens were casted in steel forms as shown in Fig. [٤] and a mechanical vibrator was used. Columns forms were removed and columns specimens were cured.

Fig.4 Casting of columns

2.3 Testing setup and procedure

All specimens were tested under static loads using the testing machine mounted on the material laboratory of Al-azhar University which has an ultimate compressive load capacity of 2000kN as shown in Fig. [٥]. the readings of loads and strains in reinforcement were recorded through the data acquisition system. The data acquisition system consisted of a laptop computer, a Keithley-500a data acquisition system and the lab tech notebook software package.

Fig. 5Test set up

2.4 Experimental test results

A comparison between the results has been done to investigate the effect of using different vertical steel bars diameter 6, 8, 10 and 12 mm with different stirrups diameters 6,8,10 and 12 mm.

2.4.1 Ultimate columns Capacity

Table (3) and Figure (٦) show the maximum failure loads and percentage column carrying capacity displayed as follows:

Gruop1: Increase in percentage column carrying capacity 11.8% from control column with increase in volumetric ratio (ρ v) from 0.27% up to 1.09% at vertical reinforcement ration (μ) 0.18%.
Gruop2: Increase in percentage column carrying capacity from 1.2% up to 12.5% with increase in volumetric ratio (ρ v) from 0.27% up to 1.09% at vertical reinforcement ration (μ) 0.32%.
Gruop3: Increase in percentage column carrying capacity from 3.2% up to 13.4% with increase in volumetric ratio (ρ v) from 0.27% up to 1.09% at vertical reinforcement ration (μ) 0.50%.
Gruop4: Increase in percentage column carrying capacity from 4.1% up to 13.3% with increase in volumetric ratio (ρ v) from 0.27% up to 1.09% at vertical reinforcement ration (μ) 0.73%.
It can be shown from previous experimental results the failure load increase by increasing vertical reinforcement ration (μ) up to 3.2%, while the failure load increase by increasing stirrups volumetric ratio (ρ v) up to 11.8%.

Table 3. Failure loads and percentage column carrying capacity from Experimental test (EXP)

	Columns name	Internal reinforcement bars diameter (mm)		Vertical steel bar (μ) %	Stirrup (ρ v) %	Ultimate load (EXP)KN	% Column carrying capacity(EXP)
		Ver. Bar	stirrups				
	C1-1	Control Column		0.18 %	0.27 %	1074.6	100.0%
Group 1	C1-1	4 Φ 6	5 Φ 6	0.18 %	0.27 %	1074.6	100.0%
	C1-2		5 Φ 8		0.48 %	1133	105.4%
	C1-3		5 Φ 10		0.75 %	1170	108.9%
	C1-4		5 Φ 12		1.09 %	1201.8	111.8%
Group 2	C2-1	4 Φ 8	5 Φ 6	0.32 %	0.27 %	1088	101.2%
	C2-2		5 Φ 8		0.48 %	1142	106.3%
	C2-3		5 Φ 10		0.75 %	1171.7	109.0%
	C2-4		5 Φ 12		1.09 %	1209	112.5%
Group 3	C31	4 Φ 10	5 Φ 6	0.50 %	0.27 %	1108.7	103.2%
	C32		5 Φ 8		0.48 %	1148	106.8%
	C33		5 Φ 10		0.75 %	1189.3	110.7%
	C34		5 Φ 12		1.09 %	1218.2	113.4%
Group 4	C41	4 Φ 12	5 Φ 6	0.73 %	0.27 %	1118.3	104.1%
	C52		5 Φ 8		0.48 %	1150.4	107.1%
	C43		5 Φ 10		0.75 %	1197.8	111.5%
	C44		5 Φ 12		1.09 %	1217	113.3%

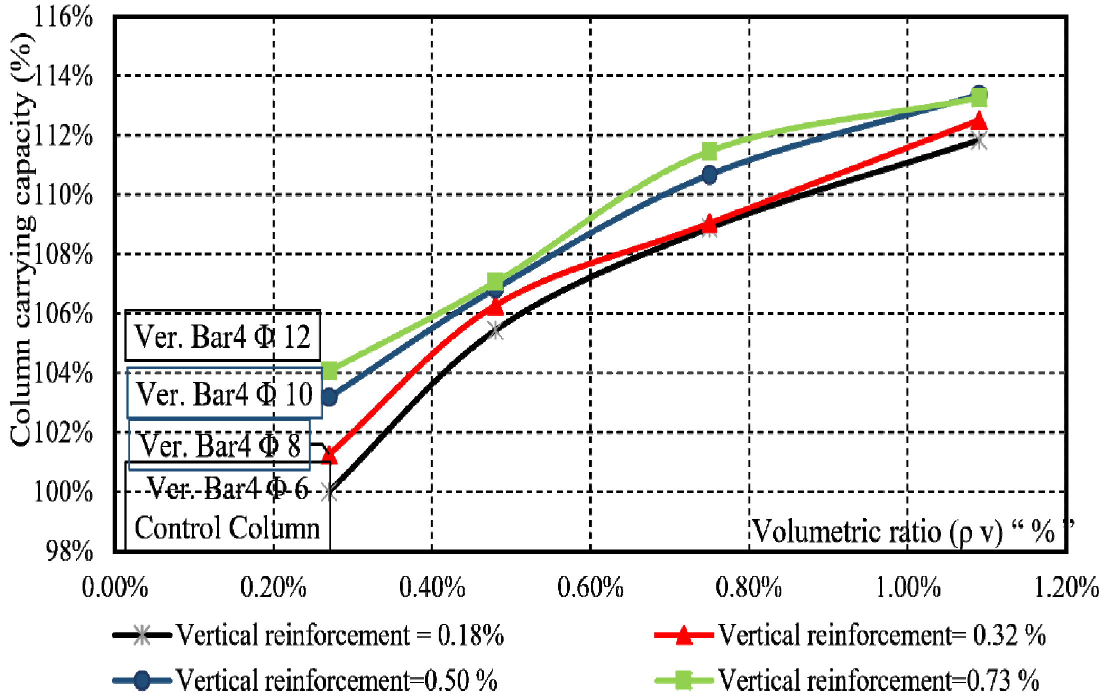

Fig. 6 Relationship between volumetric ratio (ρ v) and percentage of column carrying capacity (EXP) for different vertical reinforcement bars (μ)

2. 4. 2 Effect of the vertical reinforcement bars and stirrups on strain and ultimate capacity of RC columns (EXP)

Table (4) show the values of stresses and percentage loads in vertical bars and stirrups at ultimate loads by Experimental test. The compression forces in vertical bars were found to be ranging from (-1.39% up to -6.43%) of the ultimate failure load with increase in the vertical steel bars percentage from (0.18% up to 0.73%). Also, tension force in stirrups were found to be ranging from (2.27% up to 9.53%) with increase the volumetric ratio from (0.27% up to 1.09). Figure (7 up to 1٠) show increase in strain percentage with increase in volumetric ratio of stirrups (μ) more than increase in strain percentage with increase in vertical steel bars percentage (ρ v). Increasing in volumetric ratio of stirrups percentage has more effect on ultimate capacity of RC columns than increasing in the vertical steel bars percentage and ductility enhancement were obtained.

Table 4. Vertical bar and stirrups percentage loads from ultimate loads by Experimental test (EXP)

	Columns name	Internal reinforcement bar		Ver. bar (□) %	Stirrups (ρ v) %	Ultimate load (EXP) KN	Compression force		Tension force	
		Ver.	Stirrups				Ver. bar Stress N/mm	% ver. bar / ultimate loads	Stirrup stress N/mm	%Stirrups load / ultimate loads
Group 1	C1-1	4 Φ 6	5 Φ 6	0.18 %	0.27 %	1074.6	-629	-1.39%	822	2.27%
	C1-2		5 Φ 8		0.48 %	1133	-551	-1.16%	961	4.48%
	C1-3		5 Φ 10		0.75 %	1170	-747	-1.52%	1113	7.85%
	C1-4		5 Φ 12		1.09 %	1201.8	-770	-1.52%	753	7.44%
Group 2	C2-1	4 Φ 8	5 Φ 6	0.32 %	0.27 %	1088	-778	-3.02%	997	2.72%
	C2-2		5 Φ 8		0.48 %	1142	-804	-2.98%	1041	4.81%
	C2-3		5 Φ 10		0.75 %	1171.7	-802	-2.89%	601	4.23%
	C2-4		5 Φ 12		1.09 %	1209	-726	-2.54%	505	4.96%
Group 3	C31	4 Φ 10	5 Φ 6	0.50 %	0.27 %	1108.7	-750	-4.46%	620	1.66%
	C32		5 Φ 8		0.48 %	1148	-768	-4.42%	963	4.43%
	C33		5 Φ 10		0.75 %	1189.3	-875	-4.87%	640	4.45%
	C34		5 Φ 12		1.09 %	1218.2	-635	-3.44%	600	5.85%
Group 4	C41	4 Φ 12	5 Φ 6	0.73 %	0.27 %	1118.3	-520	-4.42%	749	1.99%
	C42		5 Φ 8		0.48 %	1150.4	-748	-6.18%	889	4.08%
	C43		5 Φ 10		0.75 %	1197.8	-811	-6.43%	876	6.03%
	C44		5 Φ 12		1.09 %	1217	-684	-5.34%	977	9.53%

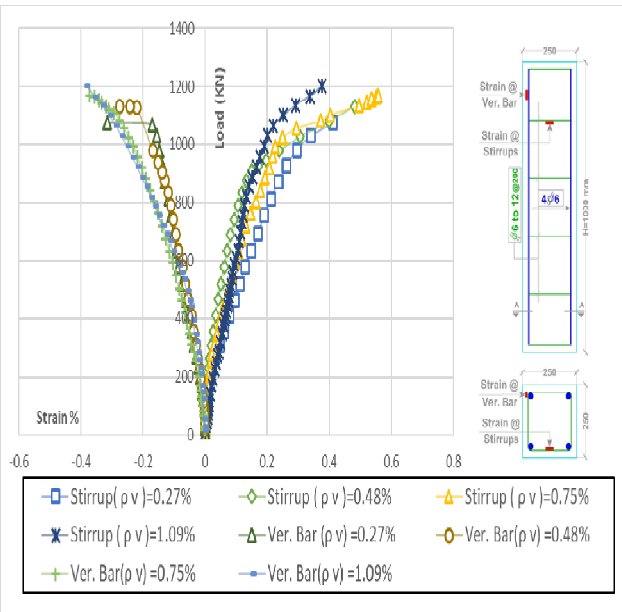

Fig. 7 Comparison between load and strain for group (1) EXP [(ρ v) from 0.27% up to 1.09% at vertical reinforcement ration (μ) 0.18%.]

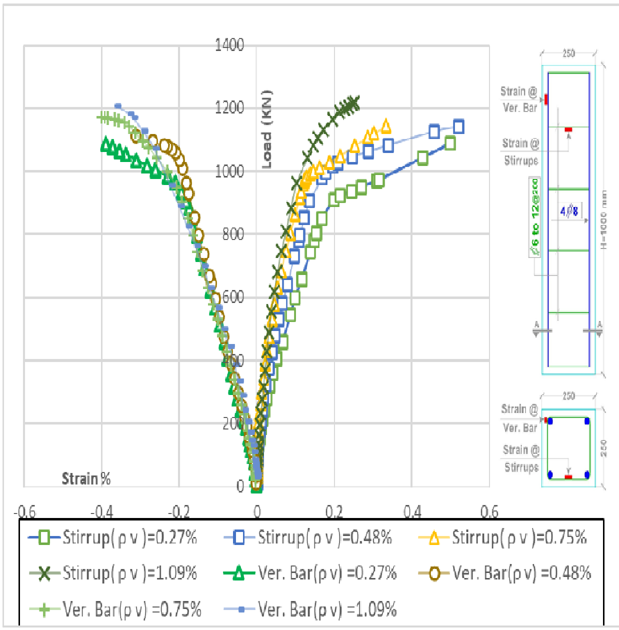

Fig.8 Comparison between load and strain for group (2) EXP [(ρ v) from 0.27% up to 1.09% at vertical reinforcement ration (μ) 0.32%.]

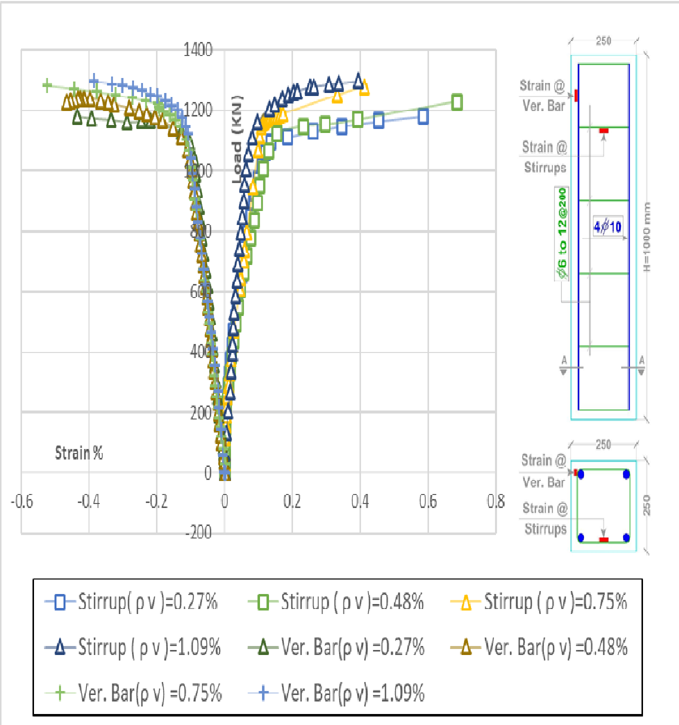

Fig. 9 Comparison between load and strain for group (3) EXP [(ρ v) from 0.27% up to 1.09% at vertical reinforcement ration (μ) 0.50%.]

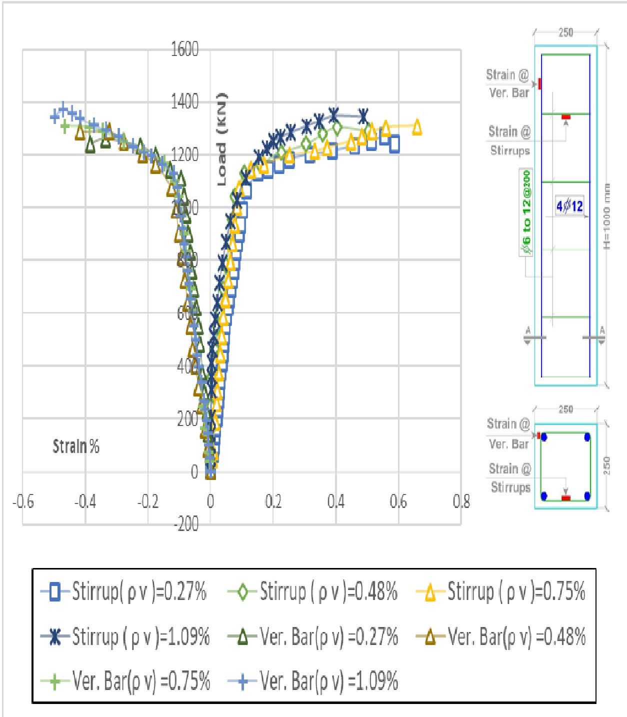

Fig. 10 Comparison between load and strain for group (4) EXP [(ρ v) from 0.27% up to 1.09% at vertical reinforcement ration (μ) 0.73%.]

3. Finite element analysis

The finite element package ANSYS 15.0 was used in order to simulate the obtained experimental testing results by introducing a numerical model. The tested columns in the experimental work were modeled to determine the failure loads and strains in each specimen. Comparison of results between experimental and finite element model (FEA) was carried out.

3.1 Defining element types, real constants, and material properties

The finite element procedure implemented in this study is developed using the available element types from ANSYS 15.0 element library as illustrated in Table [5]

Table 5. Element types used in ANSYS 15.0 Program

Material type	ANSYS element type	**Real constant**	**Material numbers**	**Item**	**Item Constant**
Concrete	Solid 65	1	1	--------	Solid 65
Vertical bars &stirrups	Link 180	2	2	Cross-sectional area (Φ 6)	28.27 (mm^2)
		3	2	Cross-sectional area (Φ 8)	50.27 (mm^2)
		4	2	Cross-sectional area (Φ 10)	78.5 (mm^2)
		5	2	Cross-sectional area (Φ 12)	113.1 (mm^2)
loading plate	Solid 45	-------	3	--------	---------

3.2 Defining concrete Properties

The Young's modulus for concrete was taken 19677 (N/mm2) and Poisson's ratio was assumed to be (0.2). Additional concrete material data needed for (SOLID 65) were the shear transfer coefficients, tensile stresses, and compressive stresses. Typical shear transfer coefficients ranges were taken from 0.0 to1.0, with 0.0 representing a smooth crack (complete loss of shear transfer) and 1.0 representing a rough crack (no loss of shear transfer). The stress- strain curve was defined for concrete element in "ANSYS" program with f cu= 20 N/mm2 as shown in Figure [11].

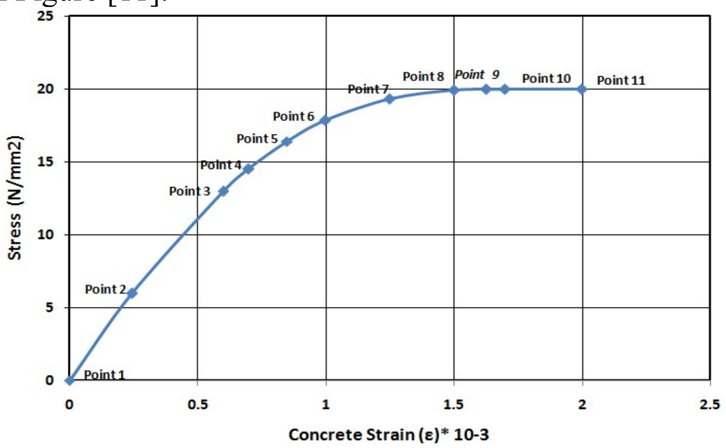

Fig. 11 Concrete stress strain curve (f cu=20 N/mm2)

3.3 Defining Of Internal Steel Reinforcement

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 = 400 (N/mm2). The Young's modulus for reinforcement was taken 2.0 x 105 (N/mm2) 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 Figure [12].

3.4 Defining Of Steel Loading Plate

The loading plate is modeled using (SOLID45) element type. The Young's modulus for internal steel was taken 2.1 x 105 N/mm2 and Poisson's ratio was assumed to be (0.3).

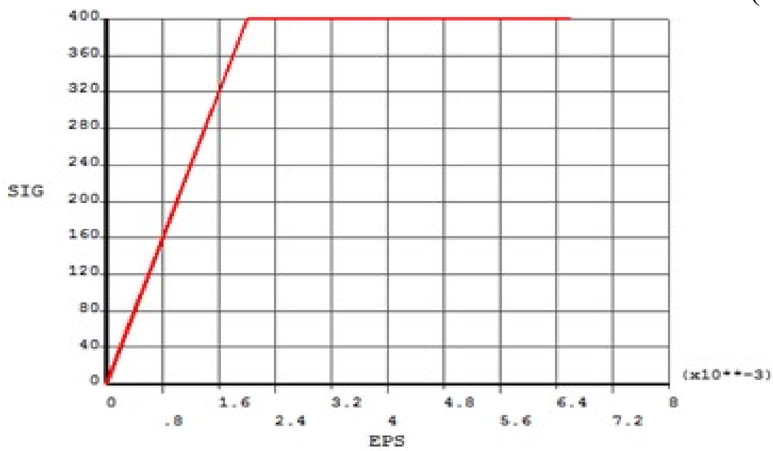

Fig 12. Idealized stress-strain for reinforcing steel bars

3.5 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 illustrated in Figure [13]. Axial load is performed on the top of column specimen as axial pressure over the top surface of the column model in (FEA) using "ANSYS15.0" program. A load step option modifier is performed to simulate the axial pressure on the top of column specimen. The incremental of loading is considered with performing the load step option of simulating axial load on column specimen. The number of load steps is performed according to the actual load steps applied during the experimental test and depend on the user's definition.

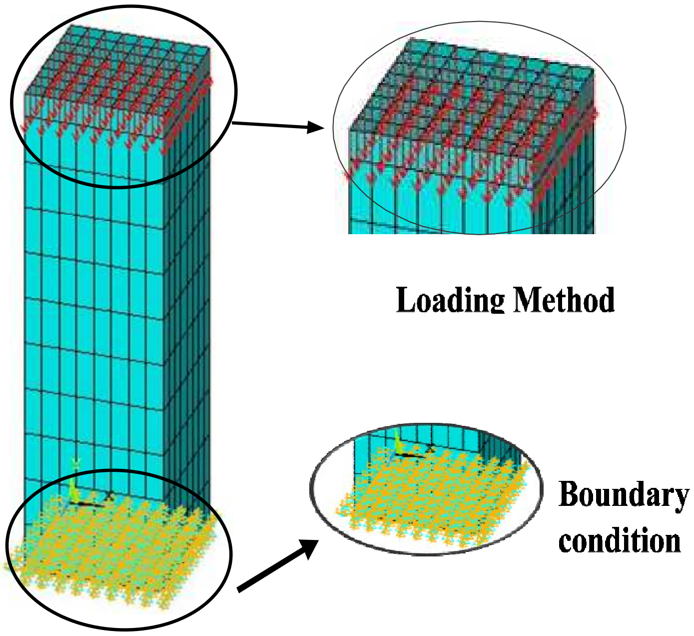

Fig.13 Boundary condition and loading of column specimen

4. NALYTICAL RESULTS

4.1 Ultimate load obtained from FEM analysis

Table (6) and Figure (14) show the maximum failure loads obtained from FEM analysis and percentage column carrying capacity displayed as follows:

Group 1: Increase in percentage column carrying capacity 12.3% from control column with increase in volumetric ratio (ρ v) from 0.27% up to 1.09% at vertical reinforcement ration (μ) 0.18%.

Group 2: Increase in percentage column carrying capacity from 1.0% up to 13.6% with increase in volumetric ratio (ρ v) from 0.27% up to 1.09% at vertical reinforcement ration (μ) 0.32%.

Group 3: Increase in percentage column carrying capacity from 4.0% up to 14.3% with increase in volumetric ratio (ρ v) from 0.27% up to 1.09% at vertical reinforcement ration (μ) 0.50%.

Group 4: Increase in percentage column carrying capacity from 9.7% up to 18.6% with increase in volumetric ratio (ρ v) from 0.27% up to 1.09% at vertical reinforcement ration (μ) 0.73%.

It can be shown from previous FEM analysis the failure load increase by increasing vertical reinforcement ration (μ) up to 6.9%, while the failure load increase by increasing stirrups volumetric ratio (ρ v) up to 12.3%.

Table 6. Failure loads and percentage column carrying capacity from analytical results (FEM)

	Columns name	Internal reinforcement bars diameter (mm)		Vertical steel bar (μ) %	Stirrup (ρ v) %	Ultimate load (EXP) KN	% Column carrying capacity (EXP)
		Vertical	Stirrups				
	C1-1	Control Column		0.18 %	0.27 %	1135	100.0%
Group 1	C1-1	4 Φ 6	5 Φ 6	0.18 %	0.27 %	1135	100.0%
	C1-2		5 Φ 8		0.48 %	1205	106.2%
	C1-3		5 Φ 10		0.75 %	1236	109.0%
	C1-4		5 Φ 12		1.09 %	1254	112.3%
Group 2	C2-1	4 Φ 8	5 Φ 6	0.32 %	0.27 %	1146	101.0%
	C2-2		5 Φ 8		0.48 %	1184	104.3%
	C2-3		5 Φ 10		0.75 %	1227	108.1%
	C2-4		5 Φ 12		1.09 %	1289	113.6%
Group 3	C31	4 Φ 10	5 Φ 6	0.50 %	0.27 %	1180	104.0%
	C32		5 Φ 8		0.48 %	1229	108.3%
	C33		5 Φ 10		0.75 %	1281	112.9%
	C34		5 Φ 12		1.09 %	1296	114.3%
Group 4	C41	4 Φ 12	5 Φ 6	0.73 %	0.27 %	1244	109.7%
	C52		5 Φ 8		0.48 %	1289	113.6%
	C43		5 Φ 10		0.75 %	1309	115.4%
	C44		5 Φ 12		1.09 %	1345	118.6%

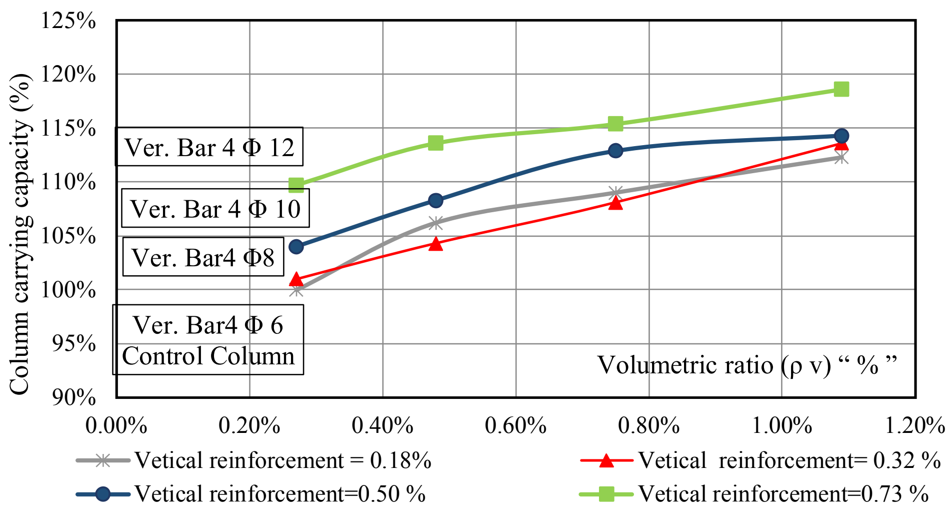

Fig. 14 Relationship between Volumetric ratio and percentage of column carrying capacity (FEM) for different vertical reinforcement bars (μ)

4.2 Effect of the vertical reinforcement bars and stirrups on strain and ultimate capacity of RC columns (FEM)

Table (7) show the values of stresses and percentage loads in vertical bars and stirrups by analytical results (FEM). The compression forces in vertical bar were found to be ranging from (-1.44% up to -7.03%) of the ultimate failure with increase the vertical bar percentage from (0.18% up to 0.73%) load. Also, tension force in stirrups were found to be ranging from (2.36% up to 8.62%) with increase in the volumetric ratio from (0.27% up to 1.09). Figures (15 up to 18) show increase in strain percentage with increase in volumetric ratio of stirrups (μ) more than increase in strain percentage with increase in vertical steel bars percentage (ρ v). Increasing in volumetric ratio of stirrups percentage has more effect on ultimate capacity of RC columns than increasing in the vertical steel bars percentage and ductility enhancement were obtained.

The results form (FEM) showed the same trend and behavior of the (EXP) results as well fair agreement were obtained.

Table 7. Percentage loads of vertical bar and stirrups from ultimate loads by analytical results (FEM)

							Compression force		Tension force	
	Columns name	Internal reinforcement diameter (mm)		Vertical Bar (□) %	Stirrups (ρ v) %	Ultimate load (FEM) KN	Vertical Bar Stress N/mm	% vertical Bar / ultimate loads	Stirrup stress N/mm	% Stirrups load / ultimate loads
		Vertical	Stirrups							
Group 1	C1-1	4 Φ 6	5 Φ 6	0.18 %	0.27 %	1134.45	-690	-1.44%	900	2.36%
	C1-2		5 Φ 8		0.48 %	1205	-649	-1.28%	1135	4.97%
	C1-3		5 Φ 10		0.75 %	1236.63	-865	-1.66%	1293	8.62%
	C1-4		5 Φ 12		1.09 %	1307.9	-965	-1.75%	908	8.24%
Group 2	C2-1	4 Φ 8	5 Φ 6	0.32 %	0.27 %	1146.02	-881	-3.25%	1052	2.73%
	C2-2		5 Φ 8		0.48 %	1183.7	-1084	-3.87%	1209	5.39%
	C2-3		5 Φ 10		0.75 %	1226.8	-1028	-3.54%	891	5.99%
	C2-4		5 Φ 12		1.09 %	1288.9	-837	-2.74%	646	5.95%
Group 3	C31	4 Φ 10	5 Φ 6	0.50 %	0.27 %	1180.3	-871	-4.87%	1170	2.94%
	C32		5 Φ 8		0.48 %	1229	-933	-5.01%	1372	5.89%
	C33		5 Φ 10		0.75 %	1280.68	-1046	-5.39%	826	5.32%
	C34		5 Φ 12		1.09 %	1296.445	-771	-3.92%	787	7.21%
Grou	C41	4 Φ 12	5 Φ 6	0.73 %	0.27 %	1244	-766	-5.85%	1175	2.80%
	C52		5 Φ 8		0.48 %	1288.9	-832	-6.13%	1007	4.12%
	C43		5 Φ 10		0.75 %	1309.47	-930	-6.75%	1318	8.30%
	C44		5 Φ 12		1.09 %	1345	-995	-7.03%	977	8.62%

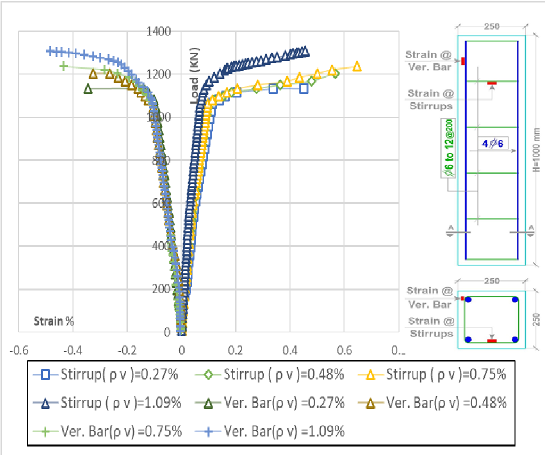

Fig. 15 Comparison between load and strain for group (1) FEM [(ρ v) from 0.27% up to 1.09% at vertical reinforcement ration (μ) 0.18%.]

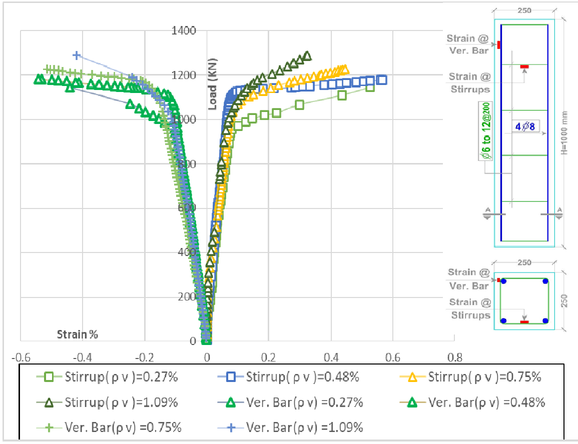

Fig. 16 Comparison between load and strain for group (2) FEM [(ρ v) from 0.27% up to 1.09% at vertical reinforcement ration (μ) 0.32%.]

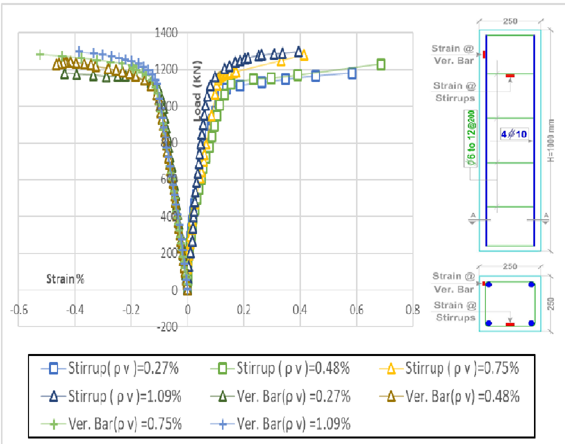

Fig.17 Comparison between load and strain for group (3) FEM [(ρ v) from 0.27% up to 1.09% at vertical reinforcement ration (μ) =0.50%.]

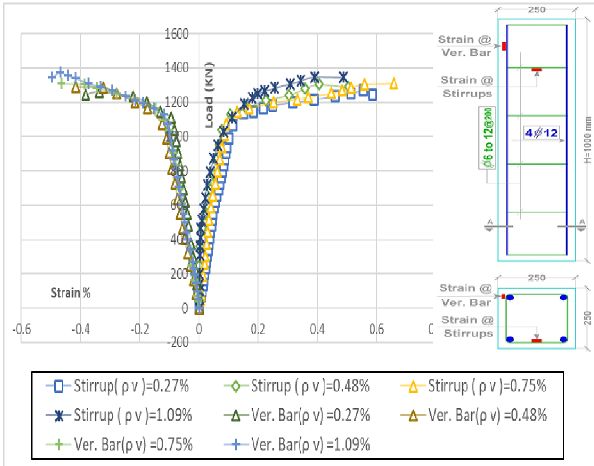

Fig. 18Comparison between load and strain for group (4) FEM [(ρ v) from 0.27% up to 1.09% at vertical reinforcement ration (μ) 0.73%.]

From the experimental results (EXP) and analytical results (FEM) the percentage of strains in vertical bars and stirrups are explained as follows:
Figures (19 up to 22) show the relationship between loads and percentage of strain from (EXP) and (FEM) results for columns at (μ) = 0.18% and (ρ v) = (0.27%, 0.48%, 0.75% and 1.09%)
Figures (23 up to 26) show the relationship between loads and percentage of strain from (EXP) and (FEM) results for columns at (μ) = 0.32% and (ρ v) = (0.27%, 0.48%, 0.75% and 1.09%)
Figures (27 up to 30) show the relationship between loads and percentage of strain from (EXP) and (FEM) results for columns at (μ) = 0.50% and (ρ v) = (0.27%, 0.48%, 0.75% and 1.09%)
Figures (31 up to 34) show the relationship between loads and percentage of strain from (EXP) and (FEM) results for columns at (μ) = 0.50% and (ρ v) = (0.27%, 0.48%, 0.75% and 1.09%)
It can be showed from figures (19 to 34) that the obtained percentage of strain from (FEM) has the almost same trend and behavior of (EXP), while the strain values in (FEM) showed an increase in strain values than (EXP). Also it can be shown the strain values increase by increasing vertical reinforcement ratio (μ) and stirrups volumetric ratio (ρ v). However, fair agreement has been obtained between experimental results and analytical results.

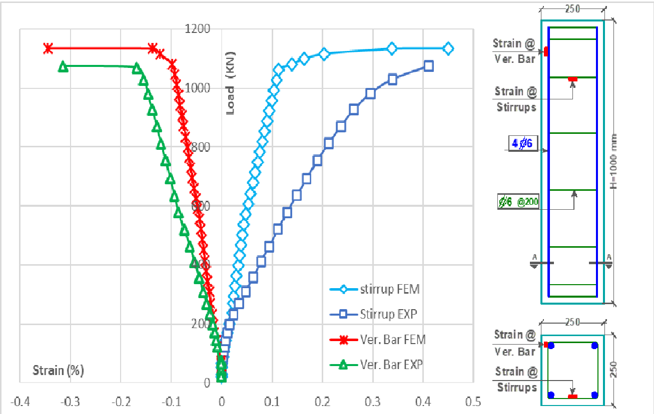

Fig. 19 Relationship between loads and strain from (EXP) and (FEM) results for columns (C11) at (μ) = 0.18% and (ρ v) =0.27%

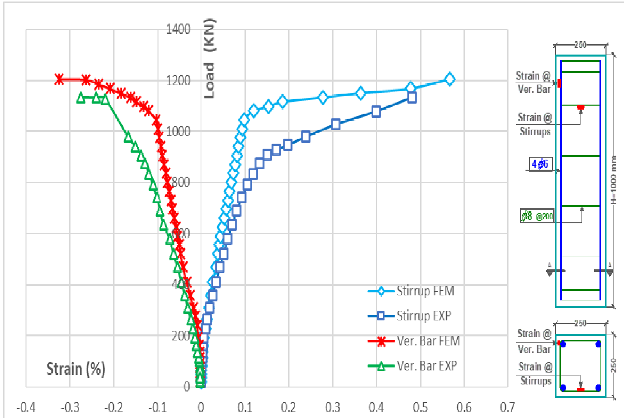

Fig. 20 Relationship between loads and strain from (EXP) and (FEM) results for columns (C12) at (μ) = 0.18% and (ρ v) =0.48%

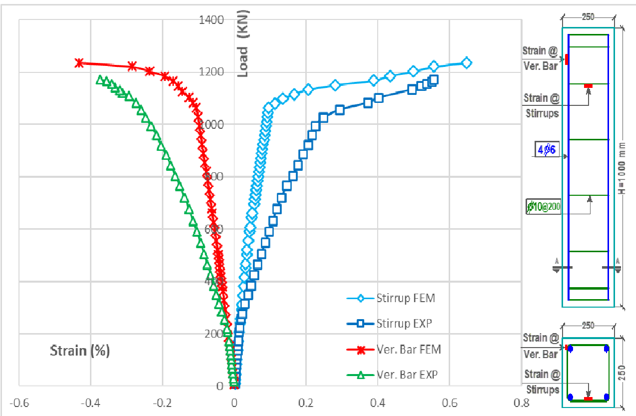

Fig. 21 Relationship between loads and strain from (EXP) and (FEM) results for columns (C13) at (μ) = 0.18% and (ρ v) =0.٧٥%

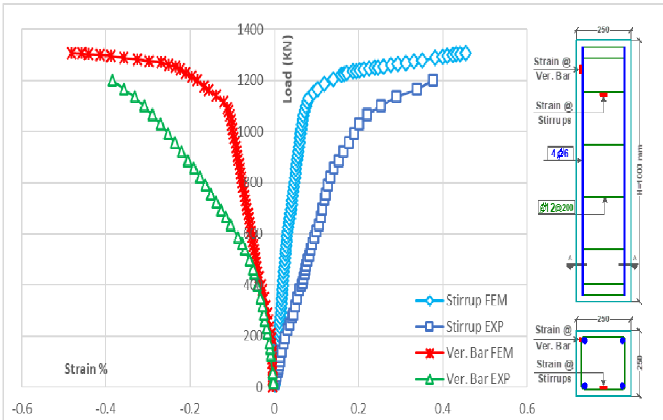

Fig. 22 Relationship between loads and strain from (EXP) and (FEM) results for columns (C14) at (μ) = 0.18% and (ρ v) =١.09%

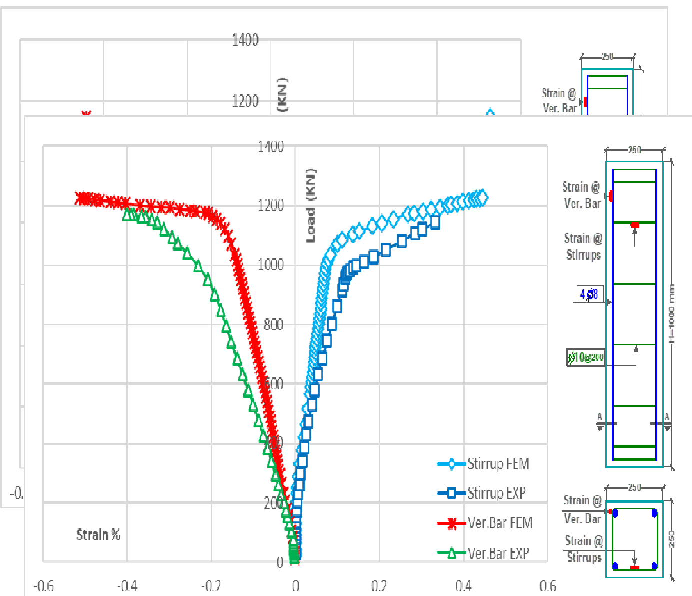

Fig. 25 Relationship between loads and strain from (EXP) and (FEM) results for columns (C23) at (μ) = 0.32% and (ρ v) =0.75%

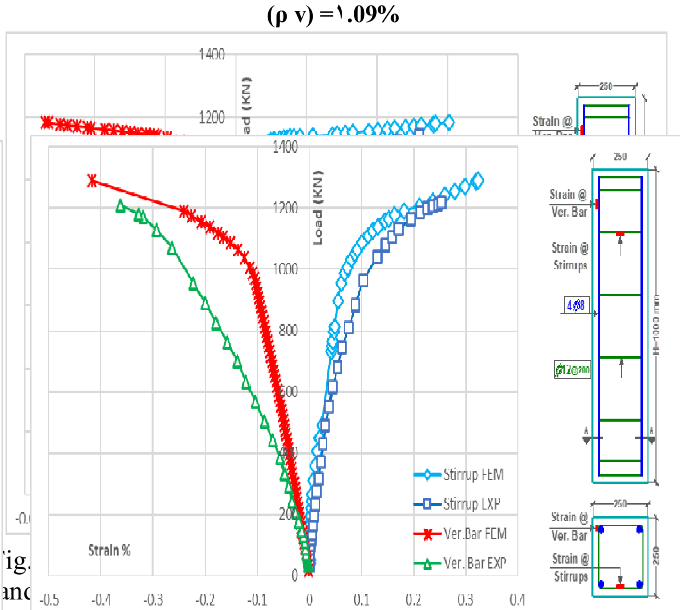

Fig. 26 Relationship between loads and strain from (EXP) and (FEM) results for columns (C24) at (μ) = 0.32% and (ρ v) =1.09 %

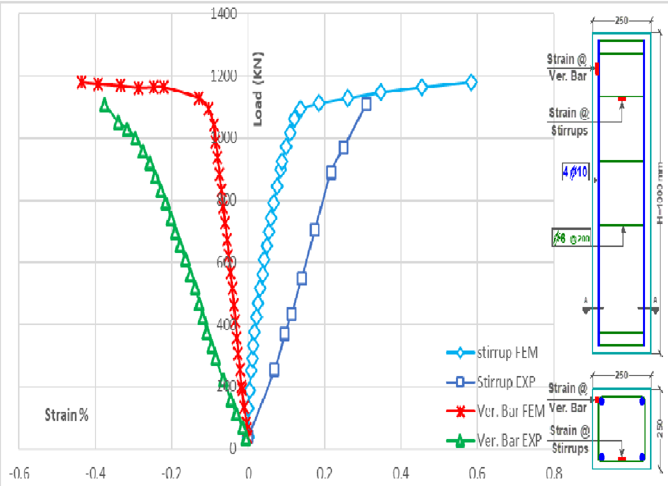

Fig. 27 Relationship between loads and strain from (EXP) and (FEM) results for columns (C٣١) at (μ) = 0.50% and (ρ v) =0.27 %

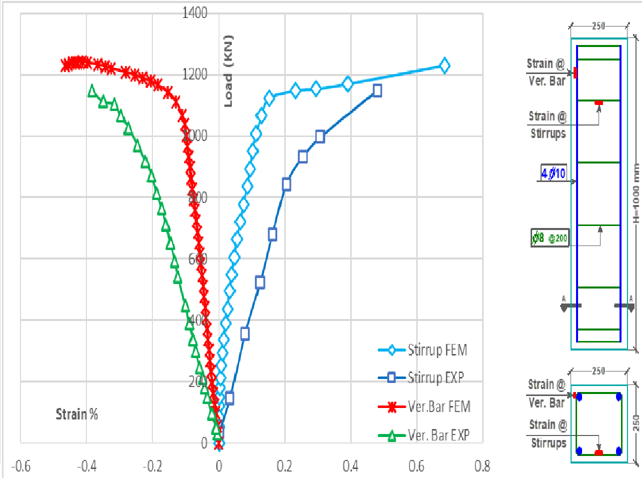

Fig. 28 Relationship between loads and strain from (EXP) and (FEM) results for columns (C٣2) at (μ) = 0.50% and (ρ v) =0.48 %

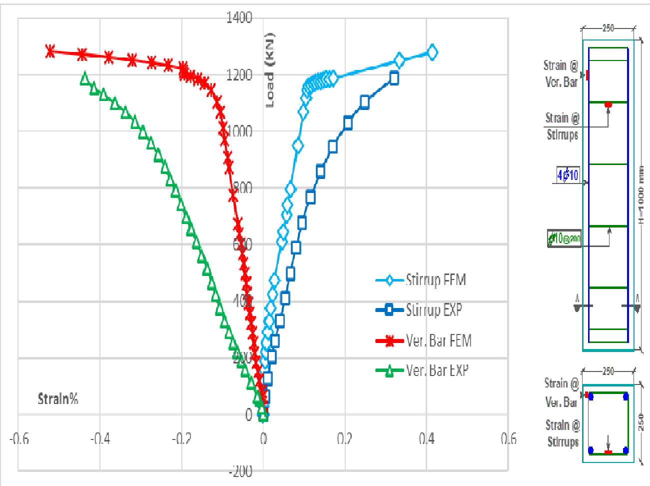

Fig. 29 Relationship between loads and strain from (EXP) and (FEM) results for columns (C٣3) at (μ) = 0.50% and (ρ v) =0.75 %

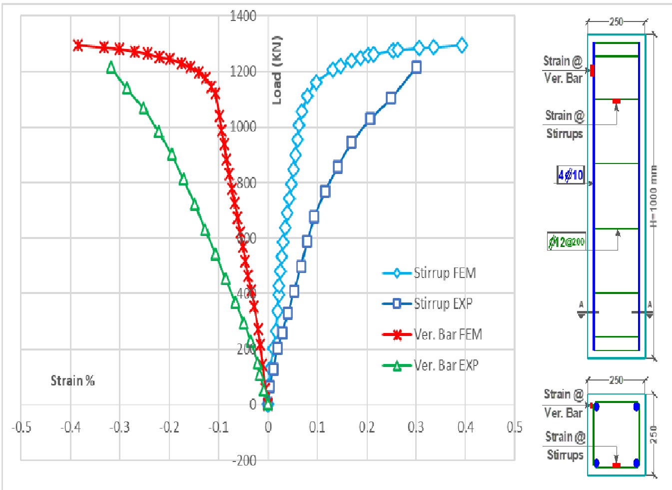

Fig. 30 Relationship between loads and strain from (EXP) and (FEM) results for columns (C٣4) at (μ) = 0.50% and (ρ v) =1.09 %

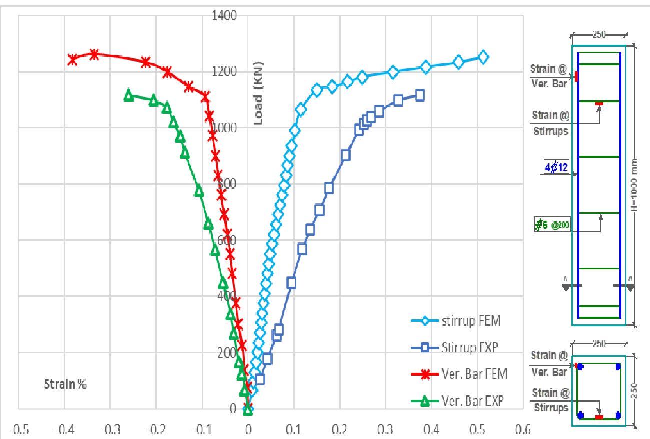

Fig. 31 Relationship between loads and strain from (EXP) and (FEM) results for columns (C41) at (μ) = 0.73% and (ρ v) =0.27 %

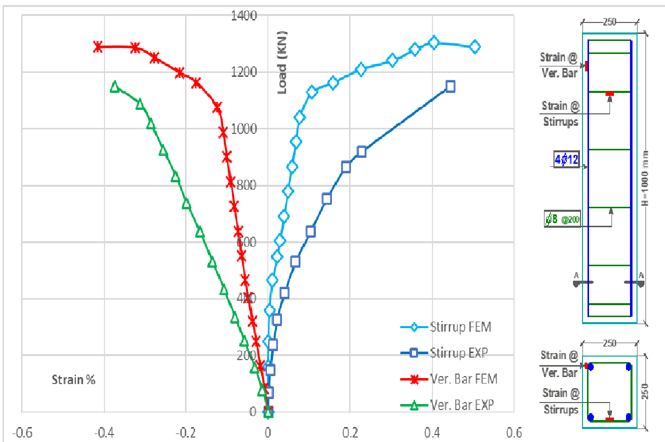

Fig. 32 Relationship between loads and strain from (EXP) and (FEM) results for columns (C42) at (μ) = 0.73% and (ρ v) =0.48 %

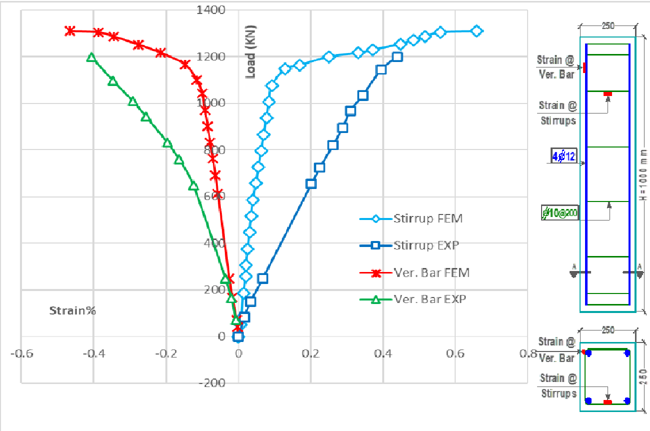

Fig. 33 Relationship between loads and strain from (EXP) and (FEM) results for columns (C43) at (μ) = 0.73% and (ρ v) =0.75 %

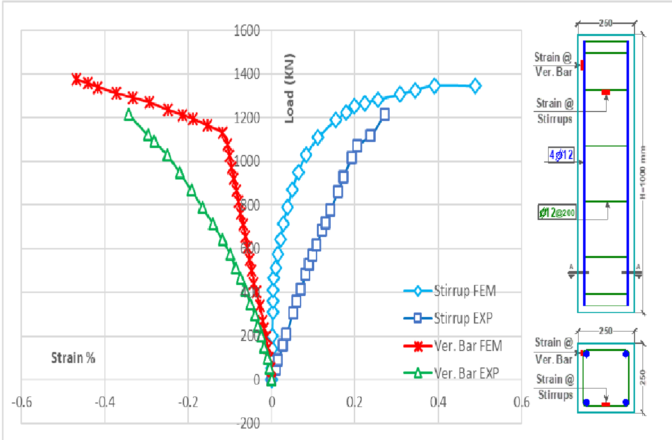

Fig. 34 Relationship between loads and strain from (EXP) and (FEM) results for columns (C44) at (μ) = 0.73% and (ρ v) =1.09 %

5. ULTIMATE LOAD OBTAINED FROM FEM ANALYSIS AND EXP RESULTS

Figures (35, 36 and 37) show the failure loads from both experimental and analytical results. The obtained comparison showed fair agreement between finite element analysis and experimental results.

6. FAILURE MODES

Figure 38 shows the failure modes for RC columns with different vertical steel bars and stirrups volumetric ratio. The failures started by separation of the concrete cover and occur in the upper third of the column height.

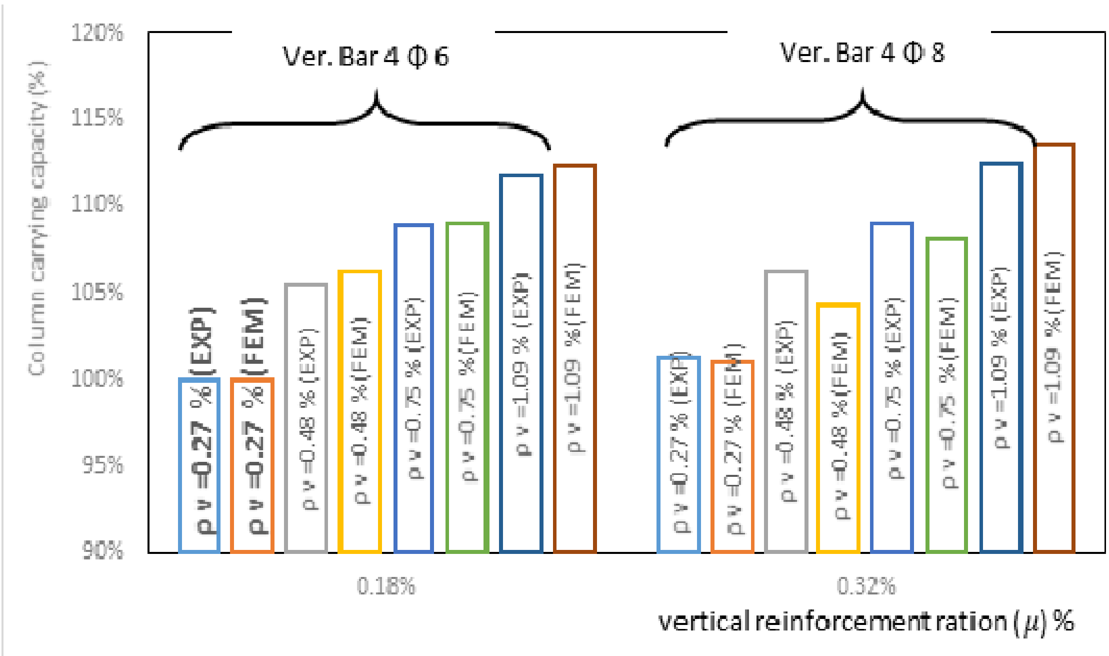

Fig. 35 Relationship between failure load form (EXP) and (FEM) results at stirrups (ρ v) = 0.27% up to 1.09%) and vertical reinforcement ration (μ) = 0.18% and 0.32%

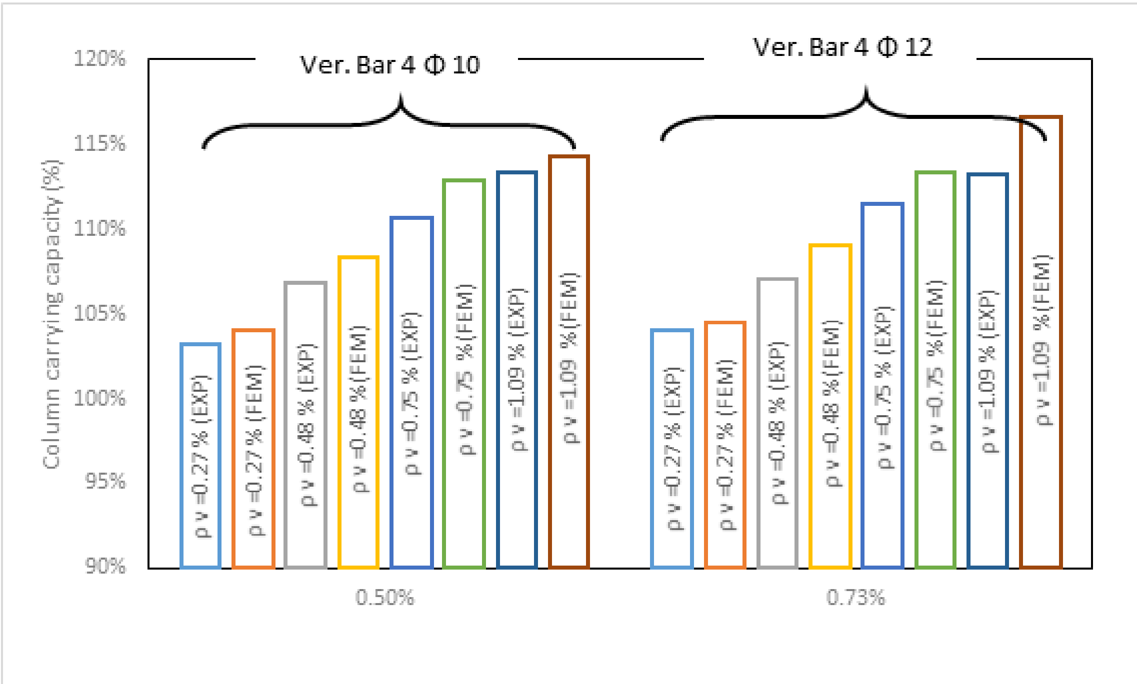

Fig. 36 Relationship between failure load form (EXP) and (FEM) results at stirrups (ρ v) = 0.27% up to 1.09%) and vertical reinforcement ration (μ) = 0.50% and 0.73%

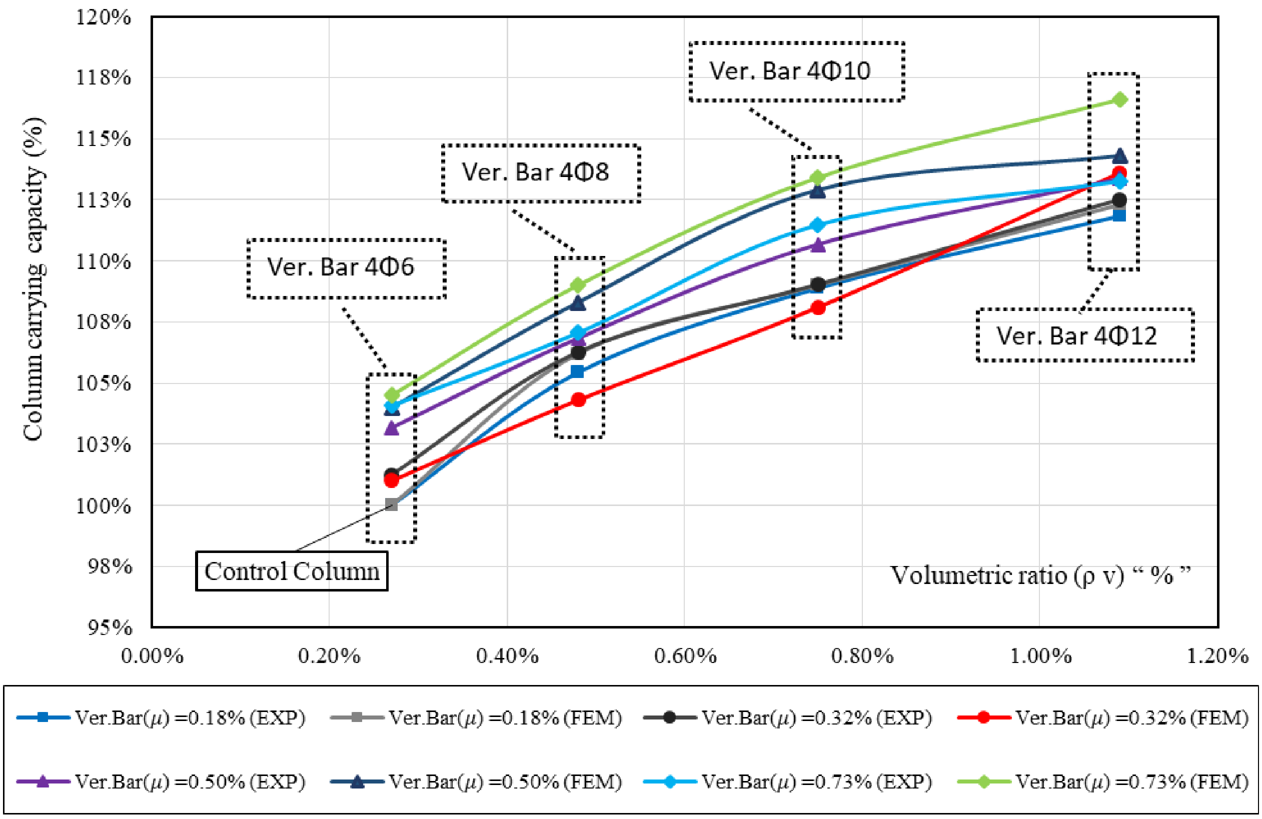

Fig. 37 Relationship between failure load form experimental and analytical finite elements results

Fig. 38 Failure modes

7. CONCLUSIONS

From the present study, the following conclusions are obtained:

1. From the experimental results the per centage of ultimate failure load increased by about 4.1% by increasing percentage of vertical reinforcement from = (0.18% up to 0.73%) at the same stirrup percentage, while the percentage of the ultimate failure load increased by about 5.7% from the finite element analysis.
2. From the experimental results the percentage of ultimate failure load increased by 11.8% with increasing percentage of stirrups from ρ v = (0.27% up to 1.09 %) at the same vertical reinforcement percentage, while the percentage of the ultimate failure load increased by about 12.3% from the analytical results.
3. Enhancement in ductility is obtained by increasing in stirrups volumetric ratio with less brittle failure of RC columns.
4. The stirrups have a good contribution effect with vertical steel bars on the ultimate load capacity. Thus, it should be taken into consideration the contribution of the concrete, vertical steel bars and stirrups in design of RC columns.

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