EFFECT OF TRANSVERSE REINFORCEMENT ON THE AXIAL COMPRESSIVE STRENGTH OF REINFORCED CONCRETE COLUMNS

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ABSTRACT

This paper presents an experimental study on the effect of transverse reinforcement on the axial compressive strength of rectangular and circular cross sectional shape reinforced concrete (RC) columns under axial compression. Twenty specimens of small scale RC columns specimens were considered in the experimental tests. Ten of the columns specimens have a square cross sectional shape with dimensions of (150×150) mm and the other ten specimens have a circular cross sectional shape with a diameter of 150mm. For each cross sectional shape, the columns are classified into two groups of five columns: the first group contains short columns according to ACI-Code requirements (ACI318, 2011) and the other group consists of long columns. Each group uses same longitudinal reinforcement ratio but with five different transverse reinforcement ratios represented as a volumetric ratio of the transverse reinforcement. An experimental test has been conducted to determine the maximum axial compressive load at which each concrete column would fail. The experimental test results have shown that increasing of the volumetric ratio of the transverse reinforcement leads to a considerable increase of the axial load resistance of the column for both rectangular and circular columns and for both cases of long and short columns. The study has also showed that using equations suggested by the ACI-Code to determine the axial compressive strength of RC columns with tie reinforcement that are spaced at distances exceed that suggested by the code, gives over- estimated predictions of the column axial resistance which may results unsafe design.

Keywords: RC columns, axial strength, transverse reinforcement, experimental tests, volumetric ratio.

تاثير التسليح العرضي على مقاومة الانضغاط للاعمدة الكونكريتية المعرضة لاحمال انضغاط محورية

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الخلاصة

يقدم المشروع دراسة عملية (مختبرية) للعلاقة بين نسبة التسليح العرضي في الأعمدة الخرسانية المسلحة و مقاومة تلك الاعمدة لقوة الانضغاط المحورية . تم إجراء الفحوصات المختبرية على عشرين نموذج من الاعمدة الخرسانية المسلحة .عشرة من نماذج الاعمدة تمتلك مقاطع عرضية مربعة الشكل بابعاد 150× 150 ملمتر و العشرة الاخرى بمقاطع عرضية دائرية الشكل بقطر يبلغ 150 ملمتر . تم تقسيم كل عشرة اعمدة ذات مقطع عرضي واحد الى مجموعتين : المجموعة الأولى وعددها خمس أعمدة صنفت كأعمدة قصيرةحسب متطلبات مدونة معهد الخرسانة الامريكي ACI 318-11 والمجموعة الثانية وعددها خمس أعمدة أيضا تم تصنيفها كأعمدة طويلة حيث تم تثبيت نسبة التسليح الطولي لكل مجموعة من الاعمدة الخمسة وتغيير النسبة الحجمية للتسليح العرضي (الأطواق) التي تمثل نسبة مجموع الحجم الكلي للتسليح العرضي الى حجم لباب الكونكريت المحاط بالاطواق. تم فحص مقاومة الانضغاط المحورية الستاتيكية لكل عمود و لكل نسبة تسليح عرضي لمعرفة تأثير تغير التسليح العرضي على قابلية تحمل المحورية . بينت الدراسة ان زيادة النسبة الحجمية للتسليح العرضي تؤدي الى زيادة ملحوضة في مقاومة الاعمدة الخرسانية (النحيفة و القصيرة) لقوة الانضغاط المحورية. كما بينت الدراسة ان استخدام المعادلات المقترحة من قبل مدونة معهد الخرسانة الأمريكي ACI 318-11 لحساب مقاومة الانضغاط المحرية للاعمدة الكونكريتية المحملة محوريا في الحلات التي تكون فيها المسافات بين حديد التسليح العرضي (الاطواق) اكبر من الحدود العظمى المحددة من قبل الكود تعطي قيم تحمل عالية الأمر الذي قد ينتج عنة تصميم غير امن للاعمدة الكونكرينية.

كلمات الدلالة: اعمدة خرسانية مسلحة , مقاومة محورية , تسليح عرضي, فحوصات مختبرية, نسبة حجمية.

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1. INTRODUCTION

Reinforced concrete (RC) columns are main structural members of any reinforced concrete building and their failure may be cause failure of the whole structure of that building. Besides the uniaxial or biaxial bending moments that a RC column may be subjected to, columns are mainly designed to resists axial compressive loads imposed from the upper stories of the buildings. For this type of column resistance (i.e. the axial compressive load resistance) **Sec. 10.3.6.1** of the American Concrete Institute design code for reinforced concrete buildings (ACI318, 2011) has suggested the following equations to predict the design axial compressive strength:

1. For columns with spiral reinforcement

$$ØP_{nmax} = 0.85Ø(0.85\ fc'(A_g - A_{st}) + Fy\,A_{st}) \quad (1)$$

2. For columns with tied reinforcement

$$ØP_{nmax} = 0.80Ø(0.85\ fc'(A_g - A_{st}) + Fy\,A_{st}) \quad (2)$$

Where A_g is the gross cross sectional area of the RC column; Ast is the total area of the longitudinal reinforcement steel bars; Fy is the yield stress of the longitudinal reinforced steel; $f\acute{c}$ is the compressive strength of the concrete; Ø is the strength reduction factor which is taken as 0.7 for spiral reinforcement and 0.65 for tie reinforcement.

Equations 1 or 2 may be expressed in a general form as follows:

$$ØP_{nmax} = (0.85\,\text{or}\,0.8)Ø(P_{Conc.} + P_{Long.}) \quad (3)$$

Where $P_{conc.}$ is the axial compressive strength of the RC column comes from the concrete; $P_{Long.}$ is the axial compressive strength of the RC column comes from of the longitudinal reinforcement. It can be noticed from Eq 3 that the ACI-Code only considers the contribution of the concrete and longitudinal steel reinforcement in the axial compressive strength of the RC columns neglecting the contribution of transverse reinforcement (ties or spirals) which may considerably affect the total axial compressive strength of the RC columns. However, sec. 7.10.5 of ACI-Code (ACI318, 2011) suggests limits for the maximum spacing (S_{max}) of the transvers reinforcement to be used in the design of RC columns, which are the minimum of: 16 times the diameter of the longitudinal reinforcement steel bars (d_b); 48 times the diameter of transverse reinforcement steel bars (d_{Tie}) or; the minimum dimension of the column cross section. Nevertheless, as will be shown in this study, these limits gives very close spacing of the transverse reinforcement and neglects the cases of higher spacing distances which may also be applicable in many design situations.

On the other hand, many research studies have been carried out to investigate the effect of transverse reinforcement on the behaviour and failure of short RC columns. However, long RC columns have rarely been considered in these previous researches. For instance, Chung et al. (2002) have suggested an equation to determine the magnitude of the increase in strength of confined concrete. The suggested equation was based on experimental data and nonlinear multiple regression method of sixty-five reinforced short concrete columns.

Sharma et al. (2005) have presented an experimental study to investigate the strength of short columns with high strength concrete confined by spirals and ties reinforcement under increasing concentric compression load. The volumetric ratio, spacing, configuration and yield strength of transverse reinforcement are all considered as test variables along with the ratio of longitudinal reinforcement.

Hong et al. (2006) and Junior and Giongo (2004) have also conducted an experimental study to determine the effect of low volumetric ratio of lateral tie reinforcement on the high strength concrete and steel fibre high strength concrete column respectively. It has been shown in Hong et al. study (Hong et al., 2006) that columns specimen’s with higher volumetric ratios in conjunction with lower-grade tie yield strength shows better performance than those with lower volumetric ratios in conjunction wiyh higher-grade yield strength. On the other hand, Junior and Giongo study (Junior and Giongo, 2004) have revealed that steel fibre may be help to avoid the premature concrete cover spalling.

Wang and Wue (2010) carried out an experimental investigation on the effect of the confinement using Aramid Fibre-Reinforced Polymer sheets on the strength of square high-strength concrete short columns. Regression formulae were developed for strength and strain based on the experimental results. Two types of axial stress-strain curves were observed from the tests results depending on the form of AFRP wrapping. It has also been shown that the strength and ductility of the columns increases when fully wrapped AFRP sheets are used whereas only the strength increases when partially wrapped AFRP sheets are to be used

Khaleek et al. (2012) has conducted an experimental study on small scale rectangular and circular cross section short columns to determine the effect of volumetric ratio of the transverse reinforcement on the axial compressive strength. It has been shown that the column axial compressive resistance significantly increases when the volumetric ratio of transverse reinforcement has been increased. However, since the study has only considered short columns, as defined by ACI-Code classification of columns, their results could not be generalized to include other cases of long columns because of the difference in behavior and failure modes between two types of columns.

Shin et al. (2012) have also conducted experimental tests on eight small scale rectangular cross section short columns subjected to axial compressive load to cause column failure. It has been concluded that increasing of the volumetric ratio of transverse reinforcement results to a considerable increase of the column ductility which is indicated by the number of cyclic loading that the column can sustain before experiencing failure. It has also been found that the increasing in ductility of the column was due to increasing of the compressive strength of the column owing to increasing of the confinement resulted from the transverse reinforcement (ties).

Öztekin (2012) suggested a method to predict the confined compressive strength of square concrete columns using artificial neural networks (ANN). The ANN model has been developed by using experimental test results of normal and high strength square concrete columns. Several parameters have been addressed in the developed model including numbers and diameters of longitudinal and transverse reinforcements, spacing and configuration of the transverse reinforcement. The validation results have shown that the developed ANN model predicted more accurate results compared to the available analytical models.

Radnić et al. (2013) have recently presented an experimental study to investigate the effect of concrete confinement on the compressive strength and ductility of concrete beam subjected to pure bending. The effect of the form and spacing of stirrups on the capacity and ductility of RC beams were investigated in the study. It has been shown that the ultimate strength capacity and deflection of RC beam increase with decreasing of stirrups spacing. Moreover, it has been concluded that the stirrup form has a considerable effect on the ultimate load carrying capacity and ductility of RC beam.

It is clear that all the previous research studies have only considered the short reinforced concrete columns in their investigations. Therefore, the main objective of the present research is to investigate the effect of transverse tie reinforcement on the axial compressive strength of the RC short and long columns. Series of experimental test will be conducted on twenty small scale rectangular and circular cross section long and short columns specimens. All RC columns specimens will be subjected to an incremental increasing static axial load up to column failure. The experimental test results will be compared with the corresponding ACI-Code design equations.

2. EXPERIMENTAL PROGRAM AND TEST SETUP

This section describes in details the experimental program including test setup and column specimens used in experimental tests of this study and present the experimental test results.

2.1. Concrete mixture ingredients

All material used in the concrete mixture used to cast the concrete column specimens (fine aggregate, coarse aggregate) are tested in the constructional material laboratory at Civil Engineering Department/College of Engineering/The University of Al-Qadissiya as follows:

2.1.1. Cement: The ordinary Portland cement type (I) available in local markets in Iraq and conform to the Iraqi specification No. 5/1984 was used in the present study.

2.1.2. Fine aggregate (Sand): Natural sand with maximum size of 10 mm was used in this study. Experimental tests have been carried out to determine the grain size distribution; sulfate and fine material contents and the results are shown in Table 1. Test results have shown that the grain size distribution conform to the Iraqi specification No.45/1984. On the other hand, sulfate and the fine materials contents are comply to the requirements of the Iraqi specification No.45/1984.

Coarse aggregate (gravel): Natural coarse aggregate with maximum size of 20 mm was used in this study. Experimental tests have been carried out to determine the grain size distribution; sulfate and fine material contents and the results are shown in

2.1.3. **Table 2**. Test results have shown that the grain size distribution conform to the Iraqi specification No.45/1984. On the other hand, sulfate and the fine materials contents are comply to the requirements of the Iraqi specification No.45/1984.

2.1.4. **Reinforcement steel bars**: The mild steel bars have been used to reinforce the concrete columns with diameters of 10mm and 8mm for longitudinal reinforcement and 6 mm for transverse reinforcement. A uniaxial tensile test has been conducted to determine the yield stress of the reinforcement steel (Fy) to be used thereafter in the ACI equations (i.e. Eq. 1 and Eq. 2). **Error! Reference source not found.** shows the uniaxial tensile test results of the reinforcement steel bars.

2.1.5. **Water**: Tap water was used in this study for mixing and curing test specimens.

2.2. RC columns specimens.

All the ingredients of the concrete mixture were mixed with each other using a mix ratio of 1:1.75:3.5 (cement: sand: aggregate). A tap water was added using water to cement ratio (w/c) equal to 0.48 to form a fresh concrete mixture. The concrete mixture with the aforementioned properties has been used to cast twenty reinforced concrete columns with dimensions, longitudinal and transverse reinforcements as shown in Table 4 and Figure 1. Ten of RC column specimens have a square cross section with dimensions of (150×150) mm and the other ten columns have a circular cross section with a diameter of 150mm. For each cross sectional shape, the columns are divided into two groups of five columns: the first group contains short columns defined according to Sec. 10.10.1 of AIC- Code (AIC318, 2011) and have a total length of 800mm for rectangular section column which are designated as (RS0- RS4) and 750 mm for circular section columns which are designated as (CS0- CS4). The other group contains long column (AIC318, 2011) with a length of 1200mm for square cross section columns which are designated as (RL0- RL4) and of 1300mm for circular cross section column which are designated as (CL0- CL4). Each group of five RC columns uses same longitudinal reinforcement ratio but with five different transverse tie reinforcement ratios represented as a ratio of the tie reinforcement volume to the concrete core volume. The transverse tie reinforcement ratio has been changed by changing number of ties in each column as shown in Table 4. Ply-wood and PVC pipes were used as forms to cast the rectangular and circular columns respectively. Due to the limitation in resources available in the laboratory, each ten columns with same cross sectional shapes were cast in two different batches. For each cast batch, twelve concrete cubes with dimensions of (150×150×150) mm have also been case to determine the compressive strength of concrete corresponding to each ten columns. After casting, all RC column specimens and concrete cubes have been remolded, marked and cured for time duration of 28 days by immersing in a warm water basin (at 20 ∓ 2)C^o to gain the maximum concrete strength and to be ready for the test.

2.3. Testing and loading of RC column specimens.

2.3.1. **Concrete cubes**: After curing, axial compressive tests have been carried out on the twelve concrete cubes to obtain the compressive strength of concrete corresponding to each ten column. The compression test machine available at constructional material laboratory at Civil Engineering Department/ College of Engineering/ The University of Al-Qadissiya was used to perform the tests; Table 5 shows the compressive strength of the concrete cubes corresponding to each concrete batch with the average values used for each group of ten columns.

2.3.2. Concrete Columns: After a 28 day of curing, a static axial compressive load bearing tests were conducted for the reinforced concrete columns specimen to capture the axial compressive strengths to each column. The universal test machine available at constructional material laboratory at Civil Engineering Department/ College of Engineering/ The University of Al-Qadissiya was used to perform the tests, see **Figure 2**. The ends supports of all tested columns simulate the simply support conditions with no sideways movement (braced columns) because the top and bottom ends of the columns are not capable to move laterally. To ensure a uniform distribution of the axial compressive load, a square steel bearing plate with dimensions of (200×200×5) mm (width ×length× thickness) was fixed at the top end of each column during the test. An incremental increasing axial static load has been applied to each RC column until the column experienced failure represented by a reloading of loading gages of the test machine. The axial load at which failure occurs was recorded for each tested column and the results will be presented and discussed in the next section.

3. DISCUSSION OF THE TEST RESULTS

3.1. Failure modes

Figure 3 and **Figure 4** show the RC column specimens shapes after failure. As can be seen from these figures, all tested columns have experienced similar failure pattern represented by concrete crushing at the top of the column followed by generating of cracks and splitting of the concrete cover surrounding the transverse reinforcements at the top quarter of the RC column. It can also be noticed from **Figure 3** and **Figure 4** that the longitudinal reinforcement bars have also experienced global buckling particularly near to the loaded end of the column. This can be attributed to the effect of the axial load and because the longitudinal reinforcement bars have no lateral support when the concrete surrounding the longitudinal reinforcement bars have been crushed at the beginning of loading. One of the functions of transverse reinforcements in columns is preventing the main longitudinal bars from buckling outward, spalling the concrete and causing early collapse. Without ties being properly spaced, the main steel could not be relied upon to reach its yield stress.

3.2 Axial compressive strength.

As mentioned before, each column specimen has been subjected to an increment axial static load until the column experienced failure using a load increment of 5kN. Failure of each column was detected by a reloading of the loading gage of the test machine which occurs when the RC column crushes or buckles. **Table *6*** and

Table 7 and **Figure 6 to** Figure 8 show the relationship between failure load and the volumetric ratio of transverse reinforcement for all tested columns. It can be seen form **Table *6***, Figure 5 and Figure 6 which demonstrate the relationship between the axial compressive strength of short columns and volumetric ratio of the transverse reinforcement that increasing of the volumetric ratio of the transverse reinforcement resulted increasing of the axial compressive load at which the columns have failed. Increasing of the volumetric ratio of the transverse reinforcement from 1.4961×10^{-3} to 3.9896×10^{-3} for rectangular sections and from 3.16×10^{-3} to 9.49×10^{-3} for circular sections has increased the column axial compressive resistance from 316.5kN to 410. 8kN and from

292.4kN to 394.7kN for rectangular and circular sections respectively with increasing rate of 30% and 35% for rectangular and circular sections respectively. Similarly,

Table 7, Figure 7 and Figure 8 show that increasing of the volumetric ratio of the transverse reinforcement from 2.3271×10^{-3} to 6.2056×10^{-3} for rectangular sections long column and from 5.48×10^{-3} to 16.45×10^{-3} for circular sections long columns has increased the column axial compressive resistance from 385kN to 523kN and from 270kN to 455.6kN for rectangular and circular sections respectively with increasing rate of 36% and 68.7% for rectangular and circular section respectively. This is an expected behavior since increasing of the volumetric ratio of the transverse reinforcement causes increasing of the confinement of the concrete core surrounded by the transverse reinforcement hence results increasing of the concrete compressive resistance (Cusson, D. Paultre, P., 1994, Öztekin, 2012, Radnić at al., 2103) and then increasing of the column axial compressive load strength. Moreover, increasing of the transverse reinforcement may also increase the strength of longitudinal steel bars and prevent the steel bars from buckling out and causing early failure, see Figure 3 and Figure 4.

4. COMPARISON WITH ACI318-2011 CODE EQUATIONS

In this section, a comparison is presented and discussed between the column axial compressive strength recorded from the experimental test with that calculated using the equations suggested in **Sec. 10.3.6.1** of ACIM318-11 code (i.e. Eq 1 and Eq. 2 in present study). As mentioned before, the **sec. 7.10.5** of ACI-Code has suggested maximum spacing limits between the transverse reinforcement which is equal to 150mm for RC column specimens used in the presents study However, the actual spacing used in the present study exceed this limit as listed in **Table *6*** and

Table 7. Nevertheless, in order to investigate the applicability of the ACI equations for spacing values higher that maximum spacing limits suggested by ACI -code, the following comparisons were conducted.

Firstly, the axial compressive strength of RC columns was calculated according to the equations Eq. 2. The average of the experimental values of concrete compressive strength corresponding to each cast batch as listed in Table 8 were substituted in Eq. 2. One the other hand, the experimental value of the yield stress of the reinforcement steel bars obtained from the uniaxial tensile test of steel bars as presented in Table 8 has also been used in Eq. 2 to calculate the axial compressive strength of RC columns. **Table *6*** and

Table 7 list the calculated axial compressive strength for each column along with the experimentally recorded values.

Table *6*,

Table 7, **Figure 9** and **Figure 10** compare the experimentally recorded values of the column axial compressive strengths with those calculated by ACI – Code equation. It can be noticed from **Table *6*** and **5** along with, **Figure 9** and **Figure 10** that the ACI-Code equation gives overestimated values of the axial compressive strength of the rectangular shape RC columns compared with the values recorded experimentally particularly for long RC columns specimens. However, the ACI-Code equations predict underestimated values of the axial compressive strength of circular shape column especially for high values of the volumetric ratio of transverse reinforcements. The axial compressive strength values calculated by ACI-Code equations do not account the effects of transverse reinforcement of the RC columns strength. It only accounts for the compressive strength of concrete and strength of the longitudinal reinforcement steel bars. The overestimated perdition of the column’s axial compressive strength of the RC column may result unsafe design of the column. On the other hand, the underestimated prediction of the column’s axial strength may results uneconomic design particularly when high values of the volumetric ratio of transverse reinforcements would be used.

5. SUMMARY AND CONCLUSIONS.

This study has presented, in detail, the research undertaken by the author to investigate the effect of transverse reinforcement on the axial compressive strength of reinforced concrete columns subjected to axial compressive load. The study is also aimed to assess the accuracy of equations suggested by ACI-Code to determine the design axial capacity of RC column. The main findings and conclusions that may be extracted from the study are as follows:

1. Increasing of the volumetric ratio of the transvers reinforcement of the RC column results increasing of the axial compressive strength of the RC column. This behavior is valid for short and long columns.
2. Failure of the RC column under axial compressive load starts by bearing or crushing at the loaded end followed by splitting of the concrete cover. For long column specimens with low transverse reinforcement ratios, the aforementioned failure is accompanying with buckling of the longitudinal reinforcement, particularly near the loaded end of the column caused by increasing of the effective length of the longitudinal reinforcement due to crushing the concrete surrounding it.
3. Using the ACI-Code equations for RC column with transverse or ties reinforcements spaced at distances exceed the maximum limits suggested by the code may give either over estimated or underestimated prediction of the axial compressive strength of the column. This could result unsafe or uneconomical design.
4. The effect of increasing the transverse reinforcement on increasing the axial compressive strength of RC column is more visible in short columns than that in long columns. This can be attributed to the confining due to transverse reinforcement which has more effect in short columns than long columns.

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Table 1: Experimental test results of the fine aggregate

Fine minerals		Sieve size analysis	
% (SO3) Sulphate contents	Materials finer than75µm, %	% A cumulative passing	Sieve size
0.149	3	100	10mm
		98	4.75mm
		93	2.36mm
		88	1.18mm
		72	600micron
		26	300 micron
		5	150micron

Table 2: Experimental test for the coarse aggregate

Fine minerals		Sieve size analysis	
% (SO3) Sulphate contents	Materials finer than75µm, %	% A cumulative passing	Sieve size
0.03	1	100	75mm
		100	63mm
		100	37.5mm
		100	20mm
		84	14mm
		41	10mm
		1.2	5mm
		0.4	2.36mm

Table 3: Mechanical properties of the reinforcement steel bars form uniaxial tensile test.

Fy (N/mm²)	ε_y(%)	E(N/mm²)	Fu (N/mm²)	ε_u(%)
647.89	0.00318	204×10^3	742.76	0.134

Table 4: Dimensions and reinforcement details of the RC column specimens

Column specimen designation	Dimensions (m) H×W×L or D×L	KL/r	Longitudinal reinforce.	Volumetric ratios of transverse reinforce.(ties) $\times(10^{-3})$	No. of ties used (Ø6mm)
RS0	0.15×0.15 ×0.8	17.78	4Ø10	2.33	2
RS1	0.15×0.15 ×0.8	17.78	4Ø10	3.10	3
RS2	0.15×0.15 ×0.8	17.78	4 Ø10	3.88	4
RS3	0.15×0.15 ×0.8	17.78	4 Ø10	4.66	5
RS4	0.15×0.15 ×0.8	17.78	4 Ø10	6.21	6
RL0	0.15×0.15 ×1.2	26.67	6 Ø10	1.50	2
RL1	0.15×0.15 ×1.2	26.67	6 Ø10	1.99	4
RL2	0.15×0.15 ×1.2	26.67	6 Ø10	2.99	6
RL3	0.15×0.15 ×1.2	26.67	6 Ø10	3.49	7
RL4	0.15×0.15 ×1.2	26.67	6 Ø10	3.99	8
CS0	0.15×0.75	20	4 Ø8	5.48	2
CS1	0.15×0.75	20	4 Ø8	8.23	3
CS2	0.15×0.75	20	4 Ø8	10.97	4
CS3	0.15×0.75	20	4 Ø8	13.71	5

CS4	0.15×0.75	20	4 Ø8	16.45	6
CL0	0.15×1.3	34.67	4 Ø8	3.16	2
CL1	0.15×1.3	34.67	4 Ø8	4.75	3
CL2	0.15×1.3	34.67	4 Ø8	6.33	4
CL3	0.15×1.3	34.67	4 Ø8	7.91	5
CL4	0.15×1.3	34.67	4 Ø8	9.49	6

Table 5: Compressive test results of the concrete cubes

Section	Cast batch	Compressive strength($\acute{f}c$) (N/mm^2)												$\acute{f}c_{Average}$ (N/mm^2)
Rect.	1	37.1	37.5	40.5	34.7	41.8	40.74	33.9	35.0	34.7	34.6	37.1	32.3	36.64
Circ.	2	31	29	31	31	27	32	31	31	30	26	31	32	30.25

Table 6: The experimentally recorded values of the axial compressive strength for short RC columns with the values calculated using ACI-Code equations

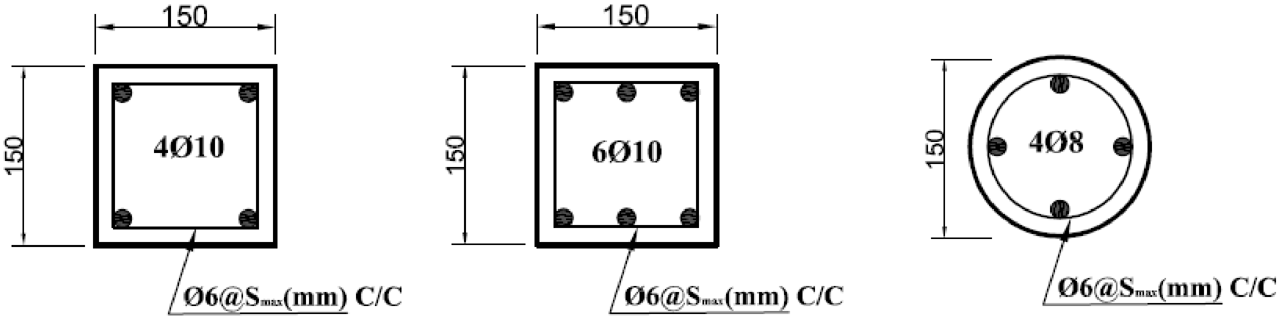
Column designation	*Volumetric ratio ×10^{-3}*	*Experimental values of the axial compressive strength, kN*	*Spacing between tie reinforcement (mm)*	*Calculated values of the axial compressive strength, kN*
RS0	2.3271	385	748	465.2
RS1	3.1028	401	371	465.2
RS2	3.8785	410	245	465.2
RS3	4.6542	486.3	183	465.2
RS4	6.2056	523	145	465.2
CS0	5.48	270	698	301.3
CS1	8.23	310.6	349	301.3
CS2	10.97	327.5	229	301.3
CS3	13.71	358.7	170	301.3
CS4	16.45	455.6	135	301.3

Table 7: The experimentally recorded values of the axial compressive strength for long RC columns with the values calculated using ACI-Code equations

Column designation	Volumetric ratio ×10^{-3}	Experimental values of the axial compressive strength, kN	Spacing between tie reinforcement (mm)	Calculated values of the axial compressive strength, kN
RL0	1.4961	316.5	1198	515.5
RL1	1.9948	346	395	515.5
RL2	2.9922	354.4	295	515.5
RL3	3.4909	393.3	195	515.5
RL4	3.9896	410.8	166	515.5
CL0	3.16	292.4	1248	301.3
CL1	4.75	319.8	621	301.3
CL2	6.33	348.6	412	301.3
CL3	7.91	373.2	307	301.3
CL4	9.49	394.7	245	301.3

Table 8: Concrete compressive strengths and steel yield stress used to **c**alculated the compressive strength of column specimens according to ACI-Code.

Cast Batch	Section shape	f_c' Average (N/mm^2)	Fy (N/mm^2)	Axial strength (kN)	
				Short columns	Long columns
1	Rect.	36.64	648	465.156	515.54
2	Circ.	30.25	648	301.337	301.337



(A) (B)

Figure 1: Reinforcement details of rectangular sections (A) and circular sections (B) RC columns

Figure 2: Universal test machine used in experimental tests.

Figure 3: Failure modes of square and circular short columns

Figure 4: Failure modes of square and circular long columns.

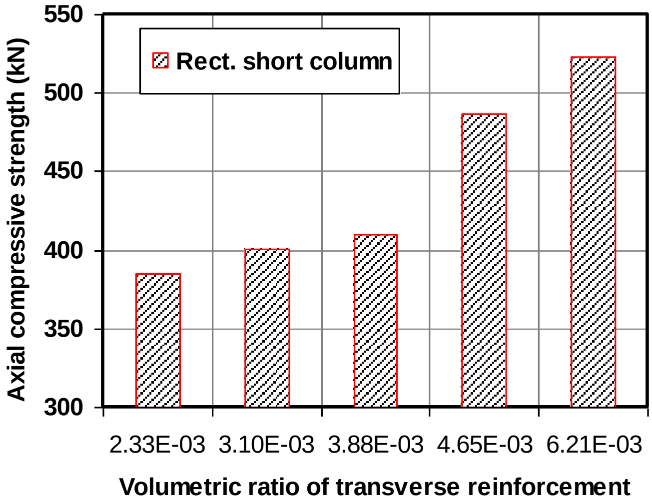


Figure 5: Relationship between the axial compressive load and the volumetric ratio of the transverse reinforcement of short columns with rectangular sections.

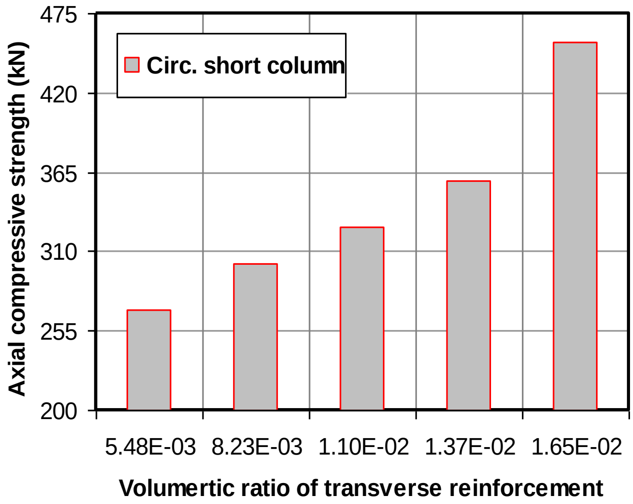


Figure 6: Relationship between the axial compressive load and the volumetric ratio of the transverse reinforcement of short columns with circular sections.

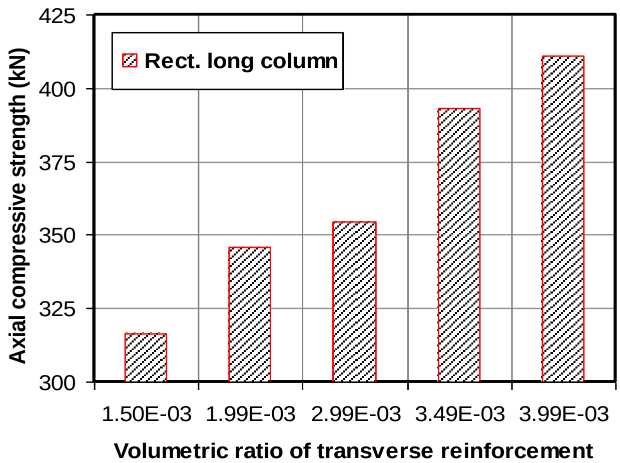


Figure 7: Relationship between the axial compressive load and the volumetric ratio of the transverse reinforcement of long columns with rectangular sections.

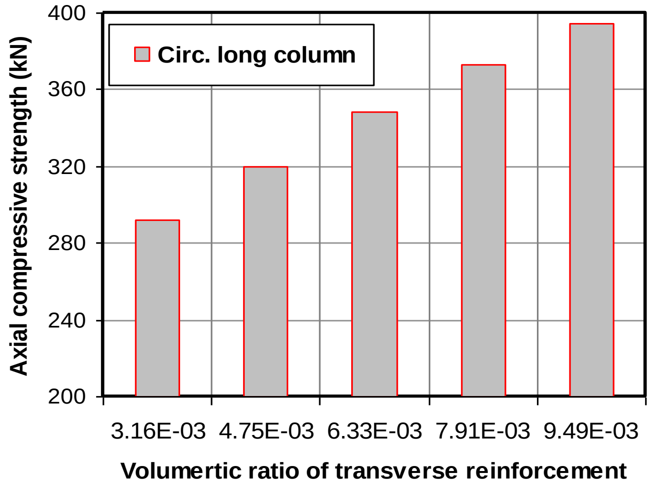


Figure 8: Relationship between the axial compressive load and the volumetric ratio of the transverse reinforcement of long columns

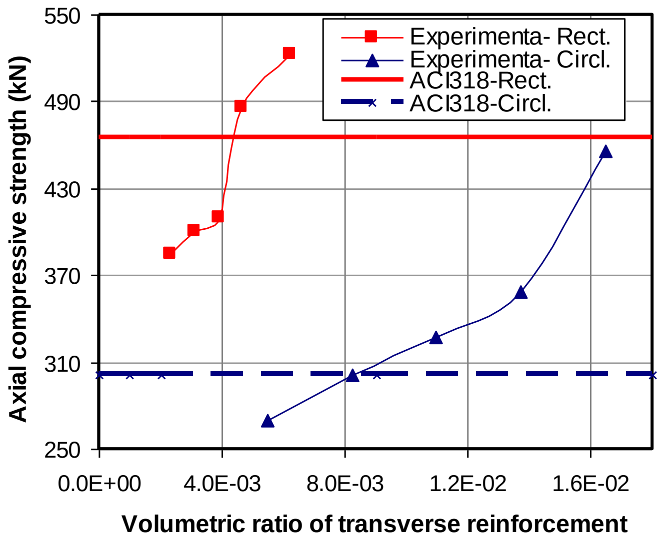


Figure 9: Comparison between the recorded and the calculated values of the column axial compressive strength for short columns

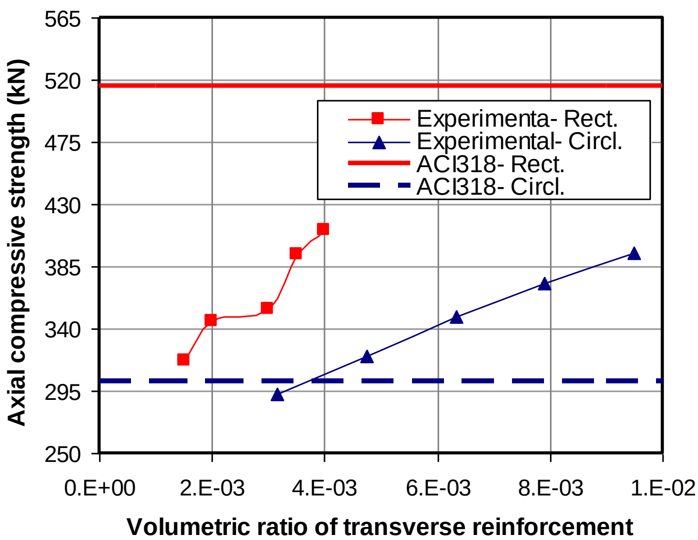


Figure 10: Comparison between the recorded and the calculated values of the column axial compressive strength for long columns