Ethiopian Journal of Science and Sustainable Development

e-ISSN 2663-3205 *Volume 8 (2), 2021*

Journal Home Page: www.ejssd.astu.edu.et

EJSSD ETHIOPIAN JOURNAL OF SCIENCE AND SUSTAINABLE DEVELOPMENT

Research Paper

Investigation of Reinforced Concrete Columns Confined by Rectangular Spiral Reinforcement using Finite Element Analysis

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Article Info

Article History:
Received 02 Sept. 2020
Received in revised form 02 February 2021
Accepted 15 February 2021

Keywords:
Confinement
Deformation Capacity
RC column
Spiral Reinforcement

Abstract

The load carrying and deformation capacity of square reinforced concrete (RC) column confined by rectangular spiral lateral reinforcement subjected to axial load were investigated numerically using abaqus. Thirty one short square RC columns were modeled where seventeen had conventional hoop tie and the remaining fourteen columns had rectangular spiral lateral reinforcement configuration. The configuration, amount and spacing of the lateral reinforcement were included as a factor of confinement in the investigation. Different amounts of lateral reinforcement including 1.4%, 1.6%, 1.8%, 2% and 2.3% were provided in the investigated columns. The diameters of lateral reinforcement used for confinement purpose were 6 mm, 8 mm and 10 mm. The primary objective of this study was focused on the investigation of confinement effect of continuous lateral reinforcement configuration in terms of stress carrying and deformation capacity of confined reinforced concrete columns. RC columns confined with either configuration (hoop or spiral) of lateral reinforcement and provided with amount of reinforcement in the range of 1.6% to 2% where the spacing to core depth (s/dc) ratio was maintained in the range of 0.4-0.5 had exhibited improved deformation and stress capacity. Accordingly, confined RC columns with rectangular hoop lateral reinforcement had 12% and RC columns with continuous spiral lateral reinforcement had 40% higher deformation capacity compared to RC columns with the same amount and configuration of lateral reinforcement but where the spacing was in such a way s/dc ratio was ≥ 0.5. Clearly, the use of rectangular spiral reinforcement as lateral reinforcement could be considered as a better alternative for lateral reinforcement of short square RC columns particularly, where the deformation capacity is the main importance.

1. Introduction

The ability of structural element to withstand the load imposed on without significant deformation maintains the stability of the structure. In skeletal frame structure, local failure (plastic hinge) in column intercepts the flow of load transfer leading to partial or global collapse of structure. Hence, the ductile behavior of column is required critically for avoiding formation of plastic hinge in the column. Due to this reason, several National codes (ACI-318-08, 2008; ES EN 1998-1: 2013) had incorporated strong column-weak beam design philosophy and the flexural strength ratio of column to beam $(\sum Mc / \sum Mb) \geq 1.2$ set to realize the above requirement. An effort to enhance the strength and ductility of the column member has led to the application of confinement. The research on the confinement of RC column member around the globe could be classified into two categories.

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https://doi.org/10.20372/ejssdastu:v8.i2.2021.291

The first category includes research studies incorporating additional materials to enhance the strength and ductility of RC column member. These are studies on RC column member confined by fiber reinforced polymer (FRP) (Ali et al., 2018), and the application of buckling restraint reinforcement (BRR) (Lukkunaprasit et al., 2011). However, the additional cost of these materials, installation and availability hinder the applicability of these confinement techniques in ordinary column construction.

The second category is a widely practiced lateral reinforcement confinement. The pioneer works of Rechart et al. (1929) demonstrated steel lateral reinforcement had significantly improved the strength and ductility of axially loaded RC column. Since then Sheikh (1983), Mander et al. (1989) and Sheikh and Yeh (1990) had conducted investigation on the effect of lateral reinforcement confinement on RC column. Sheikh (1983) identified core concrete area, nominal strength of lateral reinforcement and concrete, spacing and amount of reinforcement, and tie configuration as the primary factors affecting the confinement in RC column. Mander et al. (1989) considered the reduced core concrete area in the development of analytical model for strength and ductility of confined concrete.

Sheikh and Yeh (1990) investigated rectangular RC column and mentioned that inadequate configuration of lateral reinforcement had resulted in unstable strength degradation on the post–peak behavior of stress–strain curve for tested RC column. Saaticoiglu and Razvi (1992) pointed out that the non-uniformity of confinement stress at a tie level and along the RC column height reduced the improvement on the strength and ductility of confined concrete. Sheikh and Toklucu (1993) investigated circular RC column, and pointed out the contribution of an optimum combination of the spacing and amount of reinforcement for enhanced strength and ductility of confined concrete.

The shape of the cross-section of the member under consideration had significant effect on the effectiveness of confinement provided to the core concrete (Mander et al., 1989; Saaticoiglu and Razvi, 1992). Studies on circular RC column revealed that both spiral and hoop configurations had resulted in significant enhancement of ductility and strength of the member (Mander et al., 1989; Sheikh and Toklucu, 1993). Whereas, on rectangular RC column or generally edged cross section the non-uniform confinement pressure both at tie level and along the height of column had reduced the enhancement on load carrying and deformation capacity of the column.

Sheikh and Yeh (1990) and Zeng (2017) demonstrated the use of various configurations such as diamond and other shapes to eliminate the non–uniformity at a tie level and also suggested the use of additional longitudinal bars in between corners of edged cross section RC columns. However, apart from close spacing of lateral reinforcement as means to minimize the non-uniformity of confinement yet no investigation was availed on the effectiveness of continuous confinement in reducing the non–uniformity of confinement pressure along the length of square RC column.

Since recent times, several studies have been conducted on the use of rectangular spiral reinforcement (RSR) in RC beam–column joint. Karayannis and Sirkelis (2005) and Saha and Meesaraganda (2018) conducted experimental investigation on RC beam-column joint subjected to cyclic load. These studies mentioned that the use of RSR enhanced the shear capacity of the joint. It was also observed that the crack propagation through the joint was delayed. Athira and Remya (2017) numerically investigated beam-column joint subjected cyclic load and mentioned that spirally tied beam-column joint had exhibited improved energy absorption capacity.

However, studies focused on the load carrying behavior of square RC column confined by RSR and subjected to axial loading were not or rarely available yet. Hence, study had focused on the confinement effect of continuous spiral lateral reinforcement on the stress and deformation capacity of square short RC column subjected to axial load.

The continuous configuration of rectangular spiral reinforcement expected to eliminate the problem related to non-uniformity of confinement along the length of square/rectangular RC column. Therefore, the main objective of this research was focused on the investigation of the effect of spiral lateral reinforcement on the strength and deformation capacity of square short RC column subjected to axial load. In addition, the effect of considerable factors affecting RC column confinement including the amount and spacing of traverse reinforcement was investigated. Finally, the enhancement in load carrying capacity and deformation capacity due to rectangular spiral configuration was examined in comparison with the conventional (discrete hoop) configuration of the lateral reinforcement.

2. Materials and Methods

2.1. Materials

Two materials, concrete and reinforcing bar were required to model the RC column in the computer program (Abaqus). These two materials were assembled together and a model of RC column was created in the analysis program.

The mechanical property of the materials, their interaction, load and boundary condition were simulated to reflect the actual as constructed RC column. The mechanical properties of both materials were taken from national code mainly ES EN 1992-1-1: 2013, from manuals of analysis program and research papers.

ES EN 1992-1-1: 2013, classifies concrete into several strength classes based on 28 days characteristic compressive cylinder strength. Table-2 summarizes the mechanical properties of concrete and steel reinforcement that were used for modeling specimens in this study. Uniaxial compressive stress–strain relationship was obtained from the analytical model recommended by ES EN 1992-1-1: 2013. The non-linear quasi-brittle mechanical behavior of concrete was defined according to concrete damage plasticity (CDP) model.

The elastic nature of both tensile and compressive behavior is defined by modulus of elasticity (E_{cm}) and poisons ratio (ν=0.16) (Abaqus get started user's manual, 2014). The inelastic behavior is obtained by subtracting the elastic behavior from the total uniaxial stress–strain relationship (Abaqus user's manual, 2014). The stiffness degradation beyond the elastic range was characterized by tension (d_t) and compression damage (d_{cm}) variables (Abaqus user's manual, 2014).

The CDP model in abaqus defines yield criteria using plastic strain in compression and tension (Abaqus user's manual, 2014). Other parameters related to concrete flow properties including eccentricity, the ratio of equi-biaxial compressive yield stress to uniaxial compressive yield stress (Kc) and the ratio of stress invariant on tensile to stress invariant on compression (σ_{bo}/σ_{co}) (Table 1) were taken from abaqus-6.14 user's manual (Abaqus user's manual, 2014). Others parameters including poison's ratio, dilatation angle and viscosity parameter were determined based on convergence and validation test and were summarized in (Table 2).

Table 1: Flow parameters in concrete damage plasticity model

Dilatation angle	Kc	σ_{bo}/σ_{co}	Eccentricity (ε)	Viscosity
31^{o}	0.67	1.16	0.1	0.0001

Table 2: Properties of material used

.	Material		Yield strength (MPa)	Diameter (mm)	Modulus of elasticity (Gpa)	Poison's ratio
1	Concrete		25	-	31.5	0.16
2	Steel	Long. Rein.	400	16	200	0.3
		Lat. Rein.	400	6-10	200	0.3

The yield strength (f_y) $= 400\ Mpa$ was considered for both lateral and longitudinal steel reinforcement. The nominal elastic stress–total strain relation was determined using the analytical expression from EN 1992-1-2:2004. The elastic behavior up to the yield stress is defined by specifying the modulus of elasticity, $Es\ = 200\ GPa$ and $\nu = 0.3$ for poison's ratio. The inelastic behavior was obtained by subtracting the elastic behavior from the total uniaxial stress–strain relationship (Abaqus user's manual, 2014).

2.2. Method

The investigation was conducted through the use of a computer program, Abaqus. In this work pin supported short, square RC columns subjected to axial load were modeled and simulated in the Abaqus/Standard analysis product. And the results of analysis were used to investigate the effect of the study variables namely amount, spacing and configuration of lateral reinforcement on load carrying and deformation capacity of RC column.

A total of thirty one specimens were modeled (Figure 1) and submitted into computer program namely Abaqus and the result of all thirty one specimens were considered in the investigation. All specimens had the same size dimension 200 x 200 x 1000 mm. The concrete cover was provided according to the provision of EN 1992-1-1:2004 for minimum concrete cover. Accordingly 25 mm thick concrete cover was provided on each sides of the RC column. The middle region extending over 250 mm length was identified as test region where the remaining top and bottom was strengthened by doubling the amount of reinforcement to avoid premature failure.

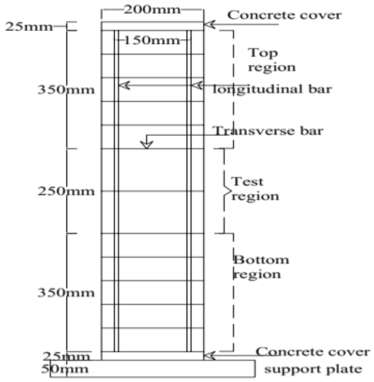

Figure 1: Typical model of investigated RC columns

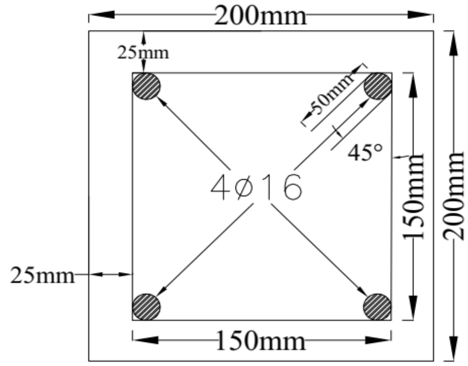

Figure 2: Typical cross-section of investigated RC columns

Table 3: Summary and detailed data of tested specimens

S. No.	Category	Specimen	Lat. rein. configuration	Lat. rein. spacing (mm)	s/dc ratio	Amount of lat. rein. (ρ_S) in (%)	Bar dia. of lLat. rein.(mm)
1	Group 1	R50Am14	Hoop tie	50	0.33	1.4	6
		R90Am14	"	90	0.6		8
		R140Am14	"	140	0.93		10
		S50Am14	Spiral	50	0.33		6
		S90Am14	"	90	0.6		8
3	Group 2	R45Am16	Hoop tie	45	0.3	1.6	6
		R60Am16	"	60	0.4		7
		R80Am16	"	80	0.53		8
		R120Am16	"	120	0.8		10
		S45Am16	Spiral	45	0.3		6
		S60Am16	"	60	0.4		7
		S120Am16	"	120	0.8		120
3	Group 3	R40Am18	Hoop tie	40	0.27	1.8	6
		R60Am18	"	60	0.4		7.4
		R80Am18	"	80	0.53		8
		R110Am18	"	110	0.73		10
		S40Am18	Spiral	40	0.23		6
		S60Am18	"	60	0.42		7.4
		S110Am18	"	110	0.73		10
4	Group 4	R35Am20	Hoop tie	35	0.23	2.0	6
		R60Am20	"	60	0.4		8
		R100Am20	"	100	0.67		10
		S35Am20	Spiral	35	0.23		6
		S60Am20	"	60	0.4		8
		S100Am20	"	100	0.67		10
5	Group 5	R30Am23	Hoop tie	30	0.2	2.3	6
		R55Am23	"	55	0.37		8
		R85Am23	"	85	0.57		10
		S30Am23	Spiral	30	0.2		6
		S55Am23	"	55	0.37		8
		S85Am23	"	85	0.57		10

Core depth (dc = 150mm)

The typical cross-section for all investigated RC column specimens was given in Figure 2 and for all columns 16 mm diameter longitudinal bars were assumed in assembling the column model. At a time all variables reasonably were kept constant except the variable to be studied. The investigated column specimens vary either in amount, spacing or configuration of the lateral reinforcement. In assembling most columns, commonly known diameters of lateral reinforcement (Table 3) were used but, on few columns where particular spacing of lateral reinforcement was needed for comparison, unfamiliar diameters of lateral reinforcement were assumed for analysis purpose.

Sheikh and Toklucu (1993) mentioned that for amount of lateral reinforcement ≤ 1% and ≥ 2%, changing the spacing of lateral reinforcement had no significant effect on stress– strain relationship of axially loaded RC column. In this research, in order to have enough data for comparative investigation, the columns with five different amounts of lateral reinforcement including (1.4%, 1.6%, 1.8%, 2% & 2.3%) were investigated.

The spacing of lateral reinforcement was determined using equation 1 and it is a function of amount of lateral reinforcement (ρ_s), core depth of the column cross-section (d_c) and cross-sectional area of the lateral reinforcement (a_s). At a time one amount of lateral reinforcement (ρ_s) was selected and kept constant, and since the cross-section of all columns was constant, the spacing of lateral reinforcement was varied through altering the diameter (d_b) or cross-sectional area (a_s) of the lateral reinforcement.

$$Spacing\ (s) = \frac{4a_s(d_c - d_b)}{\rho_s {d_c}^2} \ldots\ldots\ldots\ldots (1)$$

The name of model specimens (Table-3) follows from spacing, configuration and amount of reinforcement. For instance, in designation of specimen R40Am18: R stands for rectangular hoop configuration, 40 stands for spacing in mm and Am18 indicate the amount of lateral reinforcement in percent (ρ_S = 1.8%). Similarly, in designation of specimen S60Am18: S stands for continuous spiral configuration, 60 stands for spacing in mm and Am18 indicate the amount of reinforcement in percent (ρ_S = 1.8%).

3. Result and Discussion

Specimens with different amount of reinforcement and spacing had been modeled and analyzed using the computer analysis program- Abaqus 6.14. The analysis result for different comparable RC column models were contrasted with each other, mainly based on the maximum stress developed on the test region of RC column, the strain at maximum stress, and overall non-linear stress–strain curve behavior. In general, the investigated models could be identified as model with continuous spiral and hoop tie lateral reinforcement based on the lateral reinforcement configuration.

As it will be discussed in the proceeding section, varying the spacing of lateral reinforcement for the amount of reinforcement (ρ_S) ranging from 1.6% − 2% had a significant effect on stress-strain behavior of RC column particularly on post peak stress-strain curve behavior.

3.1. Effect of lateral reinforcement spacing

The stress-strain diagram (Figure 3 through 12) show the effect of lateral reinforcement spacing with respect to the amount of lateral reinforcement. Reducing the spacing almost by half such that from 90 mm to 50 mm had no significant effect on stress carrying and deformation capacity of both (R90Am14 and R50Am14) tested columns, indeed the stress–strain curve of each column overlap over each other (Figure 3) and both columns attain peak stress at the same strain (Table 4).

Similarly, in spiral tied specimen with amount of lateral reinforcement 1.4%, column S50Am14 and S90Am14 where the lateral reinforcement spacing was 50mm and 90mm respectively, both had nearly the same peak stress (Figure 4) and attained the peak stress at the same strain. Thus, reducing the spacing between lateral reinforcement for specimens with amount of reinforcement 1.4% had insignificant improvement on the stress and deformation capacity of tested confined concrete RC column specimens. The effect of lateral reinforcement spacing was more significant on columns with amount of reinforcement in the range of 1.6-2%.

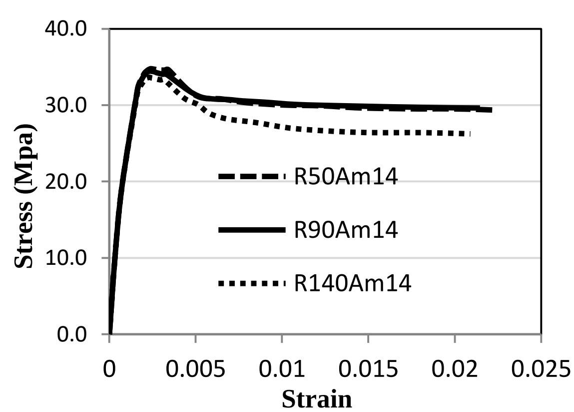

Figure 3: Stress-strain curve for hoop tied specimen (ρ_S = 1.4%)

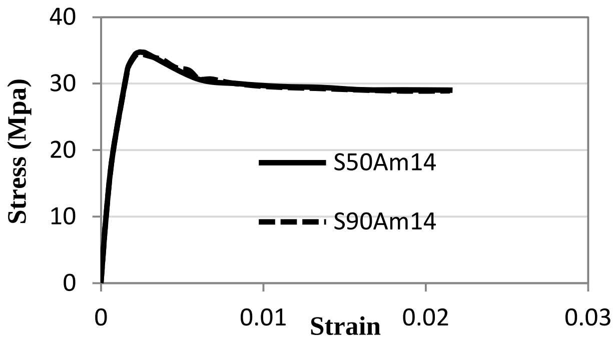

Figure 4: Stress-strain curve for spirally tied specimen (ρ_S = 1.4%

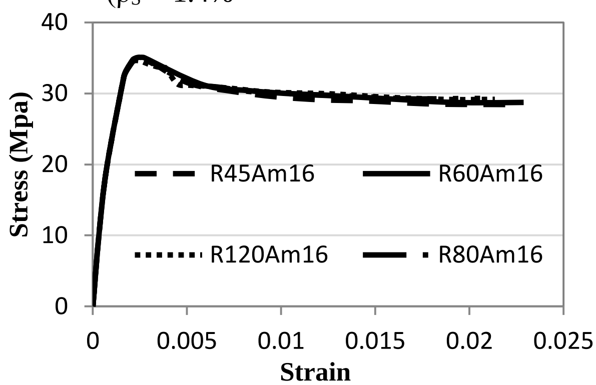

Figure 5: Stress-strain curve for hoop tied specimen (ρ_S = 1.6%)

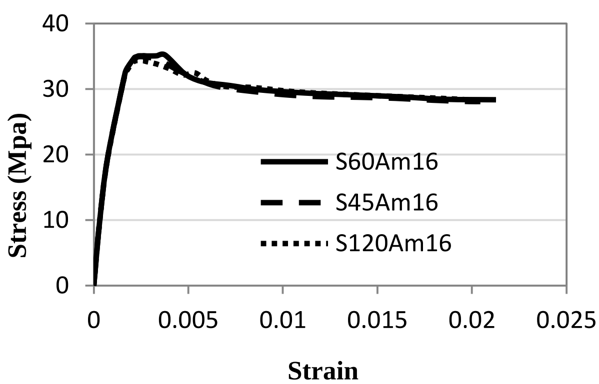

Figure 6: Stress-strain curve for spirally tied specimen (ρ_S = 1.6%)

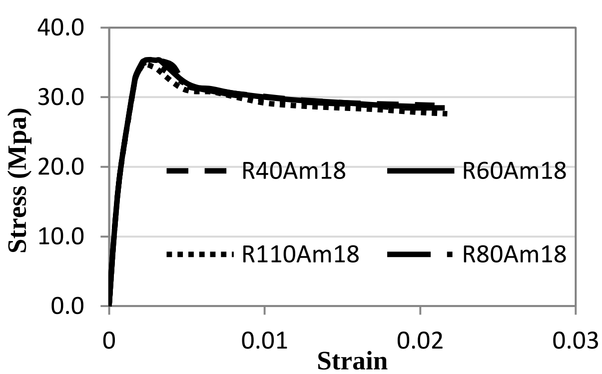

Figure 7: Stress-strain curve for hoop tied specimen (ρ_S = 1.8%)

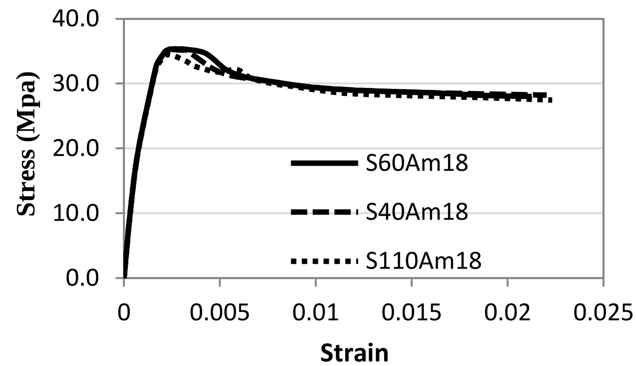

Figure 8: Stress-strain curve for spirally tied specimen (ρ_S = 1.8%)

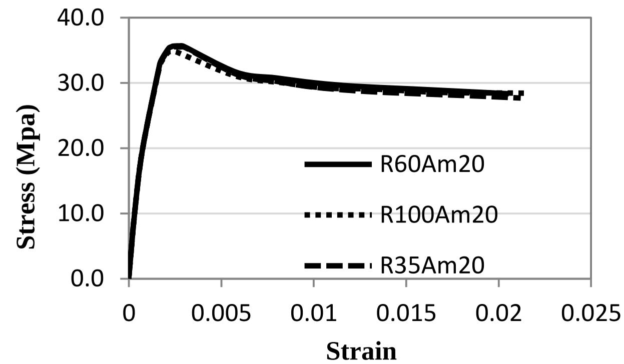

Figure 9: Stress-strain curve for hoop tied specimen (ρ_S = 2%)

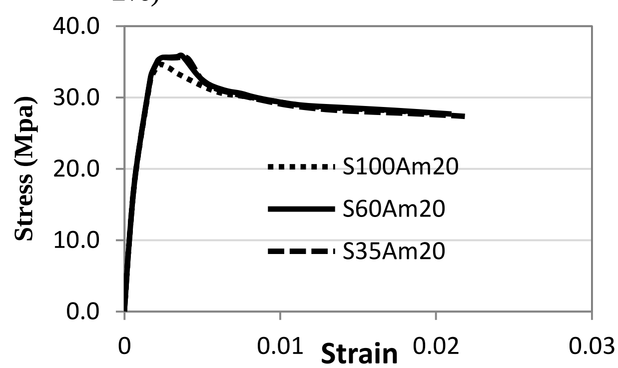

Figure 10: Stress-strain curve for spirally tied specimen (ρ_S = 2%

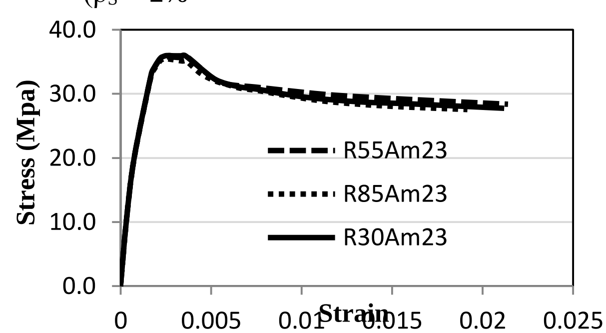

Figure 11: Stress-strain curve for hoop tied specimen (ρ_S = 2.3%)

Table 4: Summary of values on the stress-strain curve for specimens (ρ_S = 1.4%)

S. No.	Specimen name	Max. stress (MPa)	Strain at max stress	Strain at 85% of max stress	Strain ductility ratio
1	R50Am14	34.76	0.0024	0.0165	6.9
2	R90Am14	34.46	0.0024	--	--
3	R140Am14	33.66	0.0023	0.0062	2.7
4	S50Am14	34.35	0.00234	0.0115	4.9
5	S90Am14	34.44	0.00234	--	--

-- = stress capacity not reduced to 85% of the maximum stress

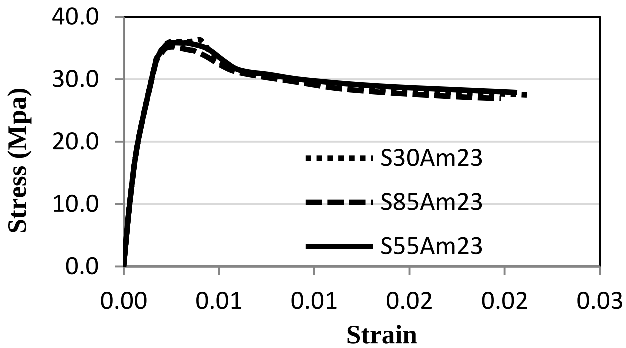

Figure 12: Stress-strain curve for spirally tied specimen (ρ_S = 2.3%)

As summarized in Table 5, column specimens (R45Am16, R60Am16 and R120Am16) had nearly the same peak/maximum stress, however indispensable enhancement was observed on the strain at which the peak stress was attained. Specimen R60Am16 attain peak stress at 12.5% higher strain compared to strain at peak stress in specimen R120Am16 respectively. Similarly, in spirally tied specimen the peak stress for specimen S60Am16 was 2.3% higher compared to the peak stress for specimen S120Am16. Regarding the deformation capacity, the strain at peak stress for specimen S60Am16 was 54.5% higher (Table 5) than the strain at peak stress for specimen S120Am16.

In specimen under Group-3, with 1.8% lateral reinforcement, reducing the spacing from 110 mm in specimen R110Am18 to 60mm in specimen R60Am18 resulted in 2% higher peak stress and offset the strain at peak stress by 12.5% (Table 6) compared to that in specimen R110Am18. Similarly, in spirally tied specimen, the peak stress and strain at peak stress in specimen S60Am18 was 2.6% and 12.5% higher (Table 6) compared to that in specimen S110Am18, respectively.

Table 5: Summary of values on the stress-strain curve for specimens (ρ_S = 1.6%)

S. No.	Specimen name	Max. stress (MPa)	Strain at max. stress	Strain at 85% of max. Stress	Strain ductility ratio
1	R45Am16	34.92	0.00244	0.0092	3.77
2	R60Am16	35.08	0.0026	0.0115	4.423
3	R80Am16	34.77	0.00245	0.0143	5.84
4	R120Am16	34.63	0.00231	0.0189	8.2
5	S45Am16	34.94	0.00254	0.0082	3.23
6	S60Am16	35.2	0.00377	0.0087	2.31
7	S120Am16	34.4	0.00244	0.0132	5.41

Table 6: Summary of values on the stress-strain curve for specimens (ρS = 1.8%)

S. No.	Specimen name	Max. stress (MPa)	Strain at max stress	Strain at 85% of max stress	Strain ductility ratio
1	R40Am18	35.25	0.0025	0.0106	4.24
2	R60Am18	35.4	0.0027	0.01	3.7
3	R80Am18	35.06	0.0024	0.0097	4.04
4	R110Am18	34.73	0.0024	0.0093	3.87
5	S40Am18	34.35	0.00234	0.0084	3.6
6	S60Am18	35.38	0.0027	0.0083	3.07
7	S110Am18	34.5	0.0024	0.0094	3.92

The same trend was observed on columns with 2.0% lateral reinforcement, the peak stress in specimen R60Am20 was 2.2% higher compared to peak stress in R100Am20 and the strain at peak stress was enhanced by 10% (Table 7) than that in specimen R100Am20. Similarly, in spirally tied specimen S60Am20 with reduced lateral reinforcement spacing had 2.6% higher peak stress capacity than that of comparable specimen S100Am20 (Table 7) and offset the strain at peak stress by 54% compared to that in specimen S100Am20.

In case of specimens with amount of reinforcement 2.3%, the peak stress in specimen R55Am23 was 0.8% higher than the peak stress in specimen R85Am23, and the strain at peak stress was enhanced by 8.3% (Table-8) compared to the strain at peak stress in specimen R85Am23. Similarly, in spirally tied specimen both (S55Am23 and S85Am23) had equal peak stress and the strain at peak stress for specimen S55Am23 was 7% (Table 8) higher than that in specimen S85Am23.

Clearly the enhancement of stress and deformation capacity through reducing lateral reinforcement was lower in specimens with 2.3% lateral reinforcement compared to the enhancement on specimens included in Group 2 - 4 with 1.6% - 2% reinforcement. On the other hand, reducing the lateral reinforcement spacing beyond certain limit had no significant effect on the stress carrying and deformation capacity of confined concrete. As shown in Table 5, specimens R60Am16 with wider spacing had relatively higher stress capacity and the strain at peak stress was 6.5% higher compared to specimen R45Am16 which had close spacing of lateral reinforcement.

The same result was observed on columns with 1.8% lateral reinforcement. The stress-strain diagram (Figure 7 & 8) for specimen R60Am18 and S60Am18 with wider spacing than R40Am18 and S40Am18 respectively had exhibited similar stress strain curve, indeed specimen R60Am18 and S60Am18 attain peak stress at comparatively larger strain (Table 6). Thus, reducing the lateral reinforcement spacing beyond certain limit such that s/dc ratio less than (≤0.35) couldn’t enhanced the stress and deformation capacity of tested columns with both configurations.

The results observed on columns with 2.0% and 2.3% lateral reinforcement bear a witness to the same conclusion. As shown in Table 7, specimens R60Am20 and S60Am20 with wider spacing of lateral reinforcement had the same peak stress capacity compared to the corresponding specimens R35Am20 and S35Am20, respectively. Indeed, the strain at peak stress in specimen S60Am20 and R60Am20 was 4% and 8% higher compared to the peak stress in S35Am20 and R35Am20, respectively.

Actually, specimen S30Am23 had 10% and 70% higher peak stress and strain at peak stress, respectively (Table-8) compared to that of specimen S55Am23. However, the rapid strength degradation on the falling branch of the stress-strain curve reduced the significance of reducing the lateral reinforcement in columns with the amount of reinforcement 2.3%. Hence, the selection of lateral transverse reinforcement spacing should consider the important outcome due to redistribution of forces through deformation.

It was noted that, specimens R80Am16 and R80Am18 with lower spacing (s/d_c = 0.53) had exhibited no significant improvement on load carrying and deformation capacity relative to comparable specimens R120Am16 (s/d_c = 0.8) and R110Am18 (s/d_c = 0.73), respectively. Thus, more reduction of the lateral reinforcement could not cause significant improvement on stress and deformation capacity of the investigated column specimens. Therefore, an optimum combination of spacing and amount of lateral reinforcement had to be provided to improve the load carrying and deformation capacity of axially loaded RC column.

Referring to the cases observed on specimen with lateral reinforcement of 1.4%, 1.6%, 1.8%, 2% and 2.3%, reducing the spacing of lateral reinforcement had significant effect on the stress and deformation capacity such that, for the amount of reinforcement in the range of 1.6% - 2 percent. Reducing the spacing where the amount of reinforcement was in the mentioned range, improved the peak stress capacity, on average by 2.3% and enhanced the strain at the peak stress, on average, by 12% and 40% in hoop tied and rectangular spiral tied square RC column specimens respectively. The spacing to depth (s/d_c) ratio of these specimens was existed in the range of 0.4-0.5.

Clearly, the rectangular spiral configuration of lateral reinforcement had contributed to the observed higher deformation capacity of investigated confined RC column specimens. Spiral configuration of the lateral

Table 7: Summary of values on the stress-strain curve for specimens with (ρ_S = 2%)

S. No.	Specimen name	Max. stress (MPa)	Strain at max. stress	Strain at 85% of max. stress	Strain ductility ratio
1	R35Am20	35.56	0.00245	0.0081	3.3
2	R60Am20	35.7	0.00265	0.0092	3.5
3	R100Am20	34.88	0.0024	0.0094	3.92
4	S35Am20	35.6	0.00356	0.0075	2.07
5	S60Am20	35.84	0.0037	0.0077	2.08
6	S100Am20	34.64	0.0024	0.0097	4.04

Table 8: Summary of values on the stress-strain curve for specimens with (ρ_S = 2%)

S. No.	Specimen name	Max. stress (MPa)	Strain at max. stress	Strain at 85% of max stress	Strain ductility ratio
1	R30Am23	36.0	0.00367	0.0077	2.88
2	R55Am23	35.8	0.0026	0.0097	3.5
3	R85Am23	35.5	0.0024	0.0082	3.4
4	S30Am23	36.2	0.0041	0.0073	2.07
5	S55Am23	35.87	0.0026	0.0082	3.15
6	S85Am23	35.4	0.00243	0.0083	3.4

reinforcement had favorable inclination to delay the inclined crack propagation that was likely to ensue after enough disintegration of the core concrete had taken place. To the effect, comparatively extended yielding plateau was observed on the stress-strain curve (Figure 6, 8 & 10) plotted for spirally tied columns.

Clearly, the effect of reducing the spacing of the lateral reinforcement was more significant on enhancing the deformation capacity than improving the strength of confined concrete. Several studies (Rechart et. al, 1929; Saaticoiglu and Razvi, 1992; Mohammadreza and Mohammadehsan, 2017) mentioned that the conception of failure in confined concrete begins at the same level of load and strain to that of plain concrete.

This implied that the confinement through the lateral reinforcement became effective after enough disintegration of core concrete had taken place. However, due to confinement the disintegration of core concrete was delayed and the concrete member was enabled to sustain maximum stress while undergoing degrading strain deformation.

The stress-strain diagram plotted on (Figure 3 through to 12) had confirmed the same observation. Prior to the attainment of the maximum stress, columns with different lateral reinforcement spacing had overlapping stress-strain relationship and exhibited their respective unique path on the descending branch of the stress strain curve.

Thus, the effect of the confinement was observed on the descending branch of the stress strain diagram such that the lateral reinforcement became effective after the attainment of the maximum stress capacity of the core concrete. Hence, once the maximum stress was attained, the increment on the stress capacity was no more significant and the enhancement on deformation capacity, as a result of adequate confinement was more pronounced than the improvement on stress carrying capacity of the investigated columns.

3.2. Buckling Mode of Longitudinal Reinforcement and Spacing of Lateral Reinforcement

Several studies (Sheikh and Yeh, 1990; Rajput and Sharma, 2018) had mentioned that the disintegration of core concrete and buckling of the longitudinal bar were the major causes for failure of reinforced concrete column member subjected to higher loads. The buckling modes of longitudinal reinforcement for various representative column specimens were shown in Figure 13 through to 18.

Invariably, Sheikh and Yeh (1990) and Sheikh and Toklucu (1993) mentioned that under applied axial load, unreasonably close spacing of lateral reinforcement tends to temporarily restrain buckling of the longitudinal reinforcement. At the same time the ensued confinement had restrained the expansion of the core concrete up to higher concrete strain deformation leading to sudden and localized buckling of longitudinal reinforcement (Sheikh and Yeh, 1990).

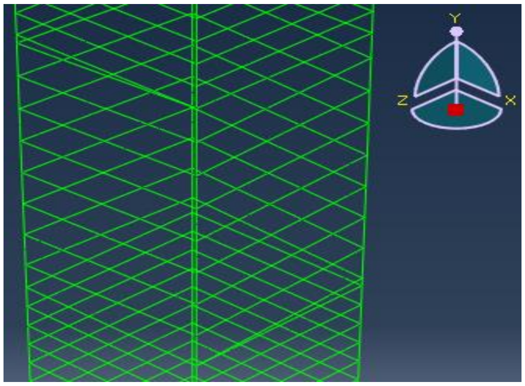

Figure 13: Undeformed shape of the reinforcement embedded in specimen S30Am23

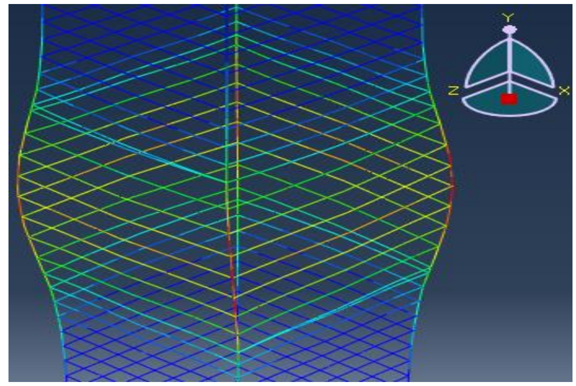

Figure 14: Deformed shape of the reinforcement embedded in specimen S30Am23

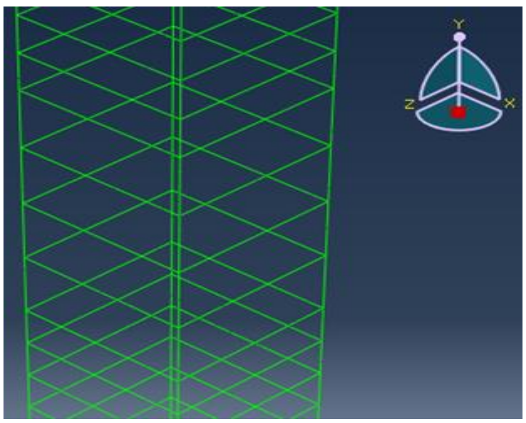

Figure 15: Undeformed shape of the reinforcement embedded in specimen R60Am18

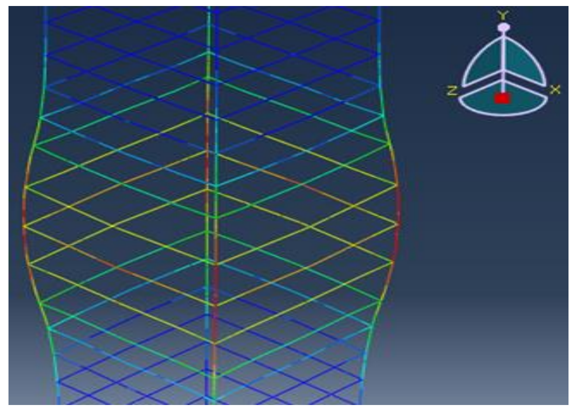

Figure 16: Buckling mode of the reinforcement embedded in specimen R60Am18

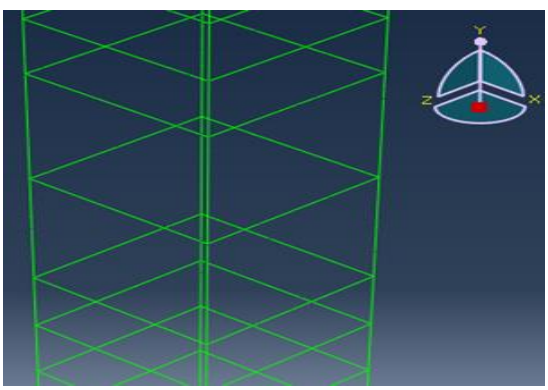

Figure 17: Undeformed shape of the reinforcement embedded in specimen R120Am16

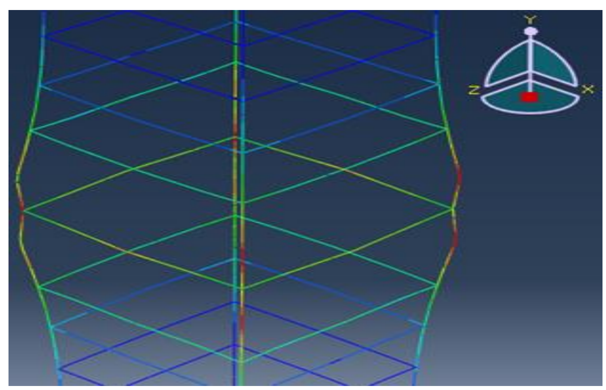

Figure 18: Buckling mode of the reinforcement embedded in specimen R120Am16

This case was more clearly observed on column specimens with 2.3% lateral reinforcement where the spacing of the lateral reinforcement was in such a way that s/dc was ≤ 0.35. Accordingly, in column specimen S30Am23, the closer spacing of lateral reinforcement and relatively higher amount of lateral reinforcement had prevented gradual buckling of longitudinal bar and limited the buckling to few spacing (Figure 14) of transverse bar (localized failure). Testifying the same observation, the stress-strain curve (Figure 12) behavior for column specimen S30Am23 had exhibited rapid strength degradation on the falling branch of the curve.

On the other hand, in column specimens where amount of reinforcement was ≥1.6% and the spacing of transverse bar was in such a way that s/dc ratio was ≥0.5, buckling of longitudinal reinforcement at relatively lower concrete strain had reduced the stress and deformation capacity of confined concrete. As a result the peak stress in these specimens was attained at strain less than 0.24% (Table 4-8) which was relatively lower strain compared to the strain of specimen with the same amount but, with closer spacing of lateral reinforcement.

In these specimens, buckling of longitudinal reinforcement was due to the lack of support at relatively lower concrete strain of the core concrete. Conformably, the mode of buckling of the longitudinal reinforcement (Figure 18) for column specimen R120Am16 (s/dc ≥ 0.5) had clearly demonstrated that buckling of longitudinal reinforcement was appeared over the length where no lateral bars support was provided. Thus, inadequate support for longitudinal bar failed to delay severe buckling of longitudinal reinforcement leading to reduction of load carrying capacity of RC column member.

In contrast buckling of longitudinal reinforcement that was observed in Figure-16 range over several spacing of lateral reinforcement and hence, gradual buckling of longitudinal reinforcement. Consequently, column specimens in Group 2 - 4, where the ratio of the spacing to core concrete dimension (s/dc) was in the range of $0.4 - 0.5$, had exhibited enhanced overall stress -strain curve behavior for confined concrete. Accordingly detailed specimens in Group-2 (Figure 5 and 6), Group-3 (Figure 7 and 8) and Group-4 (Figure 9 and 10) had exhibited stress-strain curve with considerable yielding plateau, particularly spirally tied specimens had extended yielding plateau after the attainment of the maximum stress.

3.3. Strain ductility

In this study, the strain ductility ratio was calculated from the ratio of the strain corresponding to 85% of the peak stress on the descending branch to the strain at peak stress (Table 4-8) for each investigated RC column specimen. As it could be observed the conclusion based on the strain ductility alone would lead to misinterpretation of the analysis result. For instance, specimen S60Am20 and S100Am20 in Group-4 have 2.1 and 4 strain ductility, respectively.

Thus, specimen S100Am20 with higher strain ductility expected to have higher stress sustaining performance and better stress-strain relationship compared to specimen S60Am20. However, specimen S60Am20 has 3.5% higher stress capacity and the strain at peak stress in specimen S60Am20 was 54% higher than that of specimen S100Am20. In addition, at their respective strain at 85% of the peak stress on the descending branch both specimens possess nearly equal strain capacity. Thus, the higher strain ductility observed on specimen S100Am20 did not necessarily to mean the specimen had better stress and deformation capacity.

4. Conclusion and Recommendation

Axially loaded confined RC column specimens with s/dc ratio in the range of 0.4–0.5 and amount of transverse reinforcement in the range of 1.6% – 2% had exhibited better non-linear stress-strain curve behavior. Accordingly, confined RC columns had enhanced stress and deformation capacity. The stress-strain for these columns had exhibited yielding plateau observed after the attainment of the maximum stress such that the column had the capacity of sustaining maximum stress while undergoing strain deformation.

Accordingly, detailed spirally tied square RC columns had 2.6% and 40% higher stress and deformation capacity than comparable tested RC column specimens. Whereas, detailed hoop tied RC columns had 2.3% and 12% higher stress and deformation capacity than comparable tested RC column specimens. Clearly, in both cases the enhancement on deformation capacity, due to adequate confinement was more considerable than the improvement on stress carrying capacity of the confined concrete. It was also noted that the rectangular spiral configuration of the lateral reinforcement had more significant enhancement on the axial deformation capacity compared to the enhancement due to rectangular hoop tie configuration.

Lower amount of lateral reinforcement (≤ 1.4%) failed to provide sufficient confinement to core concrete as a result; the peak stress was attained at comparatively low strain. On the other hand, column specimens with higher amount of lateral reinforcement (≥ 2.3%) where the spacing was provided in such way s/dc ratio was ≤ 0.35 had experienced over confinement that hindered gradual buckling of longitudinal reinforcement. As a result, sudden and localized buckling of longitudinal reinforcement had caused rapid strength degradation of confined concrete as such exhibited on the falling branch of stress-strain diagram of accordingly detailed column specimens.

Whereas, in RC column members where tie spacing exceeded half (s/dc ≥ 0.5) of the core dimension, the peak stress capacity of confined concrete was attained at early stage of concrete strain (nearly similar to plain concrete). In this case the major cause for the immediate reduction of stress capacity that was observed after the attainment of the peak stress was due to the lack of adequate lateral ties that could delay the buckling of longitudinal bars.

By contrast, in column specimens with amount of transverse reinforcement in the range of 1.6%–2%, where the spacing was in such a way s/dc ratio was in the range of 0.4-0.5, the buckling of the longitudinal reinforcement had taken over comparatively extended length and hence accounted for gradual loss of the load carrying capacity of accordingly detailed column specimens.

Rectangular spiral configuration of lateral reinforcement could be considered as a better alternative particularly, where deformation capacity of RC column is the main concern. In either (hoop or spiral) case of lateral reinforcement configuration, provided that adequate amount of lateral reinforcement ratio, the spacing of lateral reinforcement ratio should not exceed half of the core dimension (s/dc≤0.5) particularly where deformation capacity is the main importance. This requirement is consistent with the requirement of Ethiopian building code for RC column where medium and high ductility class column is to be constructed.

On the other hand, for axially loaded RC column with ≥ 2% lateral reinforcement, spacing of lateral reinforcement in such a way that s/dc is ≤0.35 of core dimension should be avoided. RC columns detailed with such closer spacing had experienced over confinement that had caused sudden and localized buckling of longitudinal reinforcement, which was not a desirable behavior for load carrying RC columns.

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