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Analysis of High Strength Concrete Circular Columns under Axial and Lateral Loading Combinations

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Abstract

Columns are vertical compression members which carry primarily axial Compression load. The axial load may be associated with bending moments in one or two directions. Analysis of high strength concrete columns with circular cross section and spiral transverse reinforcement was presented in this paper. A computer program was used to do the analysis of high strength circular concrete columns. The variables considered in this article were concrete strength ranging from 55 MPa to 80MPa, volumetric ratios of steel used to confine the core concrete, amount of main reinforcement and axial load level. The results indicate that as increase in the amount of lateral steel, main steel, axial load and increase in concrete strength resulted in increases in strength capacity of column. The deformability of high-strength concrete columns can be improved significantly through confinement. The results obtained in this research are agreed with results obtained by experimental and analytical study conducted by other authors.

Keywords: ***High-strength concretes; Concrete columns; Computer analysis; Moment–curvature***

تحليل الأعمدة الدائرية ذات المقاومة العالية تحت التاثير المشترك للأحمال المحورية والجانبية

الملخص

الأعمدة هي أعضاء إنشائية عائدة تصمم لتتحمل قوى الانضغاط . في بعض الأحيان تصاحب الأحمال المحورية أحمال اخرى تؤدي إلى تكوين عزوم باتجاه واحد أو باتجاهين. تحليل الأعمدة الدائري ذات مقاومة الكونكريت العالية والتسليح الحلزوني بالنسبة للتسليح العرضي هو موضوع الدراسة في هذا البحث. المتغيرات التي تم دراستها في هذا البحث هي مقاومة الكونكريت والتي تتراوح بين (٥٥- ٨٠) ميكاباسكال، نسبة حديد التسليح العرضي ، كمية حديد التسليح الطولي ونسبة القوة المحورية . برنامج حاسوبي تم انشائة لهذا الغرض. بينت النتائج بان زيادة حديد التسليح العرضي والطولي وزيادة مقاومة الكونكريت و نسبة القوة المحورية يؤدي الى زيادة في مقاومة الأعمدة الكونكريتية. يمكن زيادة كفاءة استخدام الكونكريت ذو المقاومة العالية من خلال استخدام كميات مناسبة من الحديد العرضي. النتائج التي تم الحصول عليها متوافقة الى حد ما مع نتائج عملية وتحليلية لباحثين آخرين.

1. Introduction

Strength of concrete used in the construction has increased gradually over the years. Concretes of up to 120 MPa compressive strength have been used in structural applications, especially in columns of selected multistory buildings [1]. The main advantages of using high strength concrete in building constructions are: increased strength of structures, reduced cross-sections and more durable material. One advantageous use of high-strength concrete is in the columns of tall structures. For a given load, the high-strength concrete column has a smaller cross-sectional area, thus providing more floor space.

Columns are members that carry loads chiefly in compression. Nevertheless, their contribution in horizontal stiffness of building frames is also of great importance. The main reinforcement in columns is longitudinal, parallel to the direction of the axial load, and consists of bars arranged in a square, rectangular or circular pattern. The design primarily considers the compression and bending moments about one or both axes of the cross section. When strong horizontal shaking, as one during an earthquake, is transmitted, the columns may undergo lateral deflection which in turn affects the horizontal stiffness, therefore the study of high strength column is very important. Due to limited amount of experimental research and to the uncertainty inherent in the prediction of failure of the structural elements under earthquake loading, the use of high strength concrete structures in seismic risk areas needs extra caution in order to ensure adequate ductile behavior [2]. Some widely accepted properties of high-strength concrete, as reported in several studies [3-5], are its higher modulus of elasticity, less ductile mode of failure, and larger strain at maximum stress [6]. As mentioned, high-strength concrete offers advantages in performance and economy of construction, but, the brittle behavior of the material remains a major drawback for seismic applications. Since strength and ductility of concrete are inversely proportional, therefore, concrete confinement becomes a critical issue for high-strength concrete columns in seismically active regions. The use of transverse reinforcement in reinforced concrete columns provides confinement to compressed concrete, prevents premature buckling of compressed longitudinal bars, and acts as shear reinforcement. The quantities of transverse reinforcement present in columns designed for seismic resistance should ensure ductile behavior during severe earthquake loading. In the seismic design of moment resisting frames of buildings it is possible to use a strong column-weak beam approach to reduce the likelihood of plastic hinging in columns during a major earthquake [7].

This paper presents an analysis of high-strength concrete columns subjected to combine axial and lateral loading. The columns have a circular cross section and spiral circular transverse reinforcement. The variables studied in this article are the concrete strength, volumetric ratios of steel used to confine the core concrete, amount of main reinforcement and axial load level. The results were compared with experimental results to verify the accuracy of the analysis method. The material model for concrete used in this analysis is based on a model suggested by Mander et al.[8]. This model takes into account the different stress-strain curves of the concrete cover and the confined core. King et al. model [9] was used for the reinforcing steel.

2. Material models

The material constitutive models used in the program are described in the following sections: These include a concrete model for unconfined and confined concrete, and reinforcing steel models.

2.1 Model Proposed by Mander et al. (1988) [8]

Mander et al. [8] proposed a stress-strain model for steel-confined concrete subjected to uniaxial compressive stress (Figure 1). This model is based on the axial compressive tests of concrete with a quasi-static strain rate and monotonic loading. Their model utilized the equations developed by Popovics [10], originally proposed for stress-strain response of unconfined concrete:

$$f_c = \frac{f'_{cc}.x.r}{r-1+x^r} \tag{1}$$

Where:

$$x = \frac{\varepsilon_c}{\varepsilon_{cc}}$$

ε_c : longitudinal compressive concrete strain

$$\varepsilon_{cc} = \varepsilon_{co}\left\{1+5\left(\frac{f'_{cc}}{f'_{co}}-1\right)\right\} \tag{2}$$

ε_{co}: unconfined concrete strain

f'_{co} : unconfined concrete strength

f'_{cc} = confined concrete strength

$$r = \frac{E_c}{E_c - E_{sec}}$$

$$E_{sec} = \frac{f'_{cc}}{\varepsilon_{cc}}$$

$$\varepsilon_{cu} = 1.4\left(0.004 + \frac{1.4\,\rho_s f_{sh} \varepsilon_{su}}{f'_{cc}}\right) \tag{3}$$

E_c: tangent modulus of elasticity of concrete

For circular sections:

$$f'_{cc} = f'_{co}\left(-1.254 + 2.254\sqrt{1 + \frac{7.94 f'_l}{f'_{co}}} - 2\frac{f'_l}{f'_{co}}\right) \tag{4}$$

$$f'_l = \frac{1}{2} k_e \rho_s f_{yh}$$

f_{yh}: yielding stress of transverse reinforcement

$$\rho_s = \frac{4\,A_{sp}}{d_s\ s}$$

A_{sp}: cross section area of spiral

s: distance between spirals, center to center

d_s: diameter of the core (center to center of spirals)

$$k_e = \frac{1 - \frac{s'}{2d_s}}{1 - \rho_{cc}}$$

s': clear distance between spirals

ρ_{cc}: ratio of area of longitudinal reinforcement to area of core section

And for unconfined concrete use equ. (1) with a lateral confined stress $f'_l = 0$. The part for strains larger than $2\varepsilon_{co}$ is assumed to be a straight line which reaches zero at ε_{sp} as shown in Fig.1.

The ultimate strain was defined to be the strain at first hoop fracture and is calculated from an energy balance approach. The shaded area in Fig. 1 represents the increase in strain energy at failure resulting from confinement, which is equal to the strain energy capacity of the confining reinforcement. By equating the ultimate strain energy capacity of the confining reinforcement per unit volume of concrete core to the shaded area plus additional energy required to maintain yield in the longitudinal steel in compression, the ultimate strain corresponding to hoop fracture can be calculated as above by equ.(4).

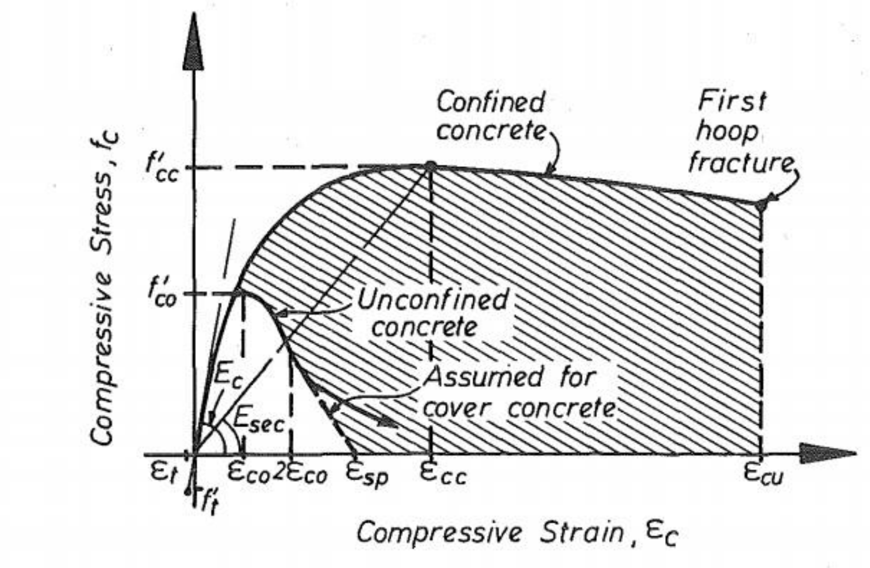


Fig.1 Stress-strain model for monotonic loading of confined concrete and unconfined (Mander et al.) [8]

2.2 Models for the Reinforcing steel:

2.2.1 King et al. model [9]

The stress-strain relation for the reinforcing steel Fig.2 is the same used by King et al. [9].

$$f_s = E_s\,\varepsilon_s \qquad for \qquad \varepsilon_s \le \varepsilon_y \tag{5}$$

$$f_s = f_y \qquad for \qquad \varepsilon_y < \varepsilon_s < \varepsilon_{sh} \tag{6}$$

$$f_s = f_y\left[\frac{m(\varepsilon_s - \varepsilon_{sh}) + 2}{60\,(\varepsilon_s - \varepsilon_{sh}) + 2} + \frac{(60 - m)(\varepsilon_s - \varepsilon_{sh})}{2\,(30r + 1)^2}\right] \qquad \varepsilon_{sh} < \varepsilon_s \le \varepsilon_{sm} \tag{7}$$

Where:

$$m = \frac{\left(\frac{f_{su}}{f_y}\right)(30r + 1)^2 - 60r - 1}{15r^2}$$

$$r = \varepsilon_{su} - \varepsilon_{sh}$$

Where:

f_s = steel stress

ε_s = steel strain,

ε_{sh} = steel strain at commencement of strain hardening

f_{su} = ultimate tensile strength of steel

f_y = yield strength of steel

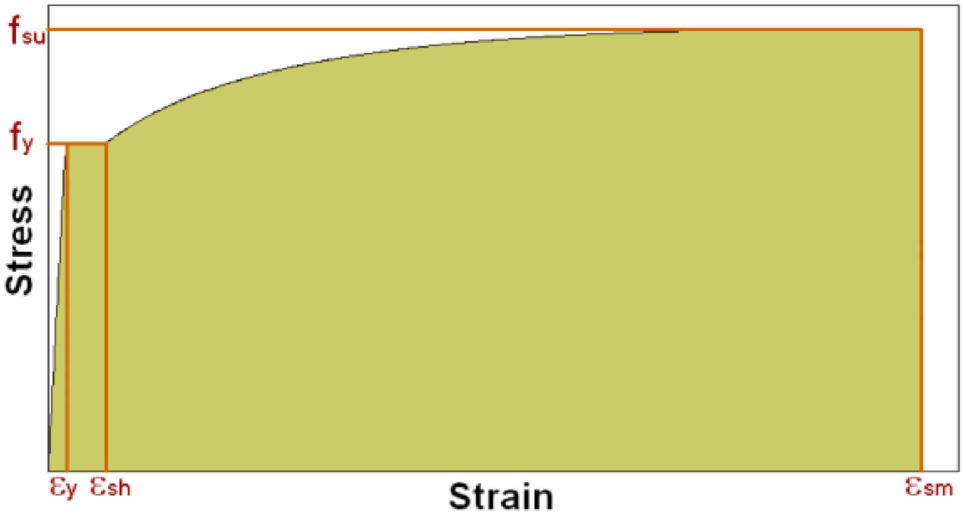


Fig.2 King et al. constitutive model for the reinforcing steel

2.2.2 Raynor et al. Model [11]

As proposed by Raynor et al. (2002).

$$f_s = E_s\,\varepsilon_s \qquad for \qquad \varepsilon_s \le \varepsilon_y \tag{8}$$

$$f_s = f_y + (\varepsilon_s - \varepsilon_y)E_y \qquad for \qquad \varepsilon_y < \varepsilon_s < \varepsilon_{sh} \tag{9}$$

$$f_s = f_u - (f_s - f_{sh})\left(\frac{\varepsilon_{sm}-\varepsilon_s}{\varepsilon_{sm}-\varepsilon_{sh}}\right)^{C1} \qquad \varepsilon_{sh} < \varepsilon_s < \varepsilon_{sm} \tag{10}$$

Where:

$$\varepsilon_y = \frac{f_y}{E}$$

$$f_{sh} = f_y + (\varepsilon_{sh} - \varepsilon_y)E_y$$

E_y: is the slope of the yield plateau

C1: is the parameter that defines the curvature of the strain hardening curve as shown in Fig. 3.

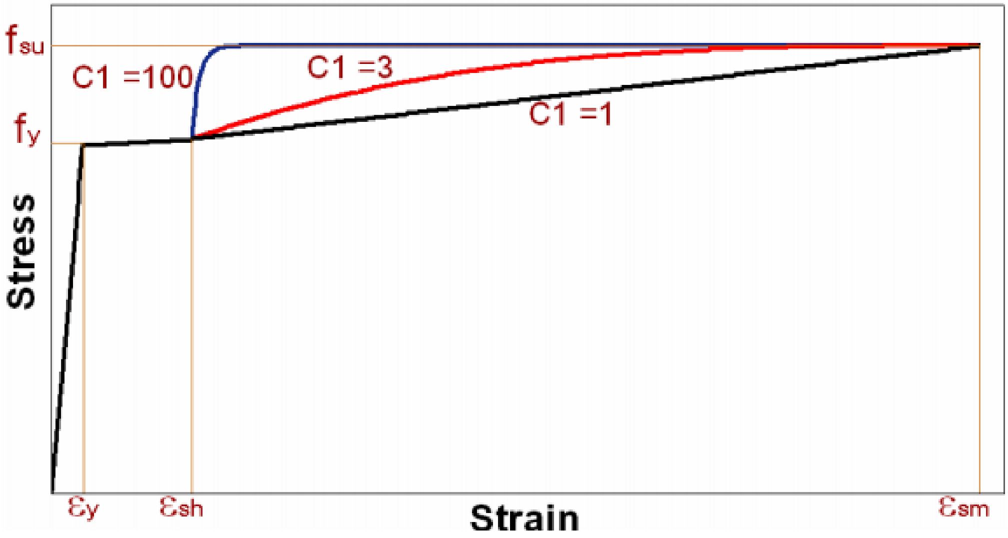


Fig.3 Raynor et al. [11] constitutive model for the reinforcing steel

3. Analytical Models

Set of codes have been written with Mattlab program depend on CUMBIA codes prepared by Montejo and Kowalsky [12] were developed to carry out calculations for theoretical moment-curvature relations of columns with a circular cross. Effect of concrete strength, volumetric ratios of steel used to confine the core concrete, amount of main reinforcement and axial load level on the behavior of column under axial load and lateral load were investigated. The required input data included cross-sectional dimensions of specimens, position, and amount of longitudinal steel, amount of and spacing of transverse steel, properties of longitudinal and transverse steel, unconfined concrete strength and applied axial load. The column was divided into 40 small slices, each one containing two types of elements, core, and cover. It must be expressed that reasonably small tolerance value (0.001) is chosen to stop the procedure.

The analysis procedure involved by assign an initial value of compressive strain at extreme concrete fiber and then increasing levels of the strain; an iterative procedure is used to find the neutral axis depth to satisfy equilibrium at each level of concrete strain; calculate strain at the middle of each element and in longitudinal steel bars. The program stops when the concrete strain in the core exceeds the maximum concrete strain, the tension strain in the steel bars exceeds the maximum steel strain or there is a suddenly lost of strength. The program may also stops if the maximum number of iteration is reached. If the solve of problem does not achieve, the allowable tolerance can be also changed.

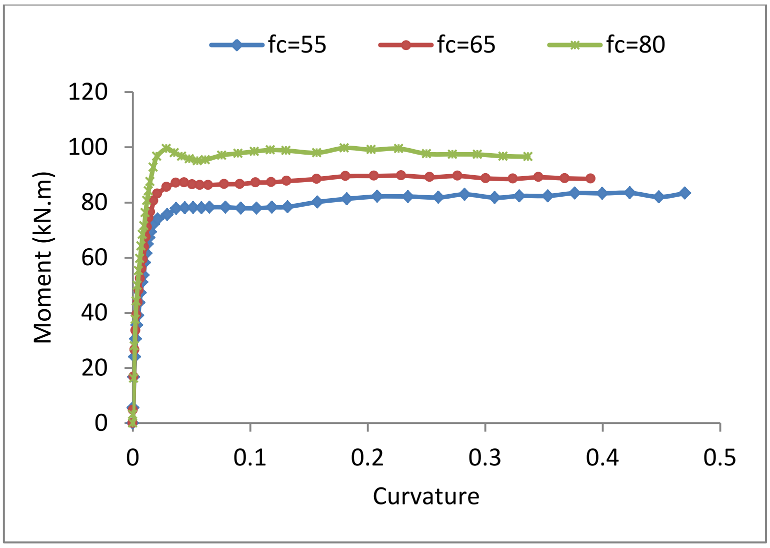
5. Results and Discussion

In the research described in this paper, a series of moment curvature analyses was performed on circular columns with varying strength of concrete, levels of axial load ratio, spacing of lateral reinforcement and longitudinal reinforcement ratio. The axial load was varied from 0.1 to $0.5 f_c' \, A_g$. The baseline section has the following information: the diameter of column was 300 mm. The length of column was 1000 mm. The concrete compressive strength was 55 MPa, while the yield stress of all reinforcement was 460 MPa. The longitudinal reinforcement ratio was chosen as 1.1%, and the transverse bar diameter was chosen as10mm @ 120mm. The concrete cover to the main reinforcement was 20 mm.

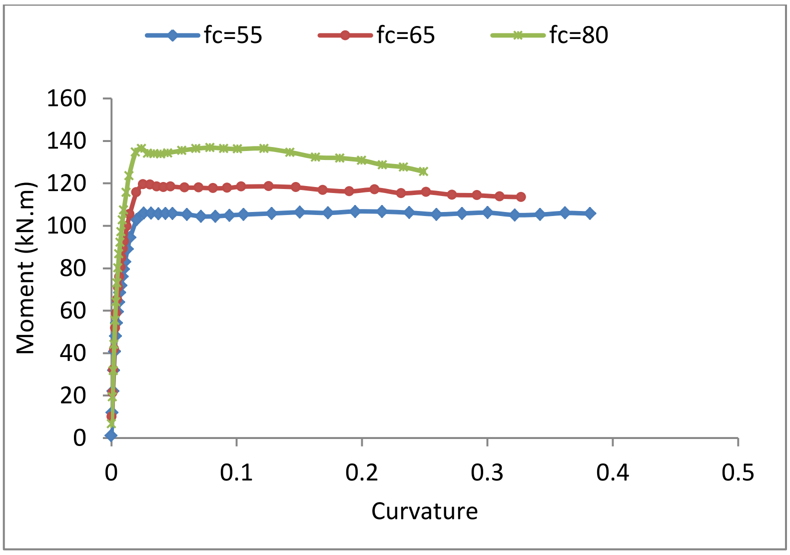
The effects of different variables have been studied by comparing moment-curvature relations of the sections of those columns in which only one major variable differed significantly. These variables are:

5.1 Effect of Compressive Strength

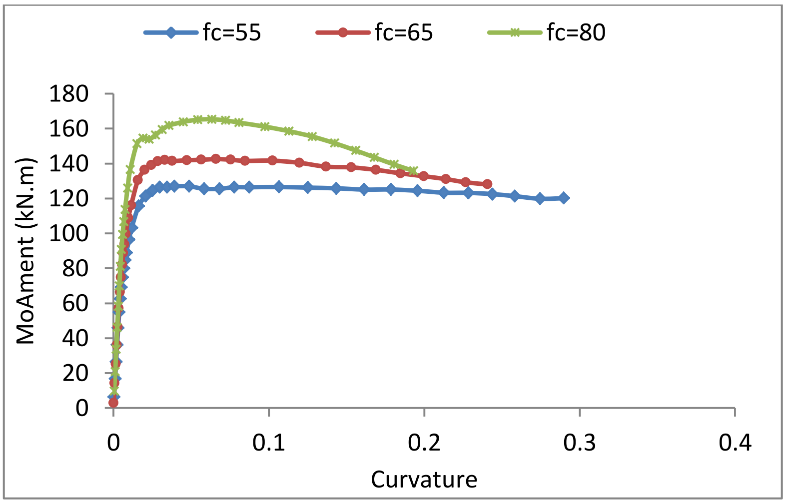
The concrete compressive strength is important parameter. Three different concrete strength (55MPa, 65 MPa and 80 MPa) were considered to investigate this parameter in this study, all these values within high strength concrete range. Figures 4(a) to 4(e) show the effect of the concrete strength on moment-curvature relationships. The axial load was varied from 0.1 to $0.5 f_c' \, A_g$ respectively for Fig. 4(a) through Fig. 4(e). All figures indicate that higher ductility is obtained in the lower strength concrete column and at lower axial load ratio. While the overall strength of column is increased with increasing the concrete strength. The results obtained here have the same trend as those obtained experimentally by Sheikh et al. [13], Sungjoong[15].



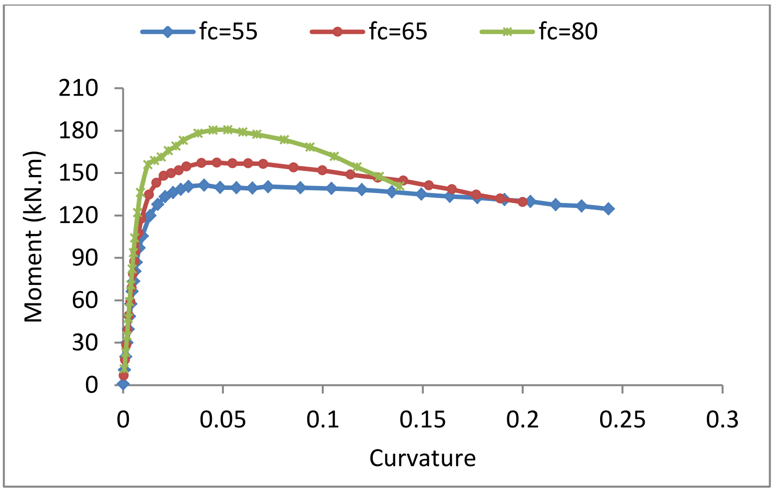
(a) Axial load ratio is 0.1



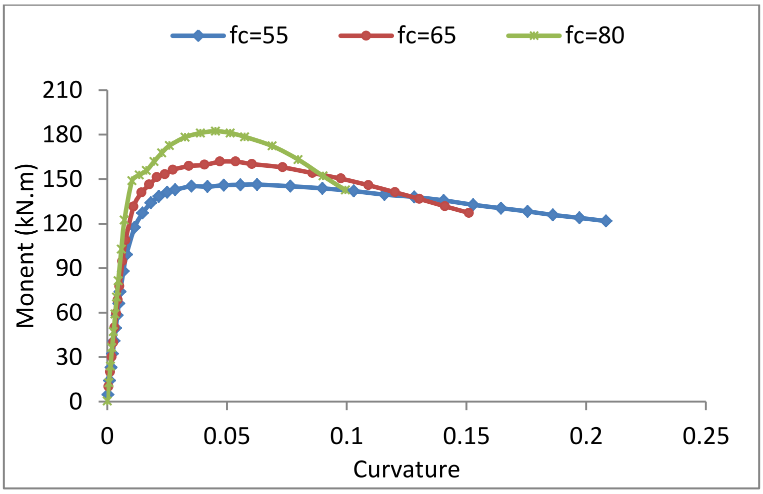
(b) Axial load ratio is 0.2



(c) Axial load ratio is 0.3



(d) Axial load ratio is 0.4

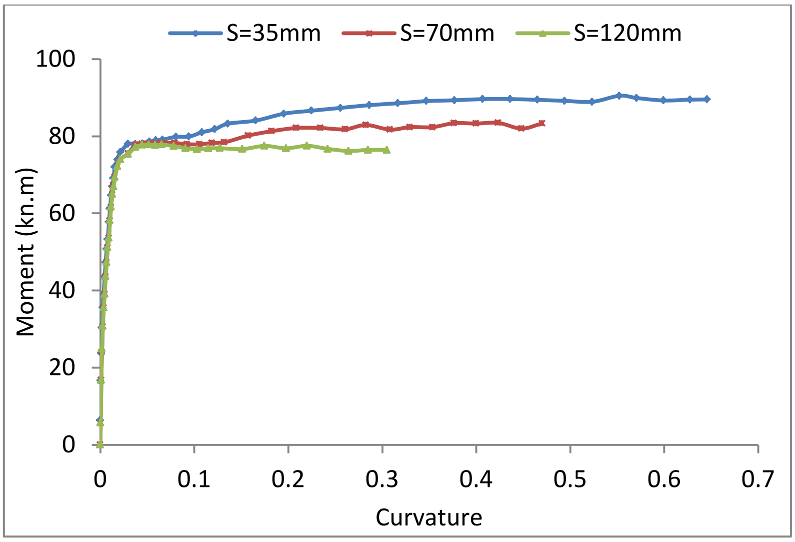


(e) Axial load ratio is 0.5

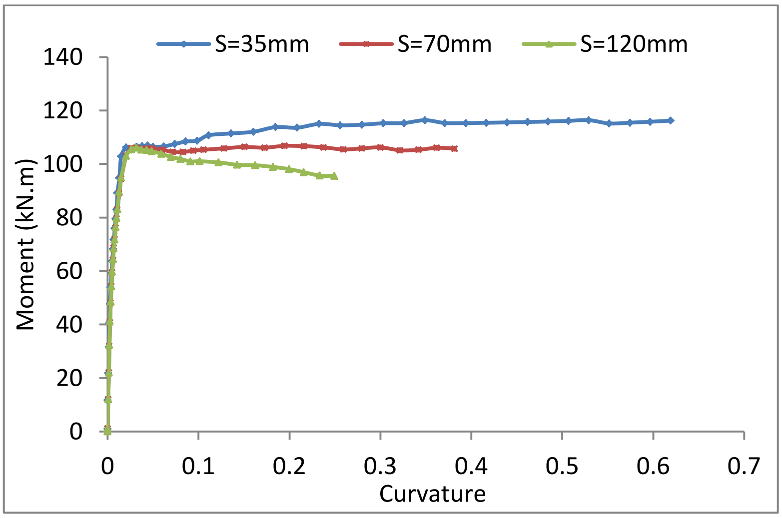
Fig.4 Effect of concrete compressive strength on moment-curvature relationships

5.2 Effect of amount lateral steel

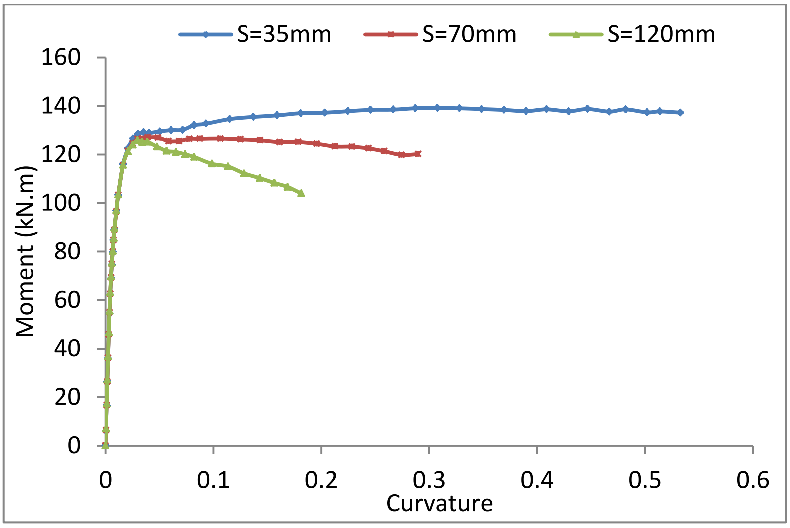
The effect of amount of the lateral reinforcement was investigated by considering three different values of spacing of lateral reinforcement (35 mm, 70 mm and 120 mm). All other parameters were kept as a baseline section as mentioned above. Figures 5(a) to 5(e) illustrate the effect of spacing of lateral reinforcement on strength and deformability of high strength concrete column. As shown from Figures a smaller spacing enhancement the strength and ductility of circular column. This may be due to that a smaller spacing increases the confined concrete area, resulting in higher confinement efficiency. Also it can be seen that more sudden drop of load resistance after peak load occurred in the columns with lower volumetric ratio or larger spacing of transverse steel. It may be concluded from these results that reducing the spacing of lateral reinforcement would result in an increased moment capacity of the section. Ductility would also be improved. The reduction of the spacing, from 120 mm to 35 mm for axial load ratios of 0.1, 0.2, 0.3, 0.4 and 0.5 results in increases of the strength gain (16%, 11%, 11%,14% and 21%) respectively. Also it can be noted that the ductility decreases with increasing the axial load ratio. The results obtained here have the same trend as those obtained experimentally by Sheikh et al. [13].



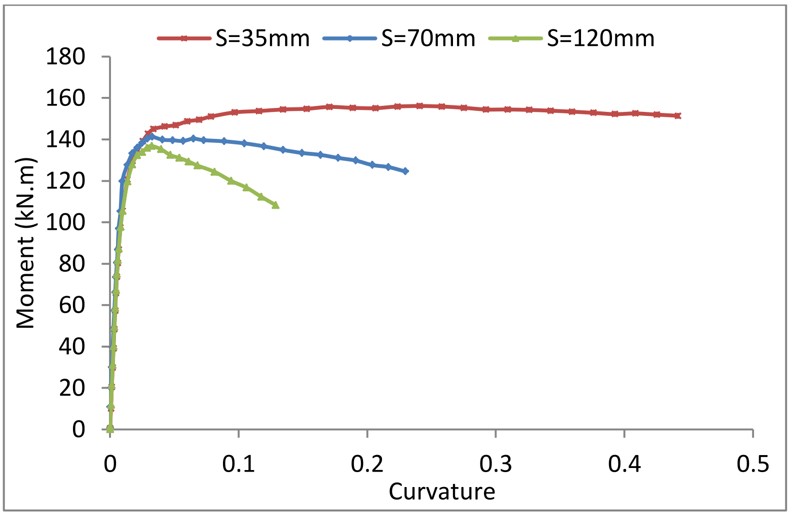
(a) Axial load ratio is 0.1



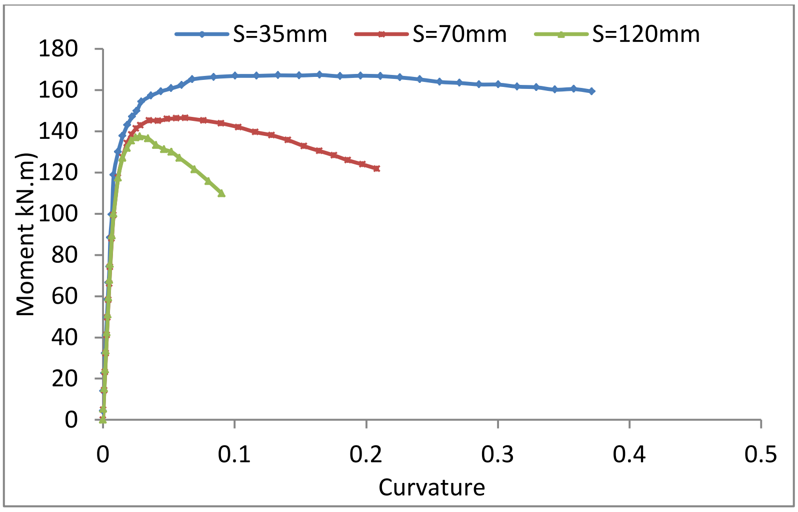
(b) Axial load ratio is 0.2



(c) Axial load ratio is 0.3



(d) Axial load ratio is 0.4

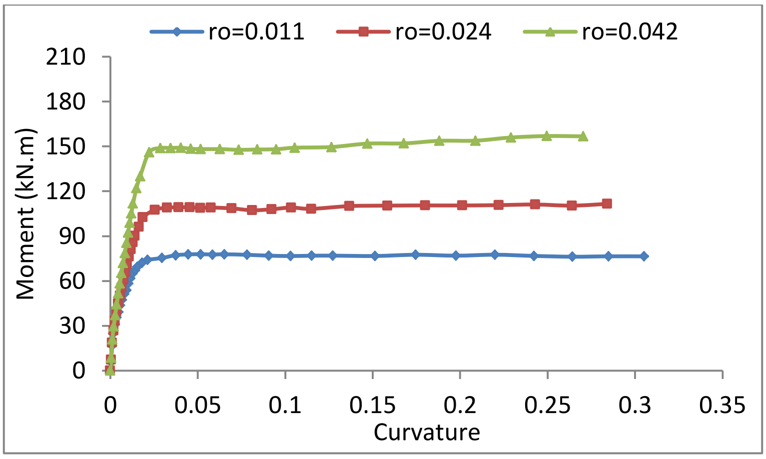


(e) Axial load ratio is 0.4

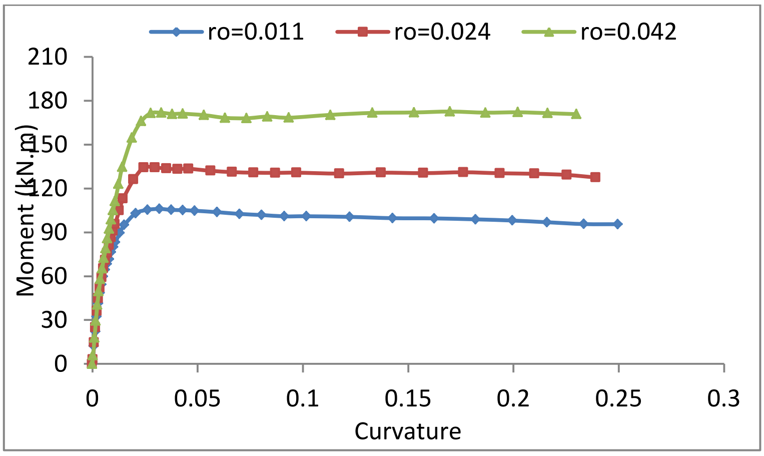
Fig.5 Effect of spacing of lateral steel on moment-curvature relationships

5.3 Effect of longitudinal reinforcement ratio

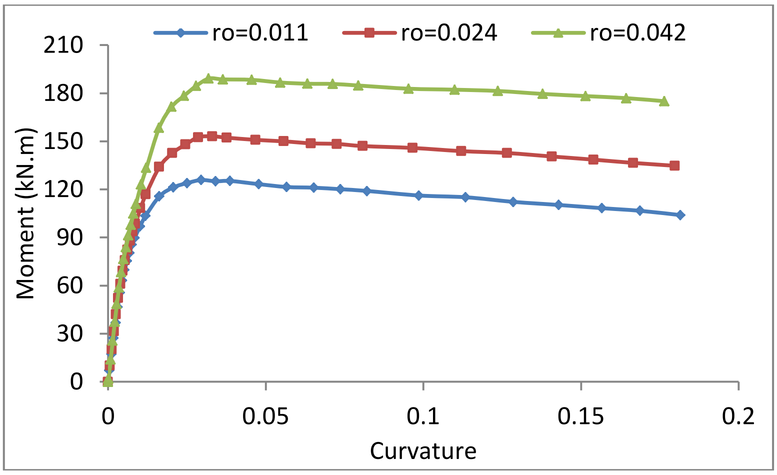
Figures 6(a) - 6(e) compare the strength and the ductility of columns with a lower ratio of longitudinal steel to the strength and the ductility of columns with a higher ratio of longitudinal steel. A larger amount of longitudinal bars, provided by a larger bar diameter. Three different ratios of longitudinal reinforcement were considered (1.1%, 2.4 % and 4.2%). Other parameters are almost same in each comparison. From the comparisons, the strength (moment capacity) increases with increasing the ratio of longitudinal reinforcement. The ductility seem to be slightly larger for columns with higher ratio of longitudinal steel. The larger amount of longitudinal steel may provide more restraining action against an inclined shear failure as dowels compared to small amount of longitudinal steel [13]. Therefore, it can be concluded that the amount of longitudinal steel has effect on the strength while has only small effect on ductility of columns. The results obtained here have the same trend as those obtained experimentally by Sheikh et al. [14] and [15].



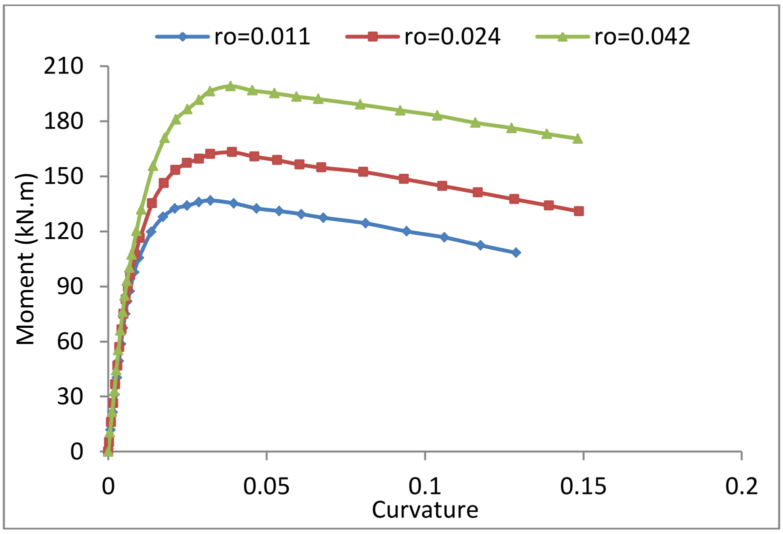
(a) Axial load ratio is 0.1



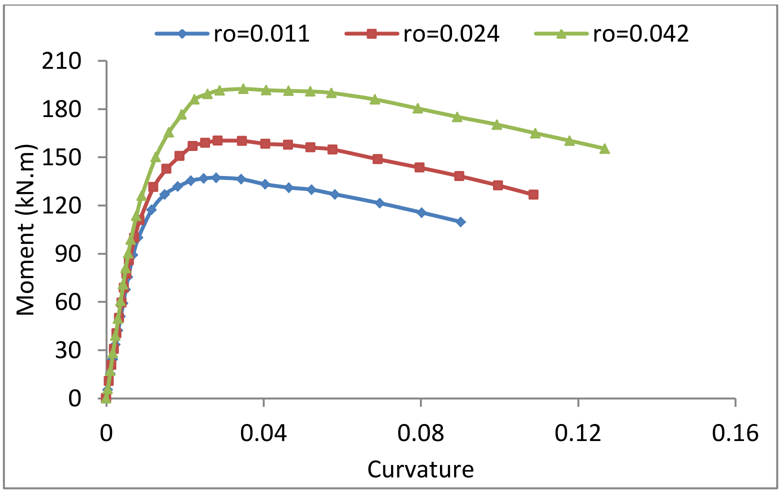
(b) Axial load ratio is 0.2



(c) Axial load ratio is 0.3



(d) Axial load ratio is 0.4



(e) Axial load ratio is 0.5

Fig.6 Effect of ratio of longitudinal steel on moment-curvature relationships

6. Conclusions

The behavior of high-strength concrete columns subjected to combine axial and lateral loading was investigated in this study. The parameters that significantly affect the behavior of high strength circular concrete column, including compressive concrete strength, amount of longitudinal steel, and spacing of lateral steel and the level of axial load have been studied in this study. The following conclusions can be drawn based on and analytical investigations reported in this study.

1-The result presented in this paper indicates that ductility of column decreases with increasing concrete strength.

2-Strength and ductility of concrete columns are improved significantly for well confined concrete core. In other words a larger number of laterally supported longitudinal bars results in higher flexural strength and ductility. While the amount of longitudinal steel has effect on the strength and has only small effect on ductility of columns.

3- The ductility of concrete columns is decreased with increasing axial load ratio.

4-High-strength concrete columns with sufficient lateral confinement pressure can be used to resist combination of axial and lateral loading such as seismic loading.

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