NUMERICAL INVESTIGATION OF REINFORCED CONCRETE COLUMNS WITH OPPOSING SPIRALS UNDER AXIAL COMPRESSION LOADS

Ahmed Ibrahim, Ph.D., P.E [1], Mohammed Al-Osta, Ph.D[2], Riyadh Hindi, Ph.D., P.E[3].

[1]Assistant Professor, King Fahd University of Petroleum & Minerals, Dhahran, 31261, Kingdom of Saudi Arabia, Lecturer (on leave), Structural Engineering Department, Zagazig University, Zagazig, 44519, Egypt.
[2]Assistant Professor, King Fahd University of Petroleum & Minerals, Dhahran, 31261, Kingdom of Saudi Arabia.
[3]Associate Professor, Parks College of Engineering, Aviation and Technology, Saint Louis University, St. Louis, MO, United States.

ABSTRACT: The spiral reinforcement is a very common technique in reinforcing columns in most active seismic regions due to its high ductility and high ability of energy absorption. This paper presents the nonlinear finite element analysis of normal and high-strength concrete confined with cross (opposing) circular spiral reinforcements. The comprehensive finite element code Abaqus is used to conduct all the numerical simulations. The concrete and steel materials nonlinear properties are considered in the simulations and the effect of confinement is considered as well. The proposed technique is developed to improve strength and ductility of concrete confined with conventional spiral systems. The experiments are conducted on twenty-one reduced scale with four different spacing spirals and four longitudinal reinforcing ratios. Three specimens were chosen from the experimental testing for the finite element validation. The results are compared with small-scale concrete columns tested experimentally and made with the same technique under monotonic axial loads. All columns with cross spiral reinforcement designed to have same lateral reinforcement volumetric ratios. The verification of all the considered specimens showed very good agreement with the experiments in terms of axial stress and strain. The developed finite element code showed reasonable results in terms of predicting the columns response with cross (opposing) spiral reinforcements.

1 INTRODUCTION

The strength and the axial capacity of concrete columns could be greatly improved by lateral confinement using different materials such as stirrups, steel jackets, and fiber reinforced polymer (FRP) wraps and reinforcements. The stress-strain behaviour of confined concrete under compression is affected by many factors like the degree of confinement, the confinement configuration, and by the type of confining material (Wu et al. 2006b). The tri-axial state of stress created by columns lateral confinement delays the crushing of concrete at the column core leading to enhancement of strength and ductility. The effectiveness of the lateral resistance is determined based on the method of confinement used. The most common methods of confinement recommended by the ACI 318 is to use conventional steel spirals, which proven to be a very effective method in reinforced concrete (RC) columns. The minimum spacing of spirals specified by the ACI is 25 mm to ensure constructability and concrete flowability. The strength and deformability are attributed to the lateral confining stress generated by the spiral confinement. Very limited data are available on the use of cross spiral systems on confining concrete columns.

Hindi (2005) proposed the use of two opposing cross spirals in lieu of the conventional single spiral. The spacing of the cross spiral could be operated to increase the behaviour and characteristics of columns and to improve constructability. The cross spirals could be used with the conventional spacing recommended by the ACI to effectively doubling the volumetric lateral confinement ratio. The cross spiral configuration could be used in areas where constructability is a question. Hindi et al. (2005) conducted experimental tests on reinforced concrete (RC) columns with the cross-spiral confinement technique. Small-scale reinforced normal weigh concrete specimens were tested under pure axial compression. The experimental results revealed, when comparing the conventional single-spiral confined columns to the cross-spiral columns with the same volumetric confinement ratios, similar behaviour in strength and ductility between the specimens.

Various methods of lateral confinement have been tested: hoops, welded-wire mesh, high-strength strands, carbon FRP spirals and hoops, and spirals [Tan et al. (1999), Tavio et al. (2011), Budek et al. (2002), Wu et al. (2014), and Tanaka et al. (1993), Afifi et al. (2014)]. These tests were conducted for various reasons: to verify code adequacy, to develop new methods and ultimately, and to increase the strength and ductility of normal and high-strength concrete columns. Ding et al. (2014) studied mechanical performance of stirrup-confined concrete-filled steel tubular stub columns under axial loading. The study recommended that the steel tube, internal stiffeners effectively enhanced ductility but there was limited improvement of ultimate loadbearing capacity.

Liang et al. (2014), conducted experimentally and analytically the axial compressive load-carrying capacity and behaviour of nine full-scale square short composite steel and concrete columns confined by multiple interlocking spirals. The study concluded that the contribution of the structural steel on the confinement, the composite columns with multiple spirals demonstrated better strength and ductility than the conventional reinforced concrete column with multiple spirals. Many theoretical RC stress-strain confinement models have been developed for columns confined with steel spiral reinforcements, Mander et al. (1988) is one of the common models used in the current study to be implemented in the finite element code.

Marvel et al. (2014) investigated the behaviour of high-strength reinforced concrete columns confined using cross-spiral technique and subjected to monotonic axial loads, and the conclusion of the study recommended that columns confined with cross spirals having similar volumetric confining ratios as conventional single spirals had a similar ultimate strength and an increased ultimate strain and ductility. On average, the cross-spiral columns obtained 120% of the ultimate strain of its conventional single-spiral

The objective of this paper is to numerically investigate the axial behaviour of concrete columns using the cross spiral confinement technique and to compare the results to the experimentally tested columns. The numerical simulations were conducted using the comprehensive finite element code ABAQUS. The following sections present the description of the experimental tested specimens and the finite element model as well.

2 EXPERIMENTAL SETUP

The experimental program consisted of twenty-one reduced-scale reinforced high-strength concrete circular columns with various longitudinal reinforcement ratios and four different confinement reinforcement ratios. The columns were subjected to monotonic axial loading to study the influence of the cross spiral on the axial strength. All columns designed to satisfy ACI 318 requirements. Seven of the twenty-one specimens were constructed using conventional single spirals and serve to compare against the proposed cross-spiral configuration. The remaining fourteen columns were constructed using the cross-spiral confinement technique. All specimens had the same overall dimensions with the only variations existing in the longitudinal reinforcement ratios and spiral spacing. All specimens had diameters of 350 mm and lengths of 1000 mm and No. 5 longitudinal reinforcing bars were used and evenly spaced over a diameter of 250 mm, giving longitudinal steel ratios of 0.016, 0.020, 0.024 and 0.028. A typical concrete column is reinforced with a longitudinal steel ratio of 0.02. The confining spiral used was U 9.5 mm (No. 3) with four base spiral spacing of 40, 50, 55, or 60 mm, covering the allowable spiral spacing set forth in ACI 318. Figure 1 shows the different spiral configuration and Figure 2 shows the Schematic representation of test specimen. More details about the columns testing matrix could be found on Marvel et al. (2014).

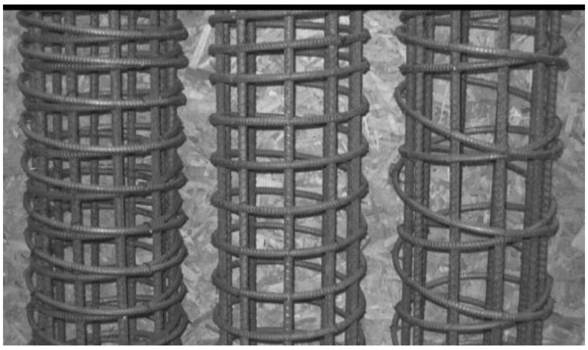


Figure 1. Specimen comparison, cross spiral spacing of S, single spiral spacing of S, cross spiral spacing of 2S (Marvel 2014).

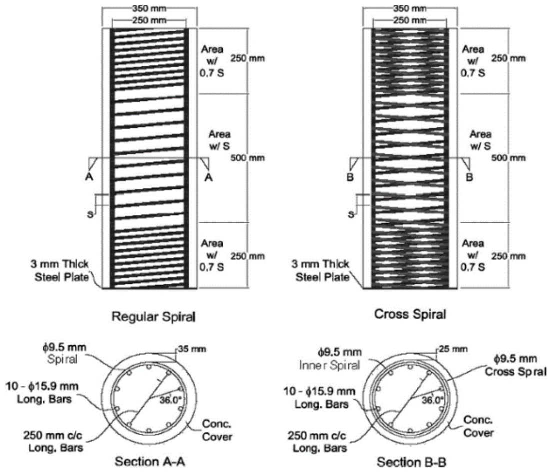


Figure 2. Schematic representation of test specimen (Marvel et al.2014).

3 FINITE ELEMENT MODELLING

In this section, the details of the finite element (FE) modelling and the geometry for the columns studied are presented. The numerical simulations were conducted using the ABAQUS code, which is a general FE analysis package for modelling the nonlinear mechanics of structures, fluids, and their interactions. ABAQUS is based on implicit and explicit numerical methods for problems associated with large deformation and multi-loading environments. The mesh consists of solid elements to represent the concrete and one-dimensional elements were used to represent the steel reinforcement. The ready-mixed concrete had a maximum aggregate size of 19 mm with a specified compressive strength f_{0c} of 70 MPa. The average 28-day compressive strength for placements was 67.3 MPa. The steel reinforcing bars and spirals were modelled as elastic perfectly plastic materials in compression and tension. The Truss element was used in ABAQUS to simulate the steel longitudinal and lateral reinforcements. Eight node solid brick elements with one Gaussian integration point were used to model the concrete columns. Figure 3 shows the concrete and steel models simulated in Abaqus. The concrete behaviour is independent of the reinforcing bars and spirals. The rebar-concrete interface is modelled assuming perfect bond. The Concrete Damaged Plasticity (CDP) Model was used to simulate the concrete behaviour. Figure 4 shows the concrete behaviour in compression and tension as implemented in the present study. Figure 5 shows the normalized inelastic stress strain curves for concrete and steel used in this study.

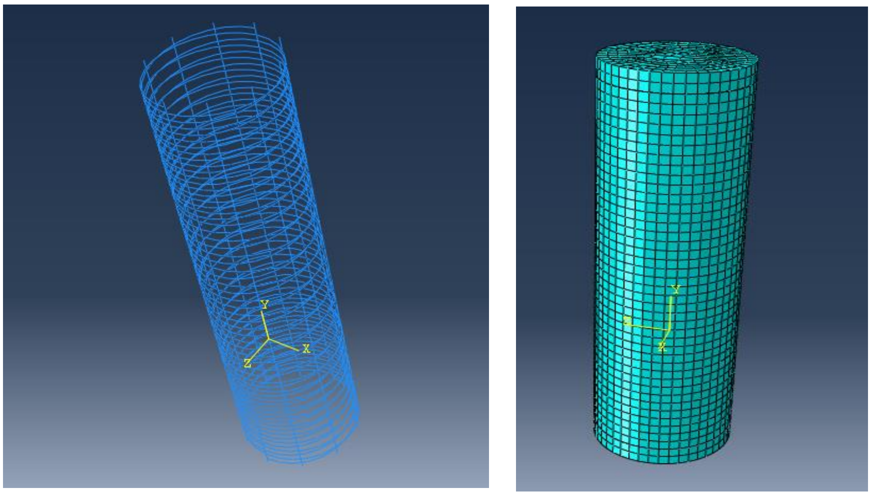


Figure 3. Finite elemnt mesh for the steel reinforcement and concrete.

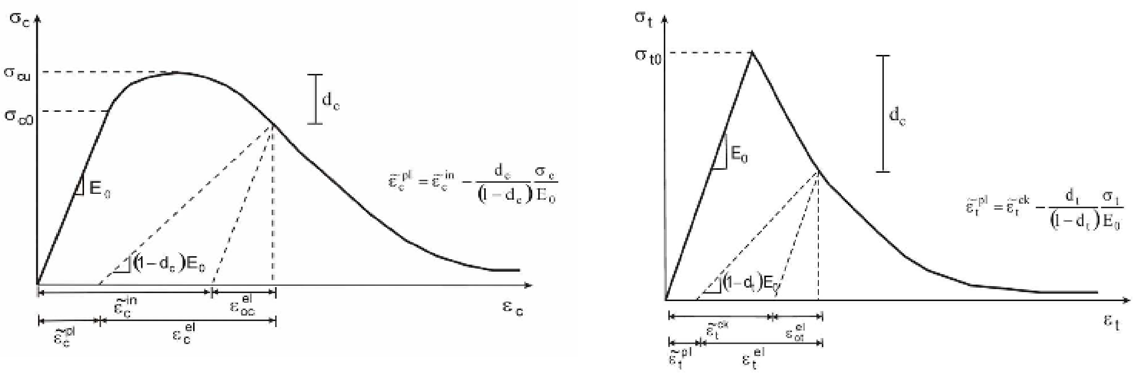


Figure 4(a). Stress-Strain of concrete in compression, (b) in tension for CDP model in tesion (ABAQUS).

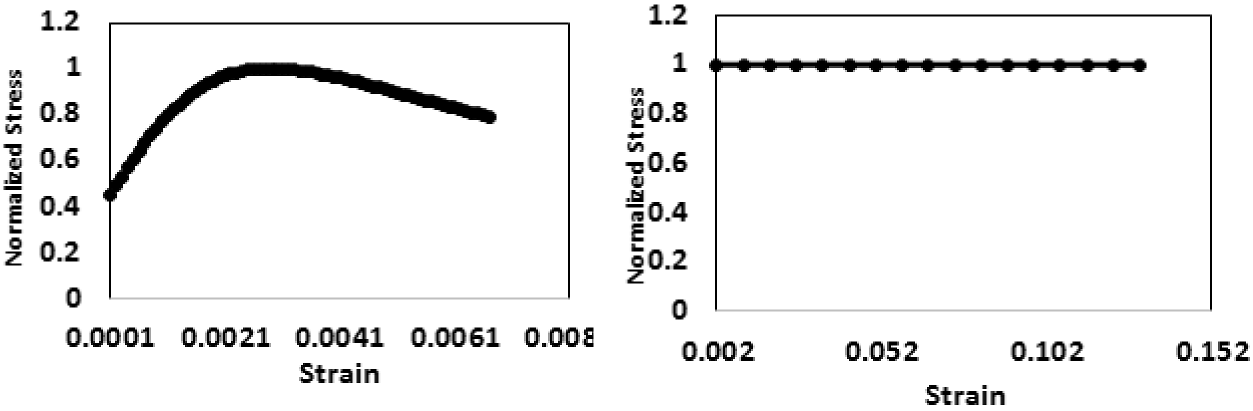


Figure 5(a). Inelastic stress-strain of concrete, (b) Plastic stress-atrain of steel.

The plastic damage model parameters implemented in ABAQUS are shown in table 1.

Table 1. Parameters Used for the Concrete in Plastic Damage Model.

Young's Modulus MPa	Poisson's Ratio	Dilation Angle, ψ Degree	Eccentricity, ε	f_{bo}/f_{co}	κ
39323	0.18	36	0 .1	1.16	0.67

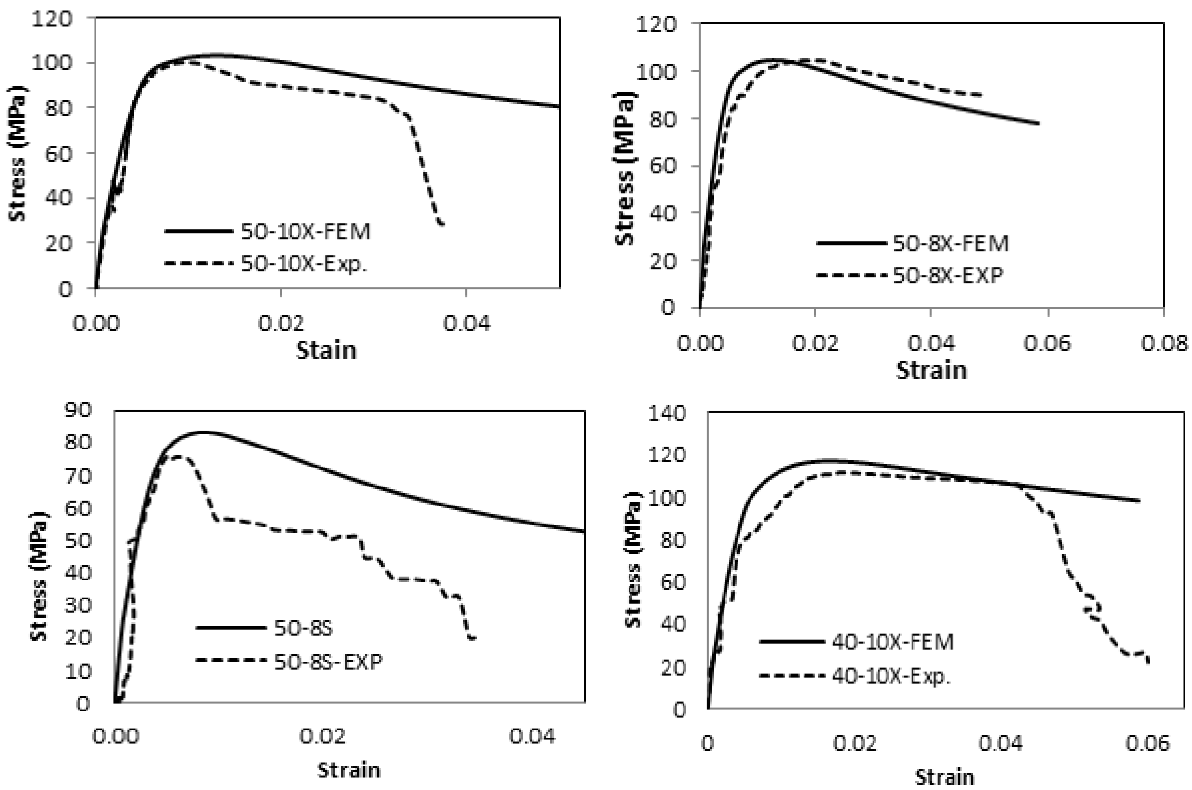
4 RESULTS OF THE FINITE ELEMENT MODELLING

All finite element models were established using ABAQUS/Explicit. In these models, the concrete and the top loading steel plate for all specimens, 8-node reduced integral format 3D solid elements were used, and the surface of loading plate was defined as rigid to ensure that the deformation of the upper and lower surfaces of steel and concrete was the same. A structured meshing option with a mesh size of 40 mm was adopted, and the resulting FE model is shown in Fig. 3. A surface-to-surface constraint is used to couple the steel and concrete with separate surfaces together so that no relative motion occurs between them. To model the decrease of load-bearing capacity of specimens, load was applied through increments of displacement and both material and structural nonlinearities were considered and solved using the incremental-interactive method in ABAQUS. The FE model results are compared with the experimental results (Marvel t al. (2014)) before the investigation of the parametric study. Table 1 shows the column cases used in the verification and the comparison of the experimental results with the finite element results in terms of stress-strain curves are shown in Fig 5.

Table 2. Columns cases considered in the FE study

Specimen	Spiral Type	Effective length (mm)	Spiral Spacing (mm)	Longitudnal Reinforcement Ratio (ρ_l)	Lateral Reinforcement Ratio (ρ_s)
50X-8	Cross (X)	1000	50	0.016	0.04
50X-10	Cross (X)	1000	50	0.020	0.041
50S-8	Regular (S)	1000	50	0.016	0.021
40X-10	Cross (X)	1000	40	0.020	0.052
55X-10	Cross (X)	1000	55	0.020	0.038
60X-10	Cross (X)	1000	60	0.020	0.034

Six reinforced columns were modeld using ABAQUS and compared to the results concluded from Marvel et al. (2014). The modelled columns have different longitudnaln and laterla reinforcement ratios. The comparsion shows that the finite element model is capable to introduce the behavior of the columns with cross spirals. As shown in Fig. 6 the stress-starin history between the numerical and experimental results are very close in terms of the ultimate stress, except for the case of using single spiral. The initial stiffeness of the FE model is in very good agreement with the experiments, while the softening behavior of the FE model is sometimes overpredict or under predcit the the beahvior till the failure point. Figur 7 compares the concrete damage of one of the tested columns, the FEM shows the maximum principle strain is reached and shows the same bahvior as the real damaged column. The cross spiral confinment added more lateral confinment presssure whereas pushed the concrete to be failed through an inclined surface.



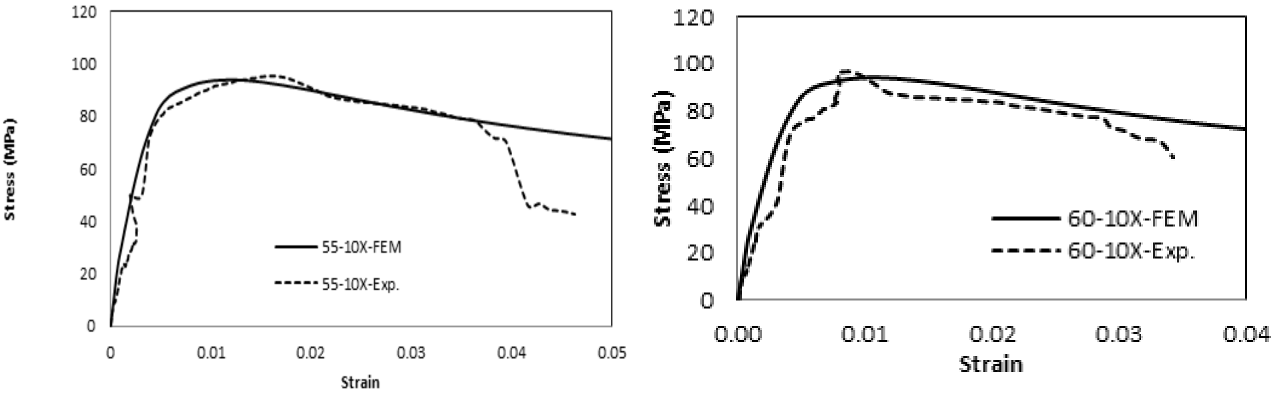


Figure 6. Comparison of Stress-Strain curves between the experimental and the FEM.

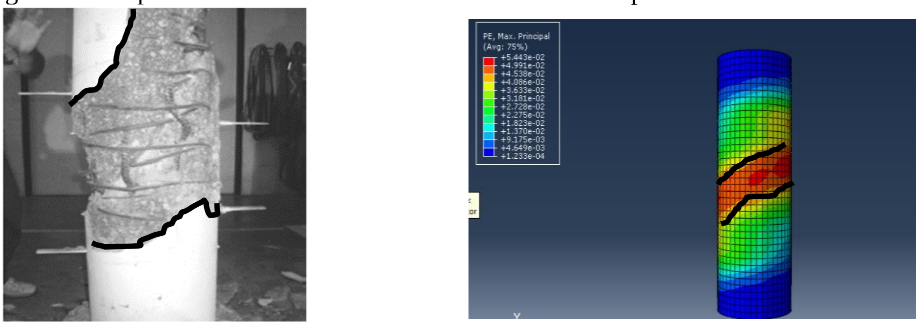


Figure 7. Comparison of concrete damage between the experimental and the FEM.

5 CONCLUSIONS

This paper presents the results of finite element modelling of concrete columns reinforced with cross spirals in a way to increase the lateral confinement pressure, which in consequence provide more ultimate axial load capacity. The proposed technique offers new generation of columns that have more ductility and more energy absorption characteristics. The finite element code Abaqus is used on the numerical simulations and the concrete and steel nonlinearity behavior is considered in the study. The damage plasticity model implemented in Abaqus is calibrated and adopted for the studied columns, the elastic-perfectly plastic model is used to simulate he steel behavior. The bond between steel and concrete is assumed perfect. The comparison between the numerical and finite element results are presented in terms of stress-strain curves, which are in very good agreement. The damage plasticity model showed very good potential representing the axial behavior of reinforced concrete columns reinforced with cross spirals. The study will be extended in the future to include more key parameters that will be very useful in developing guidelines related to the present study.

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