

# Parametric analysis of the behavior of combined FRP-Steel confinement concrete columns under eccentricity of the load

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## Abstract

Fibre-reinforced polymer (FRP) jacketing of reinforced concrete (RC) columns is now a widely accepted strengthening technique in civil engineering. Lightweight, high strength and corrosion resistance are among the properties that have made this type of material valuable in various forms in building engineering. In this paper, the behavior of combined FRP-Steel RC columns under the effect of load eccentricity is investigated using ABAQUS. The focus of the parametric studies was on a wide range of subject variables, including FRP layer thickness, shear reinforcement ratio ( $\rho_{ss}$ ), longitudinal reinforcement shear reinforcement ratio ( $\rho_{sl}$ ), height-to-diameter ratio of the circular column ( $H/d$ ), concrete cover, concrete strength and eccentricity (strain gradient). The results showed that the eccentricity of the load had the greatest effect on the maximum lateral strain and the least effect on the ductility of the circular column. Also, the reduction of compressive strength of concrete ( $f_c$ ) has the greatest effect on the ductility and yield stress of the column and the least effect on the maximum axial and lateral strain.

Keywords: FRP-Steel, confinement concrete columns, eccentricity, load  
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## 1 Introduction

RC columns as vertical structural elements that carrying over axial load with or without a moment are of particular importance in the performance and safety of structures. One of the main disadvantages of RC structures is the insufficient confinement of the columns by rebars in the plastic joint area, which leads to the brittle behavior of the structure during earthquakes. To provide additional confinement for these columns, reinforcement by FRP is a suitable solution due to its light weight and high strength [38]. FRP composites were first used for seismic reinforcement of RC columns in 1890 [16] and for circular concrete columns under axial compressive load [39]. The best way to evaluate the seismic performance of a reinforced concrete column is to test it on a seismic table with a real earthquake wave [18, 48]. This experiment was performed on FRP-confinement reinforced concrete columns by researchers [11, 12, 44] and the results showed that FRP confining significantly improves the ductility and energy dissipation capacity of an RC column, while the lateral bearing capacity of the column increases slightly.

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## 2 Background

Until the mid-1890s, concrete jackets and steel plates were used to reinforce weak concrete columns. The results of researchers regarding steel cover [24, 34] showed that concrete columns with steel cover have better performance than concrete jacket. Both methods are very difficult to implement and are associated with many problems, so in recent years FRPs have been widely used to reinforce concrete columns [10, 17, 25, 27, 31, 35, 40, 43]. Based on this, many studies have been performed on increasing the strength of concrete and the stress-strain curve of FRP-reinforced columns [26, 29, 33]. Lam and Teng [20] have reported that FRP confine has become a popular method for reinforcing damaged concrete columns. Research in this field can be divided into several groups. Some researchers have conducted experimental studies to investigate the improvement of the axial load capacity of concrete column by FRP confined [9, 13, 22, 28, 46], some of which have had eccentric loading. Some research has been done experimentally as well as finite element analysis on the compressive strength of FRP sheet and its rupture mode [21, 37]. Among the experimental researches conducted on the effect of rounding of corners in square and rectangular sections, can be mention [7, 31]. Experimental researches on the effect of longitudinal and shear FRP sheets as well as the angle of placement of them on the concrete column has been one of the most repetitive topics [8, 32, 36]. In addition to experimental researches, numerical analysis has been used using the finite element method (FEM). For example, Yousef et al. [30] simulated the length of plastic joint for FRP- confinement concrete columns using FEM. Lee et al. [21] evaluated the compressive strength and rupture mode of GFRP sheets using FEM. Mohammad et al. [28] Using FEM investigated the effect of FRP jacket on improving the axial strength of damaged concrete columns. Mai et al. [23] propose a new strain model for concrete with discrete FRP confinement. An energy absorption factor for discretely FRP confined concrete and a strain reduction factor of FRP were proposed. Yuan et al. [47] an experimental investigation of large rupture strain (LRS) FRP and conventional glass FRP-confined engineered cementitious composite (ECC) cylinders with different confinement levels under axial compression are presented. It is found that the application of external FRP jackets leads to a significant improvement in the compressive strength and deformation of the core ECC. Zhou et al. [50] has revealed certain performance concerns with such compound concrete, including reductions in strength and durability, due to the presence of recycled concrete lumps (RCLs). The confinement of compound concrete with an external FRP confining tube has recently been explored as an effective technique to improve its mechanical properties and durability. Lik Lam et al. [42] presented an experimental study on the compressive behavior of ultra-high performance concrete (UHPC) confined with FRP composites. A total of 18 cylindrical specimens were prepared from UHPC containing 2.5% of micro steel fibers by volume, among which 6 were unconfined and 12 were confined with carbon FRP (CFRP). Huang et al. [14] presented a systematic experimental study on FRP-confined concrete-encased cross-shaped steel columns (FCCSCs). FCCSCs are an emerging form of hybrid columns, consisting of a square FRP outer tube, a cross-shaped steel section and a concrete infill. It is shown that the various steel sections in the tested FCCSCs all provided substantial confinement to the concrete, while the effect of the steel confinement is less pronounced for FCCSCs with a thicker FRP tube. Ahmad et al. [1] was analytically investigated the load moment (P-M) interaction behavior of geopolymer concrete (GPC) filled FRP tube circular columns internally reinforced with FRP bars. An analytical model for the P-M interaction behavior of the column was developed and validated against the experimental investigation results. Zeng et al. [49] investigated 18 FRP spiral strip wrapped concrete cylinders of three different levels of confinement under cyclic axial compression and 12 reference specimens under monotonic axial compression. The test results show that the actual confinement effectiveness factor significantly influences the monotonic axial stress-strain curves of FRP spiral strip-confined concrete, which lie closely to the envelop curves of the corresponding cyclic stress-strain curves. Yan et al. [45] investigated the strain rate effect on Large-Rupture-Strain (LRS) FRP-confined concrete through Split Hopkinson Pressure Bar (SHPB) test. Results revealed that LRS FRP-confined concrete specimens exhibited superior impact resistance behaviors compared to the counterpart confined with CFRP composites when subjected to a single impact. Bai et al. [4] evaluated the performance of existing cyclic models (e.g., unloading path, reloading path, and plastic strain) using a database including both traditional and LRS FRP-confined concrete. Through an analytical study on the cyclic response of LRS FRP-confined concrete, two key parameters (plastic strain and stress degradation) were found to significantly influence the cyclic behavior of LRS FRP-confined concrete. Ali et al. [2] investigated about enhances the methods used for estimating the shear capacity of reinforced concrete (RC) beams with FRP bars and spirals. A database of 44 circular concrete beams reinforced with FRP bars tested under shear were compiled from different experimental studies. Two proposed models based on approaches developed for rectangular sections, to predict the shear capacity of beams without and with stirrups, were compared with the selected available shear design equations. The shear strength estimated using the proposed models are slightly more accurate.

Considering the above, it seems that the simultaneous effect of shear rebar and FRP confinement on the stress-strain behavior of RC columns in the literature needs more study. In this paper will be tried to perform a parametric analysis about the behavior of combined FRP-Steel confinement RC columns under eccentricity of the load. In this

regard, the following parameters are considered as variables: FRP layer thickness, shear reinforcement rate ( $\rho_{ss}$ ), longitudinal reinforcement rate ( $\rho_{sl}$ ), height to diameter ratio of circular column ( $H/d$ ), concrete cover, concrete strength and eccentricity (strain gradient).

### 3 Analysis of the behavior of FRP confinement concrete

The concrete core of FRP-enclosed reinforced concrete columns is affected by the combination of FRP coating enclosure and crossbars. In the case of cross-bars, the confinement pressure remains constant after the steel is delivered (before strain hardening) while the FRP confinement pressure is continuously increased due to the linear elastic stress-strain behavior of FRP [8, 32, 36]. As shown in Fig. 1, the concrete in the central core of the column is subjected to a combination of FRP enclosure and shear rebars.

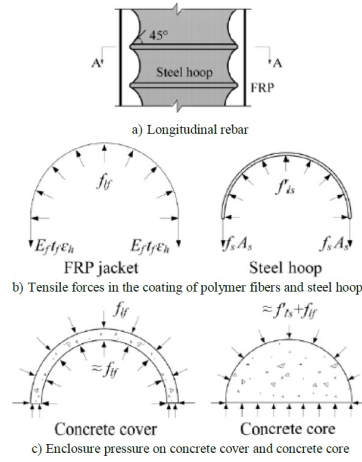


Figure 1: Circular reinforced concrete column confinement by FRP [32]

According to Fig. 2, the FRP confinement pressure can be obtained by Equation (3.1) [8]:

$$f_{lf} = \frac{2E_f t_f \epsilon_h}{D} \quad (3.1)$$

where

$E_f$ : FRP modulus of elasticity

$t_f$ : FRP thickness

$\epsilon_h$ : FRP hoop strain

$D$ : Column diameter.

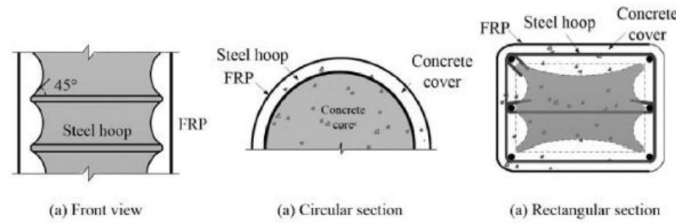


Figure 2: Confinement of concrete by steel and FRP [32]

The final confinement pressure in the FRP rupture is denoted by  $f'_{ia}$  and occurs when  $\epsilon_n = \epsilon_{n,rupt}$ .  $\epsilon_{n,rupt}$  is actually the FRP rupture strain due to the hoop tension in a FRP-enclosed concrete column, which is significantly lower than the FRP rupture strain in the standard coupon test [30]. Determining the confinement pressure due to shear reinforcements is much more complicated due to its discrete nature. Effective confinement pressure is defined by one of the most frequently mentioned models for confinement of reinforced concrete columns [19].

$$f'_{ls} = k_e f_{ls} \quad (3.2)$$

$$f_{ls} = \begin{cases} \frac{2A_s E_s \varepsilon_s}{s d_s}, & \varepsilon_s \leq \varepsilon_y \\ \frac{2A_s f_{yh}}{s d_s}, & \varepsilon_s > \varepsilon_y \end{cases} \quad (3.3)$$

where

$f_{ls}$ : The confinement pressure by the stirrups or spirals if it is applied uniformly at the height of the column.

$A_s$ : The area of the cross section stirrups or spirals

$E_s$ : Modulus of elasticity

$\varepsilon_s$ : Tensile strain

$s$ : The vertical distance from the center to the center of the stirrups or spirals

$d_s$ : Diameter of stirrups or spirals to the center of the section

$f_{yh}$ : Yield stress

## 4 Modeling and verification

This study investigates the behavior of FRP confinement RC columns under eccentricity of the load through parametric study. The focus of the parametric studies was on a wide range of subject variables including FRP layer thickness, shear reinforcement ratio ( $\rho_{ss}$ ), longitudinal reinforcement ratio ( $\rho_{sl}$ ), height to diameter ratio of circular column ( $H/d$ ), concrete cover, concrete strength and eccentricity (strain gradient). In this regard, the effect of FRP fibers on the strength of the column, lateral strain and axial strain of the column will be investigated. As mentioned, in this research, a total of seven groups of columns will be studied. In this regard, ABAQUS finite element software has been used for numerical modeling.

The basic geometry of the model consists of a concrete column with one clamping support, to which a constant pressure is applied vertically and is under eccentricity of the load. Fig. 3a shows the model geometry intended for parametric studies. The parameters that can be changed in the research topic are shown in this figure, which will be explained. This configuration is adapted from the experimental study of Al-Nimry et al. [3], the details of which are shown in Fig. 3b. Column specimens were tested under axial compression with variable eccentricities using a Universal Testing Machine. The axial load was applied using displacement control, at a rate of 0.5 mm/min, to monitor column response beyond peak capacity. The monotonic axial loading was gradually increased until failure. A set of steel loading plates was fabricated for the application of axial compression at the desired eccentricity: a top plate with a knife-edge that was fastened to the loading jack and a bottom adapter plate that was placed directly on top of the specimen. Using the compressometer-extensometer measurement system shown in Fig. 3b, each of columns was instrumented with 3 linear variable differential transformers (LVDTs). The L1 and L2 transducers, with a gage length of 450 mm, were centered at column mid-height to measure axial displacements at the compression and tension column sides. The L3 transducer was mounted onto the extensometer to measure hoop strains at mid-height.

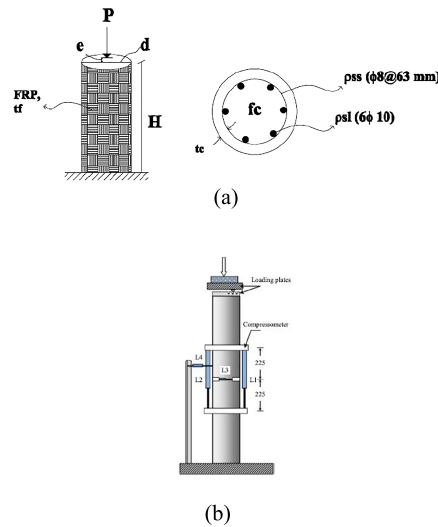


Figure 3: Model geometry for numerical studies

The parameters in Fig. 3 are described in Table 1:

Table 1: The parameters in Model geometry for numerical studies

| Parameter |                          | Parameter   |                                  |
|-----------|--------------------------|-------------|----------------------------------|
| P         | Axial pressure           | $tf$        | FRP sheet thickness              |
| d         | Column diameter          | $tc$        | Concrete cover                   |
| e         | Eccentricity of the load | $\rho_{ss}$ | Shear reinforcement ratio        |
| H         | Column height            | $\rho_{sl}$ | Longitudinal reinforcement ratio |
| FRP       | CFRP                     | $fc$        | Compressive strength of concrete |

Only in the case where the amount of eccentricity of the load is considered infinite, the loading method is as shown in Fig. 4. When the eccentricity of the load is infinite, it actually means that the axial load is zero and only the bending force must be applied to the specimen. According to Fig. 4 due to the lack of axial load, the specimens are tested in pure bending mode.

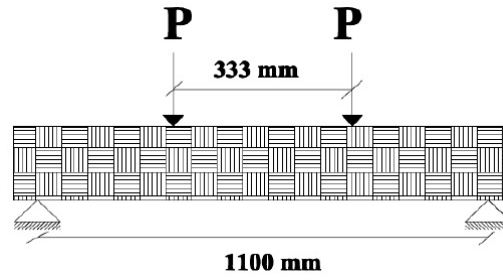


Figure 4: Loading method when  $e = \infty$

In order to parametrically analyze the behavior of RC circular columns improved using FRP fibers, the fixed and variable parameters in each analysis are generally given in Table 2.

According to this table, 7 types of parameters have been analyzed and a total of 105 different samples have been analyzed in ABAQUS.

Table 2: Variables of parametric analysis used in numerical modeling

| Rows | Fixed parameters                                                                                      | Variable parameters                      | Number of analyzes |
|------|-------------------------------------------------------------------------------------------------------|------------------------------------------|--------------------|
| 1    | $H/d = 6.25, tf = 0.16mm, d = 192mm, fc = 50MPa, tc = 12.5mm, \rho_{ss} = 0.0190, \rho_{sl} = 0.0160$ | $e/d (e = 0 : 5 : 80mm, e = \infty)$     | 17                 |
| 2    | $H/d = 6.25, tf = 0.16mm, d = 192mm, e = 25mm, tc = 12.5mm, \rho_{ss} = 0.0190, \rho_{sl} = 0.0160$   | $fc = 20 : 2.5 : 50MPa$                  | 13                 |
| 3    | $H/d = 6.25, e = 25mm, d = 192mm, tc = 12.5mm, fc = 50MPa, \rho_{ss} = 0.0190, \rho_{sl} = 0.0160$    | $tf = 0.16 : 0.15 : 2mm$                 | 13                 |
| 4    | $H/d = 6.25, e = 25mm, d = 192mm, fc = 50MPa, tf = 0.16mm, \rho_{ss} = 0.0190, \rho_{sl} = 0.0160$    | $tc/d (tc = 12.5, 25, 40, 50, 60, 70mm)$ | 6                  |
| 5    | $e = 25mm, d = 192mm, fc = 50MPa, tf = 0.16mm, tc = 12.5mm, \rho_{ss} = 0.0190, \rho_{sl} = 0.0160$   | $H/d = 5 : 0.25 : 8$                     | 13                 |
| 6    | $H/d = 6.25, e = 25mm, d = 192mm, tf = 0.16mm, tc = 12.5mm, fc = 50MPa, \rho_{sl} = 0.0160$           | $\rho_{ss} = 0.019 : 0.001 : 0.049$      | 31                 |
| 7    | $H/d = 6.25, e = 25mm, d = 192mm, tf = 0.16mm, tc = 12.5mm, fc = 50MPa, \rho_{ss} = 0.0190$           | $\rho_{sl} = 0.0160 : 0.0461$            | 12                 |

In order to ensure the accuracy of modeling such as loading, abutment conditions, materials and material interaction, the software output was validated using the test performed by Al-Nimry et al. [3] on reinforced concrete columns. Fig. 5 compares the Axial displacement - Load diagrams obtained from modeling with experimental data [3]. The results are in good agreement with the experimental data and the structural components are modeled correctly in ABAQUS software.

Al-Nimyr et al. [3] investigated the behavior of medium-scale circular reinforced concrete columns wrapped with FRP sheets under concentric and eccentric axial loads. The experimental program was devised to assess the effects of loading conditions, absence/presence of an FRP jacket as well as the FRP wrapping system. To achieve the study objectives, four column groups were tested under axial compression at 0, 25, 50 and 65 mm loading eccentricities

corresponding to eccentricity-to-diameter ratios of 0, 0.13, 0.26, 0.34, respectively. Specimens in a fifth group were tested in pure bending simulating axial compression at infinite loading eccentricities.

Three column subcategories were tested under each of the 5 loading eccentricities: unwrapped; wrapped with one ply of hoop FRP sheets; and wrapped with two FRP plies with fibers oriented at 0 and 90 to the longitudinal column axis thereby providing externally-bonded longitudinal reinforcement and hoop confinement, respectively. Tests confirmed that FRP confinement enhances the axial-flexural column resistance even at large eccentricities that exceed the balanced state of unconfined columns. Although axial column resistance decreased with increasing bending moments, relative enhancements (25–35%) in axial resistance provided by FRP confinement were found to be more significant under eccentric loading than in pure compression.

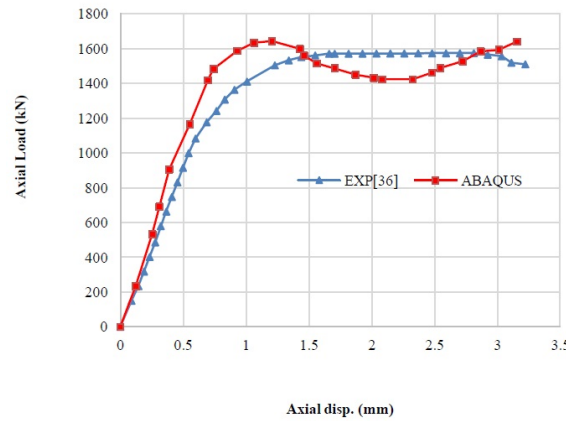


Figure 5: Comparison of load -axial displacement diagram of circular column

RC is one of the most complex materials for finite element modeling. Proper definition of elastic and plastic behavior of reinforced concrete in finite element modeling can have many effects on outputs. The strength of concrete under multidimensional stresses is a function of stress states and cannot be predicted by simple tensile or compressive or shear ranges. Usually, the yield of concrete occurs in two forms of tensile and compressive. In the tensile type, a major crack is created in the concrete and the tensile strength of the concrete in the direction perpendicular to it will decrease. In the compressive type, numerous small cracks appear in the concrete, which will lead to a major loss of strength of the concrete element. Under small tensile and compressive stresses, concrete failure will be brittle with very little plastic flow. But under compressive stresses, concrete will yield like formable materials [5]. In ABAQUS software, the nonlinear behavior of brittle materials can be defined by three methods: smeared crack concrete model (SCCM), Brittle crack concrete model (BCCM) and concrete damage plasticity model (CDPM). Each of these models has advantages that can be used as needed [6]. In this research, CDPM has been used to model RC in ABAQUS software. The CDPM is the only model that can be used in both static and dynamic analysis. In this model, it is assumed that tensile cracking and compressive crushing are the two main aspects of the concrete failure mechanism and is designed to model the failure of brittle materials so that it is possible to calculate stiffness changes during loading [41].

To use the CDPM model, it is necessary to test the concrete sample under uniaxial compression test and enter the stress and strain data obtained in ABAQUS software. Since this work is costly and time consuming despite the examples with different strengths, so in this study, the data needed to define the concrete failure mechanism (CDPM) have been extracted through the code written in MATLAB software. In MATLAB software, a program has been written that is able to predict the stress strain diagram of concrete by taking the  $f'_c$ .

FRP materials are defined as lamina in ABAQUS software. The mechanical properties of FRP sheets are shown in Table 3. The type of elements considered for concrete columns, FRP and longitudinal and shear rebars are C3D8R, S4R and T3D2, respectively.

Table 3: Characteristics of FRP sheets [15]

| FRP  | Elasticity modulus (GPa) | Tensile strength (MPa) | Ultimate strain (%) | Density ( $kg/m^3$ ) |
|------|--------------------------|------------------------|---------------------|----------------------|
| CFRP | 230                      | 4900                   | 2.5                 | 1000                 |
| GFRP | 70                       | 1900                   | 4                   | 1800                 |
| AFRP | 120                      | 4000                   | 5                   | 1200                 |

## 5 Results

### 5.1 Parametric analysis of simulations

After analyzing each column in ABAQUS software, the obtained stress and strain data are transferred to MATLAB and using the program coded based on [3] in this software, the resistance characteristics of each column are calculated. The strength characteristics of each column include maximum strength, yield strength, yield strain, ultimate strain and ductility.

Fig. 6 shows the effect of different factors on the stress-strain curve of circular column. According to this figure, with increasing the  $e/d$  ratio, the maximum axial resistance and the maximum axial strain decrease and the maximum lateral strain increases.

As the  $f'c$  decreases, the maximum strength of the column also decreases. Also, for each column, the maximum axial strain is much higher than the maximum lateral strain. In a general view, the maximum axial strain and the maximum lateral strain are first reduced and then increased by decreasing the  $f'c$ .

When the FRP thickness is low, the concrete column collapses after reaching its maximum axial strength. However, with increasing the thickness of the FRP layer, the axial strength of the concrete column increases several times. Another point is that with increasing the thickness of the FRP layer, the axial strain of the column first increased suddenly and then was almost constant. But the lateral strain of the column first increased slightly and then decreased. In other words, increasing the thickness of the FRP layer by reducing the lateral strain, which in turn reduces the effects of  $P - \delta$  will improve the behavior of the concrete column.

With increasing  $tc/d$  ratio, the axial resistance of the column has decreased significantly. Also, the maximum lateral strain and the maximum axial strain decreased with increasing  $tc/d$  ratio. Increasing the  $tc$  has caused the volume of unreinforced concrete to increase by keeping the compressive core of the concrete constant. Therefore, by increasing the distance between the FRP reinforcement sheet and the compressive core, the performance of the column during loading will be affected and thus the strength and strain of the concrete column will be reduced.

With increasing  $\rho_{ss}$  axial strength, axial strain and lateral strain of the concrete column increased and as a result the behavior of the concrete column improved. With increasing  $\rho_{sl}$ , the axial resistance is almost constant and has not changed much. Also, the maximum lateral strain and the maximum axial strain have decreased sharply.

Increasing the  $H/d$  ratio, which is actually associated with increasing the slenderness ratio of the column, has reduced the axial stress and axial strain as well as increased the lateral strain.

After numerical analysis of all samples in ABAQUS to better understand the strength parameters of the circular column using the output of MATLAB software according to different factors are given in Table 4 to 10, respectively. The data in these tables are also shown in Figures 7 to 9.

Results show that the parameters of maximum axial strength, maximum axial strain, yield strength, yield strain and ductility in net bending mode ( $e/d = \infty$ ) relative to net axial load ( $e/d = 0$ ) has decreased by 65.4%, 46.8%, 67.4%, 34.8% and 19.2%, respectively. On the other hand, the maximum lateral strain in the net bending state ( $e/d = \infty$ ) has increased by more than 90% compared to the net axial load ( $e/d = 0$ ).

With a decrease in  $f'c$  from 50 to 20 MPa, the maximum axial strength, yield strength and yield strain decreased by 40.0, 61.3 and 55.9%, respectively. With a decrease in  $f'c$  to 32 MPa, the yield strength and yield stress of the concrete column are uniformly reduced, but from a compressive strength of 30 MPa onwards, both are abruptly reduced.

With increasing "tf" from 0.16 to 2.00 mm, the maximum axial strength, yield strength, maximum axial strain, and ductility increased by 84.2, 94.4, 17.8 and 358.9%, respectively, and the maximum lateral strain and yield strain decreased by 20.4 and 74.3%, respectively.

A 3.5 times increase in the  $tc/d$  ratio caused a decrease of 52.2, 52.3, 44.3, 58.4, 29.6 and 21.7% in maximum axial strength, yield strength, maximum axial strain, maximum lateral strain, yield strain and ductility of concrete columns, respectively.

A 30% increase in  $\rho_{ss}$  increased 7.1, 7.7, 18.8, 22.2, 7.8 and 10.1% in maximum axial strength, yield strength, maximum axial strain, lateral strain, yield strain and ductility of concrete columns.

By changing the  $\rho_{sl}$ , the maximum decrease and increase of the maximum axial strength are 0.6 and 0.4%, respectively, which is very small. Also, in terms of yield strength, these values were 1.9 and 0.3 percent, respectively. An increase of 3.01% in  $\rho_{sl}$  reduced the maximum axial strain, maximum lateral strain, yield stress and ductility of concrete columns by 82.6, 88.8, 78.2 and 20.2%.

Increasing the  $H/d$  ratio by 60% caused a decrease of 37.4, 65.1 and 36.9% in the maximum axial strength, yield

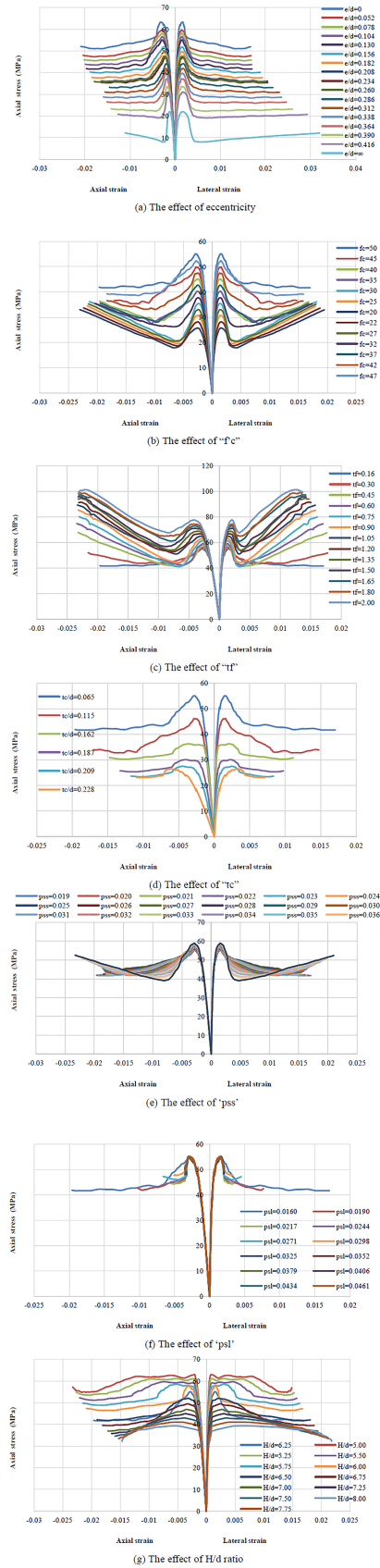


Figure 6: The effect of different factors on the stress-strain curve of circular column

strength and maximum axial strain and an increase of 47.2% in the maximum lateral strain. The yield strain and ductility have an inflection point. The yield strain has the highest value in the H/d range of 5.75 to 6.25 and the ductility has the lowest value in the same range. The yield strain increased by 15.6% in the highest case (H/d = 6) and decreased by 58.9% in the lowest case (H/d = 8) compared to the initial case. Also, ductility decreased by 25.4% in the lowest case (H/d = 6.25) and increased by 53.1% in the highest case (H/d = 8).

### 5.1.1 Circular column strength parameters in terms of e/d ratio

Table 4: Circular column strength parameters in terms of e/d ratio

| e/d ratio | yield strain | yield strength (MPa) | maximum lateral strain | maximum axial strain | maximum axial strength (MPa) | ductility |
|-----------|--------------|----------------------|------------------------|----------------------|------------------------------|-----------|
| 0         | 0.0155       | 57.06                | 0.0168                 | 0.0209               | 63.33                        | 1.35      |
| 0.052     | 0.0155       | 55.26                | 0.0169                 | 0.0204               | 59.70                        | 1.31      |
| 0.078     | 0.0155       | 53.92                | 0.0169                 | 0.0201               | 58.10                        | 1.29      |
| 0.104     | 0.0153       | 52.09                | 0.0170                 | 0.0199               | 56.60                        | 1.30      |
| 0.130     | 0.0152       | 50.80                | 0.0171                 | 0.0196               | 55.01                        | 1.29      |
| 0.156     | 0.0142       | 48.00                | 0.0189                 | 0.0188               | 51.80                        | 1.32      |
| 0.182     | 0.0140       | 46.09                | 0.0193                 | 0.0184               | 49.70                        | 1.31      |
| 0.208     | 0.0124       | 44.33                | 0.0200                 | 0.0164               | 47.30                        | 1.32      |
| 0.234     | 0.0124       | 43.35                | 0.0201                 | 0.0165               | 46.90                        | 1.33      |
| 0.260     | 0.0135       | 43.99                | 0.0205                 | 0.0179               | 47.61                        | 1.32      |
| 0.286     | 0.0110       | 41.18                | 0.0217                 | 0.0146               | 44.10                        | 1.33      |
| 0.312     | 0.0117       | 39.20                | 0.0232                 | 0.0156               | 41.90                        | 1.33      |
| 0.338     | 0.0118       | 36.97                | 0.0236                 | 0.0159               | 39.56                        | 1.34      |
| 0.364     | 0.0115       | 34.07                | 0.0247                 | 0.0151               | 37.10                        | 1.31      |
| 0.390     | 0.0109       | 29.32                | 0.0260                 | 0.0141               | 33.60                        | 1.29      |
| 0.416     | 0.0107       | 28.12                | 0.0293                 | 0.0126               | 31.10                        | 1.17      |
| $\infty$  | 0.0101       | 18.58                | 0.0320                 | 0.0111               | 21.90                        | 1.09      |

Table 5: Circular column strength parameters in terms of  $f'_c$

| $f'_c$ (MPa) | yield strain | yield strength (MPa) | maximum lateral strain | maximum axial strain | maximum axial strength (MPa) | ductility |
|--------------|--------------|----------------------|------------------------|----------------------|------------------------------|-----------|
| 50           | 0.0152       | 50.80                | 0.0171                 | 0.0196               | 55.01                        | 1.29      |
| 47           | 0.0150       | 48.28                | 0.0159                 | 0.0183               | 52.40                        | 1.22      |
| 45           | 0.0148       | 45.70                | 0.0144                 | 0.0170               | 49.92                        | 1.15      |
| 42           | 0.0149       | 44.39                | 0.0158                 | 0.0183               | 47.43                        | 1.23      |
| 40           | 0.0148       | 42.25                | 0.0168                 | 0.0196               | 45.10                        | 1.32      |
| 37           | 0.0145       | 39.75                | 0.0167                 | 0.0195               | 42.69                        | 1.34      |
| 35           | 0.0143       | 37.30                | 0.0167                 | 0.0194               | 40.27                        | 1.35      |
| 32           | 0.0138       | 35.07                | 0.0174                 | 0.0204               | 37.74                        | 1.47      |
| 30           | 0.0121       | 27.30                | 0.0181                 | 0.0213               | 36.19                        | 1.76      |
| 27           | 0.0115       | 25.39                | 0.0180                 | 0.0215               | 35.33                        | 1.87      |
| 25           | 0.0108       | 22.70                | 0.0180                 | 0.0217               | 34.47                        | 2.01      |
| 22           | 0.0088       | 20.92                | 0.0187                 | 0.0224               | 33.72                        | 2.54      |
| 20           | 0.0067       | 19.63                | 0.0195                 | 0.0230               | 32.97                        | 3.43      |

Table 6: Circular column strength parameters in terms of  $tf$

| $tf$ (mm) | yield strain | yield strength (MPa) | maximum lateral strain | maximum axial strain | maximum axial strength (MPa) | ductility |
|-----------|--------------|----------------------|------------------------|----------------------|------------------------------|-----------|
| 0.16      | 0.0152       | 50.80                | 0.0171                 | 0.0196               | 55.01                        | 1.29      |
| 0.30      | 0.0160       | 52.90                | 0.0178                 | 0.0216               | 56.41                        | 1.35      |
| 0.45      | 0.0162       | 59.62                | 0.0177                 | 0.0232               | 67.86                        | 1.43      |
| 0.60      | 0.0159       | 68.66                | 0.0170                 | 0.0234               | 74.86                        | 1.47      |
| 0.75      | 0.0131       | 77.42                | 0.0161                 | 0.0230               | 80.11                        | 1.75      |
| 0.90      | 0.0112       | 82.70                | 0.0158                 | 0.0232               | 85.42                        | 2.07      |
| 1.05      | 0.0096       | 83.51                | 0.0158                 | 0.0234               | 89.22                        | 2.43      |
| 1.20      | 0.0087       | 87.74                | 0.0151                 | 0.0231               | 91.60                        | 2.65      |
| 1.35      | 0.0063       | 90.49                | 0.0147                 | 0.0232               | 94.47                        | 3.68      |
| 1.50      | 0.0057       | 92.14                | 0.0143                 | 0.0232               | 95.73                        | 4.07      |
| 1.65      | 0.0051       | 94.39                | 0.0142                 | 0.0231               | 97.41                        | 4.52      |
| 1.80      | 0.0045       | 95.66                | 0.0137                 | 0.0232               | 99.22                        | 5.15      |
| 2.00      | 0.0039       | 98.78                | 0.0136                 | 0.0231               | 101.32                       | 5.92      |

Table 7: Circular column strength parameters in terms of  $tc/d$  ratio

| $tc/d$<br>ratio | yield<br>strain | yield strength<br>(MPa) | maximum lateral<br>strain | maximum axial<br>strain | maximum axial strength (MPa) | ductility |
|-----------------|-----------------|-------------------------|---------------------------|-------------------------|------------------------------|-----------|
| 0.065           | 0.0152          | 50.80                   | 0.0171                    | 0.0196                  | 55.01                        | 1.29      |
| 0.115           | 0.0148          | 42.31                   | 0.0148                    | 0.0170                  | 46.22                        | 1.15      |
| 0.162           | 0.0132          | 27.41                   | 0.0111                    | 0.0147                  | 36.33                        | 1.11      |
| 0.187           | 0.0121          | 25.62                   | 0.0097                    | 0.0132                  | 30.10                        | 1.09      |
| 0.209           | 0.0115          | 24.32                   | 0.0083                    | 0.0118                  | 27.60                        | 1.03      |
| 0.228           | 0.0107          | 24.22                   | 0.0071                    | 0.0109                  | 26.49                        | 1.01      |

Table 8: Circular column strength parameters in terms of  $\rho_{ss}$ 

| $\rho_{ss}$ | yield<br>strain | yield strength<br>(MPa) | maximum lateral<br>strain | maximum axial<br>strain | maximum axial strength (MPa) | ductility |
|-------------|-----------------|-------------------------|---------------------------|-------------------------|------------------------------|-----------|
| 0.019       | 0.0152          | 50.80                   | 0.0171                    | 0.0196                  | 55.01                        | 1.29      |
| 0.020       | 0.0153          | 51.01                   | 0.0167                    | 0.0194                  | 55.20                        | 1.27      |
| 0.021       | 0.0153          | 51.25                   | 0.0164                    | 0.0193                  | 55.30                        | 1.26      |
| 0.022       | 0.0153          | 51.29                   | 0.0160                    | 0.0191                  | 55.52                        | 1.24      |
| 0.023       | 0.0153          | 51.20                   | 0.0157                    | 0.0189                  | 55.75                        | 1.23      |
| 0.024       | 0.0153          | 51.42                   | 0.0152                    | 0.0186                  | 55.91                        | 1.21      |
| 0.025       | 0.0153          | 51.38                   | 0.0150                    | 0.0185                  | 56.00                        | 1.20      |
| 0.026       | 0.0153          | 51.41                   | 0.0147                    | 0.0183                  | 56.22                        | 1.19      |
| 0.027       | 0.0153          | 51.42                   | 0.0143                    | 0.0181                  | 56.32                        | 1.18      |
| 0.028       | 0.0153          | 51.31                   | 0.0144                    | 0.0181                  | 56.30                        | 1.18      |
| 0.029       | 0.0157          | 52.53                   | 0.0145                    | 0.0181                  | 56.33                        | 1.16      |
| 0.030       | 0.0157          | 52.51                   | 0.0146                    | 0.0180                  | 56.52                        | 1.15      |
| 0.031       | 0.0157          | 52.59                   | 0.0147                    | 0.0180                  | 56.76                        | 1.15      |
| 0.032       | 0.0158          | 52.68                   | 0.0148                    | 0.0179                  | 56.94                        | 1.14      |
| 0.033       | 0.0159          | 53.01                   | 0.0148                    | 0.0179                  | 57.03                        | 1.13      |
| 0.034       | 0.0159          | 53.06                   | 0.0149                    | 0.0179                  | 57.25                        | 1.13      |
| 0.035       | 0.0159          | 53.08                   | 0.0150                    | 0.0178                  | 57.43                        | 1.12      |
| 0.036       | 0.0160          | 53.15                   | 0.0154                    | 0.0181                  | 57.56                        | 1.13      |
| 0.037       | 0.0160          | 53.23                   | 0.0156                    | 0.0182                  | 57.67                        | 1.14      |
| 0.038       | 0.0160          | 53.20                   | 0.0159                    | 0.0183                  | 57.84                        | 1.14      |
| 0.039       | 0.0160          | 53.24                   | 0.0161                    | 0.0184                  | 57.91                        | 1.15      |
| 0.040       | 0.0160          | 53.25                   | 0.0163                    | 0.0185                  | 58.02                        | 1.16      |
| 0.041       | 0.0160          | 53.35                   | 0.0165                    | 0.0187                  | 58.04                        | 1.17      |
| 0.042       | 0.0160          | 53.38                   | 0.0167                    | 0.0188                  | 58.13                        | 1.17      |
| 0.043       | 0.0160          | 53.44                   | 0.0173                    | 0.0193                  | 58.14                        | 1.21      |
| 0.044       | 0.0159          | 53.41                   | 0.0178                    | 0.0199                  | 58.10                        | 1.24      |
| 0.045       | 0.0164          | 54.49                   | 0.0183                    | 0.0205                  | 58.20                        | 1.26      |
| 0.046       | 0.0164          | 54.63                   | 0.0189                    | 0.0210                  | 58.31                        | 1.28      |
| 0.047       | 0.0164          | 54.71                   | 0.0197                    | 0.0219                  | 58.54                        | 1.33      |
| 0.048       | 0.0164          | 54.78                   | 0.0199                    | 0.0222                  | 58.69                        | 1.35      |
| 0.049       | 0.0164          | 54.71                   | 0.0209                    | 0.0233                  | 58.89                        | 1.42      |

Table 9: Circular column strength parameters in terms of  $\rho_{sl}$ 

| $\rho_{sl}$ | yield<br>strain | yield strength<br>(MPa) | maximum lateral<br>strain | maximum axial<br>strain | maximum axial strength (MPa) | ductility |
|-------------|-----------------|-------------------------|---------------------------|-------------------------|------------------------------|-----------|
| 0.0160      | 0.0152          | 50.80                   | 0.0171                    | 0.0196                  | 55.01                        | 1.29      |
| 0.0190      | 0.0088          | 50.07                   | 0.0077                    | 0.0102                  | 54.98                        | 1.15      |
| 0.0217      | 0.0053          | 50.15                   | 0.0035                    | 0.0057                  | 54.91                        | 1.08      |
| 0.0244      | 0.0054          | 50.12                   | 0.0037                    | 0.0057                  | 55.06                        | 1.06      |
| 0.0271      | 0.0061          | 50.10                   | 0.0045                    | 0.0066                  | 54.68                        | 1.09      |
| 0.0298      | 0.0049          | 50.49                   | 0.0033                    | 0.0051                  | 54.80                        | 1.04      |
| 0.0325      | 0.0034          | 50.72                   | 0.0021                    | 0.0035                  | 55.07                        | 1.04      |
| 0.0352      | 0.0031          | 50.44                   | 0.0019                    | 0.0033                  | 55.24                        | 1.05      |
| 0.0379      | 0.0033          | 50.93                   | 0.0020                    | 0.0034                  | 55.15                        | 1.03      |
| 0.0406      | 0.0031          | 49.82                   | 0.0021                    | 0.0033                  | 54.85                        | 1.06      |
| 0.0434      | 0.0032          | 50.32                   | 0.0020                    | 0.0034                  | 55.00                        | 1.06      |
| 0.0461      | 0.0033          | 50.53                   | 0.0019                    | 0.0034                  | 55.11                        | 1.03      |

## 5.2 Stresses and deformations in simulated models

Figs. 10 to 12 show the stresses and deformations of some of the simulated models. Most stresses and deformations have occurred in concrete, rebars and FRP sheets at the applied load location. As expected, with increasing  $e/d$

Table 10: Circular column strength parameters in terms of  $H/d$  ratio

| $H/d$ ratio | yield strain | yield strength (MPa) | maximum lateral strain | maximum axial strain | maximum axial strength (MPa) | ductility |
|-------------|--------------|----------------------|------------------------|----------------------|------------------------------|-----------|
| 5.00        | 0.0134       | 59.91                | 0.0148                 | 0.0233               | 62.98                        | 1.23      |
| 5.25        | 0.0138       | 57.87                | 0.0153                 | 0.0227               | 61.00                        | 1.64      |
| 5.50        | 0.0141       | 55.63                | 0.0158                 | 0.0221               | 59.71                        | 1.57      |
| 5.75        | 0.0148       | 54.15                | 0.0163                 | 0.0215               | 58.53                        | 1.45      |
| 6.00        | 0.0155       | 51.87                | 0.0167                 | 0.0209               | 57.57                        | 1.35      |
| 6.25        | 0.0152       | 50.80                | 0.0171                 | 0.0196               | 55.01                        | 1.29      |
| 6.50        | 0.0133       | 45.55                | 0.0181                 | 0.0190               | 52.13                        | 1.42      |
| 6.75        | 0.0123       | 42.69                | 0.0188                 | 0.0181               | 49.56                        | 1.47      |
| 7.00        | 0.0111       | 39.06                | 0.0194                 | 0.0171               | 46.93                        | 1.53      |
| 7.25        | 0.0101       | 36.19                | 0.0200                 | 0.0165               | 44.94                        | 1.62      |
| 7.50        | 0.0090       | 32.73                | 0.0206                 | 0.0159               | 42.97                        | 1.76      |
| 7.75        | 0.0078       | 28.80                | 0.0212                 | 0.0153               | 41.03                        | 1.96      |
| 8.00        | 0.0055       | 20.92                | 0.0218                 | 0.0147               | 39.37                        | 2.65      |

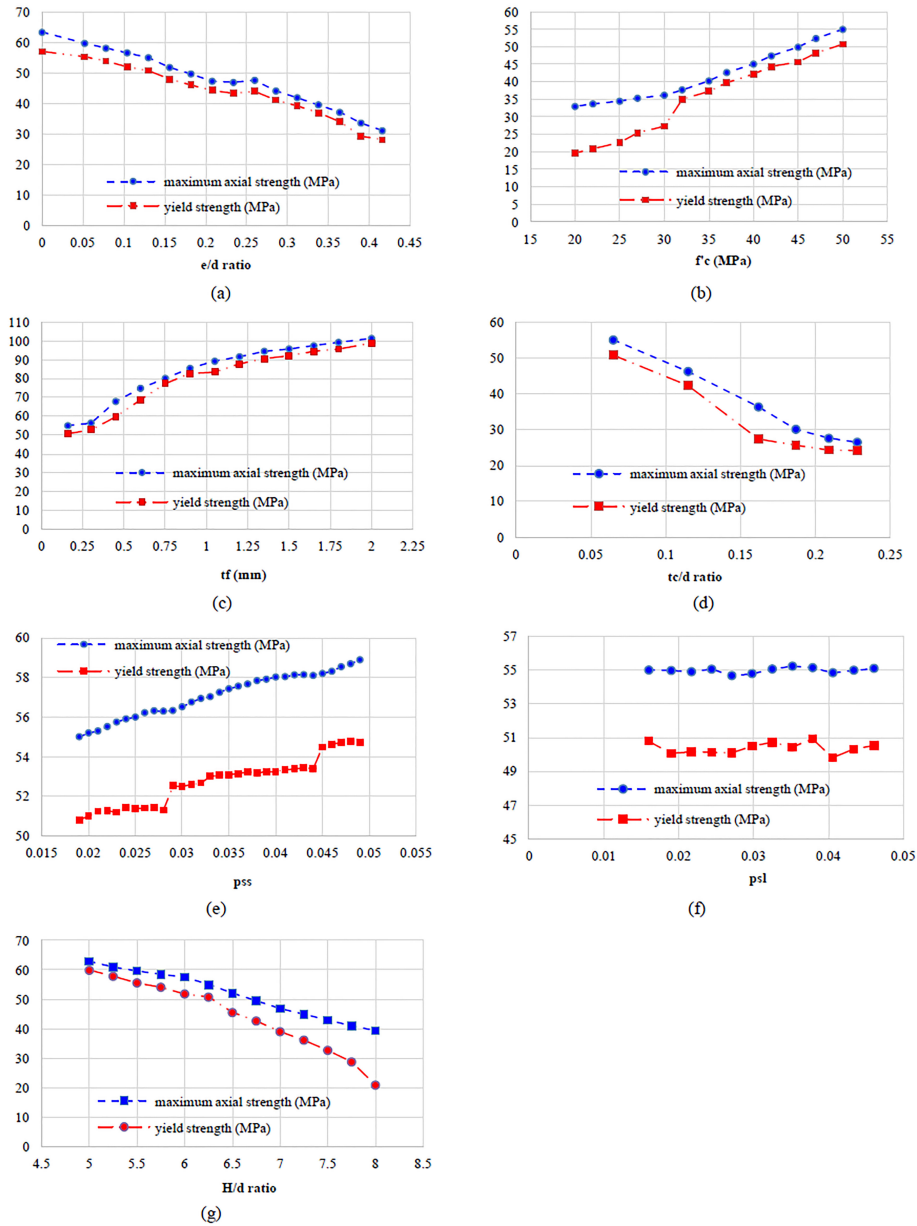


Figure 7: The effect of different factors on the maximum axial strength and yield strength of circular column

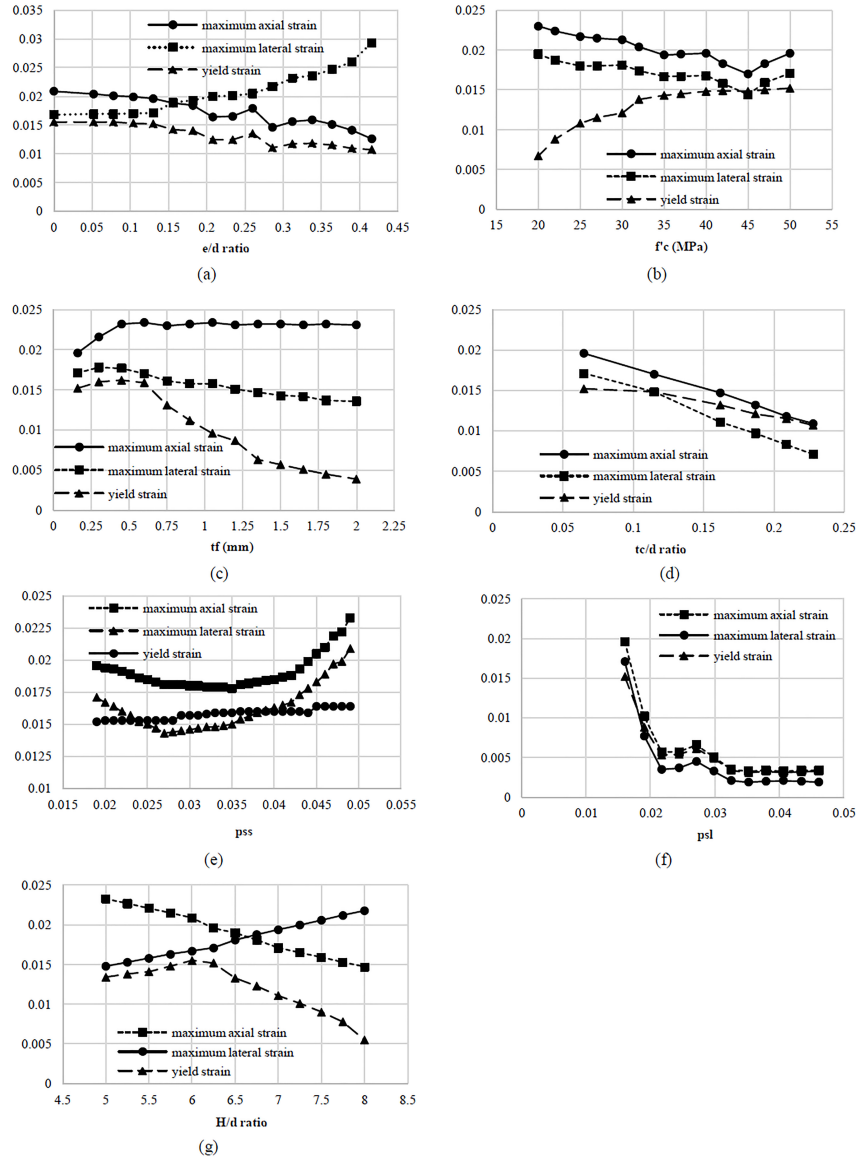


Figure 8: The effect of different factors on the maximum axial and lateral strain and the yield stress of circular column

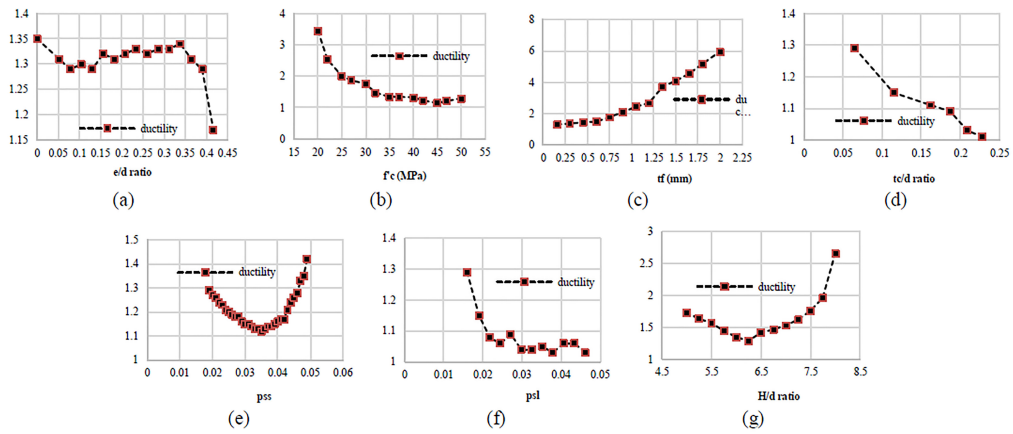


Figure 9: The effect of different factors on the ductility of circular column

ratio due to increased eccentricity of the load, the axial resistance of the sample decreased and the displacement and strain of the sample increased. Increasing the  $H/d$  ratio, which is actually associated with increasing the slenderness ratio of the column, has reduced the strength of the column. Regarding the issue of steel confinement, as it is known, shear reinforcements have a greater role in the confining of concrete specimens than longitudinal ones. In this regard, increasing  $\rho_{ss}$  has increased the axial strength of the column, but increasing  $\rho_{sl}$  has made the concrete sample from soft to brittle and, contrary to expectations, the strength of the column has decreased. Increasing  $t_f$  increases the strength of the concrete column by reducing the lateral strain, which in turn reduces the effects of  $P-\delta$ . As mentioned in the previous sections, increasing the concrete cover increases the volume of unreinforced concrete by keeping the compressive core of the concrete constant. In this regard, according to the following figures, it can be seen that with increasing concrete coverage, the strength of the column has decreased.

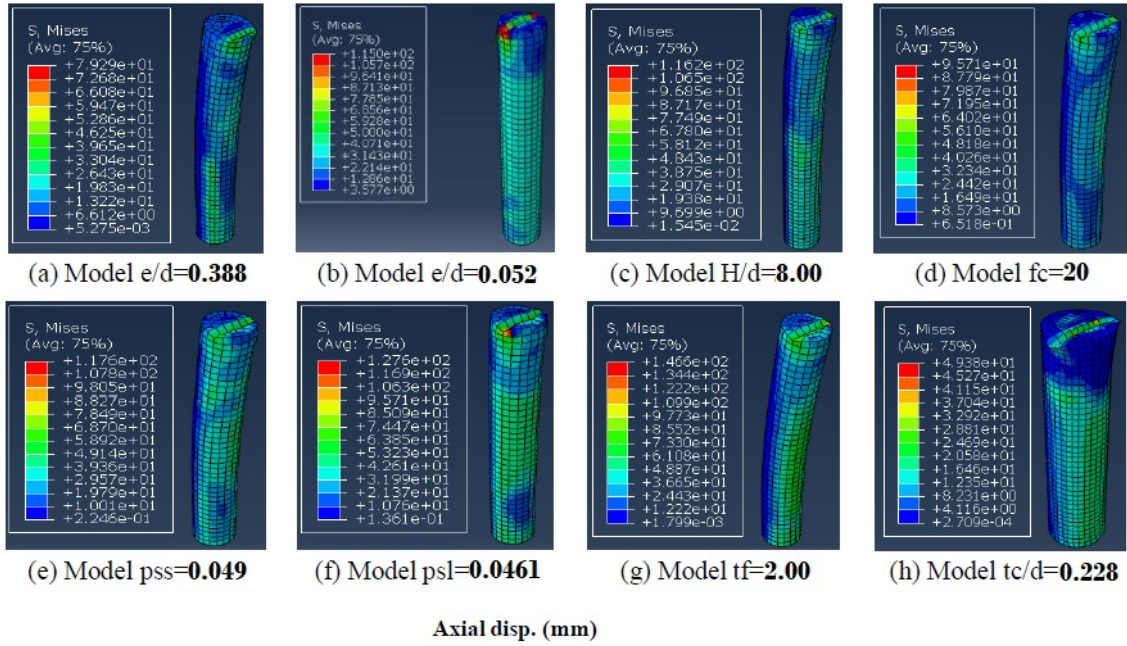


Figure 10: Stresses and deformations of concrete in different models

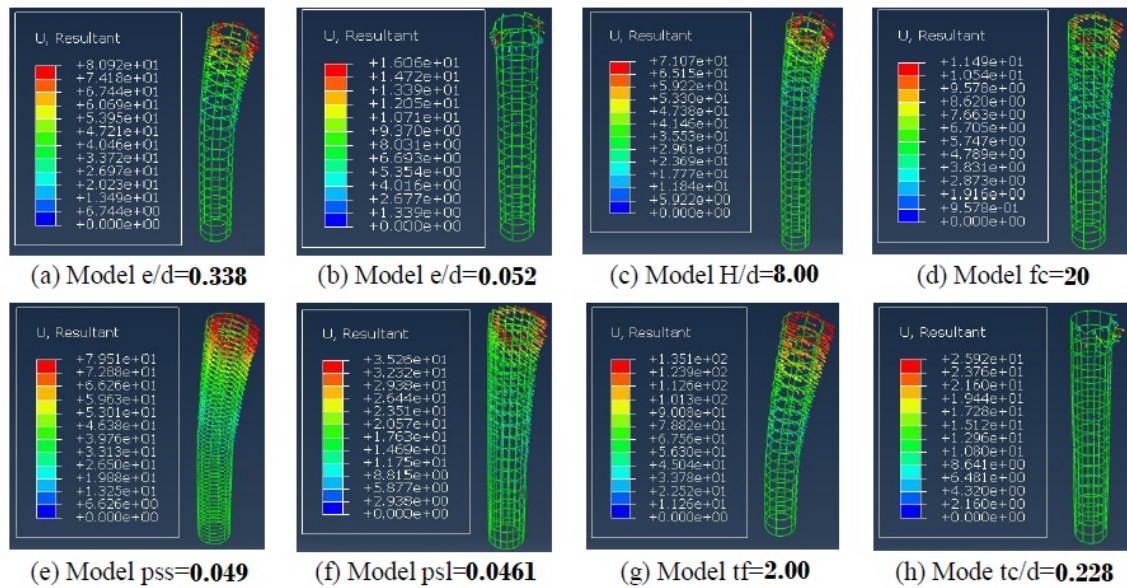


Figure 11: Stresses and deformations of rebars in different models

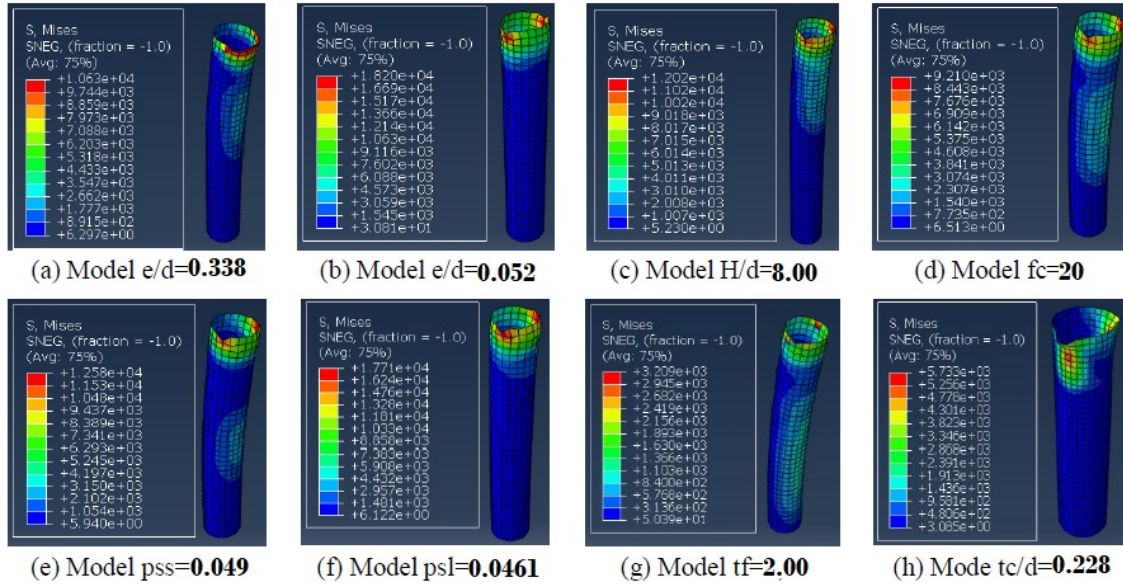


Figure 12: Stresses and deformations of FRP in different models

## 6 Conclusions

The results of this study can be summarized as follows:

Eccentricity of the load has the greatest effect on the maximum lateral strain and the least effect on the ductility of the circular column.

Decrease  $f'_c$  had the greatest effect on the ductility and yield strain of the column and the least effect on the maximum axial and lateral strain.

'tf' has a significant effect on the strength of the concrete column. Adding approximately one millimeter to the thickness of the reinforcement layer (from 0.16 to 1.20) resulted in an increase of 66.5 and 72.7% in the axial strength and yield strength of the concrete column. Also, increasing tf had the greatest effect on the ductility and strength of the column and the least effect on the maximum axial strain.

Increasing the tc/d ratio has almost the same effect on reducing the strength and strain of the concrete column and also had the least effect on the ductility of the concrete column.

The increase in  $\rho_{ss}$  in general had a positive effect on the behavior of the concrete column but was very small compared to other parameters. Therefore, compared to the cost of reinforcement used in concrete columns, it is not economical at all.

Increasing  $\rho_{sl}$  had the greatest effect on reducing the column strain and the least effect on the strength of the concrete column.

Increasing the H/d ratio had the greatest effect on reducing the yield strength of the column and the least effect on the maximum axial strength and axial strain of the concrete column.

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