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The effect of FRP characteristics on the behavior of square columns under eccentric loads

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Abstract

Modelling the stress-strain relationship of FRP confined concrete is of vital importance in predicting the structural behaviour of confined concrete columns. In recent years the axial stress-strain behaviour of confined concrete under concentric loading is well established, but the behavior under eccentric loading when axial and bending loads are combined is not well understood. Adding FRP materials to upgrade deficiencies of structural components can save lives by preventing collapse, reducing the damage, and the need for their costly replacement. The retrofit with FRP materials with desirable properties provides an excellent replacement for traditional materials, such as steel jackets, to strengthen the reinforced concrete. Existing studies have shown that the use of FRP materials restores or improves the column's original design strength for possible axial, shear, or flexure and in some cases allows the structure to carry more load than it was designed for. This paper summarizes the results of a research program to study the fundamental stress-strain behaviour of concrete confined by various types of fibre-reinforced polymer (FRP) composite jackets. By using three different types of FRP sheets with different mechanical characteristics, it can be concluded that the e/d ratio in all cases has the most effect on the square column behaviour.

Keywords: FRP, characteristics, square, columns eccentric, loads
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1 Introduction

It is now well understood that lateral confinement of concrete columns by fibre-reinforced polymers (FRP) can significantly increase their compressive strength and axial strain capacity. During the last two decades, extensive research has been conducted on the use of FRP fibre-reinforced polymers as reinforcement in the retrofitting of existing concrete columns [16, 27, 36]. Considering the damage that may be caused by various factors such as hurricanes, tsunamis and earthquakes, harmful chemical factors and continuous freeze-thaw cycles, in various members of the structure, including columns; The use of sheets reinforced by different types of polymers in order to restore the initial strength can be a suitable option considering the unique characteristics of polymers reinforced by fibres such as mechanical properties, corrosion resistance, durability, lightweight, ease of use. Application, low execution time, high-efficiency [10, 15, 25, 32]. The results of previous research have shown the effect of various factors such as concrete strength, types of fibres and resin, volume and direction of fibres, jacket thickness, cross-sectional shape, length to diameter (column slenderness ratio) and surface bond between concrete core and jacket on the degree of

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jacket containment. Also, the significant effect of polymer jackets on improving the strength and ductility of concrete is undeniable [9, 20, 21, 26, 36]. an example of ineffective confinement and resulted phenomena is shown in figure 1. The technique of strengthening reinforced concrete columns by FRP sheets is basically composed of fibres with very high tensile strength along with an epoxy resin that is interwoven and matrixed on the concrete surface. Epoxy resin is a polymer bonding material that, by creating a tensile and shear resistance far greater than concrete, together with the fibres used, creates an effect of confinement in the concrete of the column area [6, 11].

Figure 1: Column damaged during Kocaeli Earthquake Turkey, 1999 due to ineffective confinement [16]

A composite FRP jacketed column can be classified as a tubular system because the FRP jacket, once installed, forms a tube to provide additional transverse reinforcement to the main column [19, 29, 30, 40]. Depending on how and when the jacket is made, the FRP jacket can be classified into two categories: cast-in-situ systems and prefabricated systems. A jacket made on-site can be installed on the desired column by manpower or jacket installation equipment. Prefabricated jackets are very similar to steel jackets that are produced in a factory environment and their quality is controlled in safer ways. Jackets can be produced in a semi-circular or rectangular form or in a roll form and installed [22, 24, 39].

In real structures, concrete columns are subjected to eccentric loading. A number of studies have investigated the effect of load eccentricity on the behaviour of FRP-encased concrete columns with circular [5, 12, 18] and non-circular [8, 27, 28, 31] sections. These studies have shown that concrete columns under off-centre axial force behave differently from columns under center loading because confinement is affected by the presence of eccentricity of the load. However, there are different results regarding the effect of load eccentricity on the axial stress-strain behaviour of FRP-confined concrete. However, one thing is clear that axial stress-strain models under a central load of FRP-encased concrete are not able to accurately predict the behaviour of the column under off-centre load, and special models are needed for accurate modelling [27, 28, 37].

FRP sheets can be used to increase the axial bearing capacity of the columns with the least increase in the cross-sectional area of the member. These sheets are implemented around the column section and by creating lateral confinement, they increase the axial capacity and ductility of the concrete column [4]. The effect of using FRPs is better and greater in columns with circular sections than in columns with square and rectangular sections due to the stresses transferred to the corners of non-circular sections; This effect can be improved by increasing the radius of the corners [1, 14, 23, 25, 34]. This phenomenon is shown in figure 2.

Choosing the type of fibre and resin used can affect the properties of the final product. In the field of civil engineering and in order to increase the bearing capacity, usually, three general categories of fibres are used, including

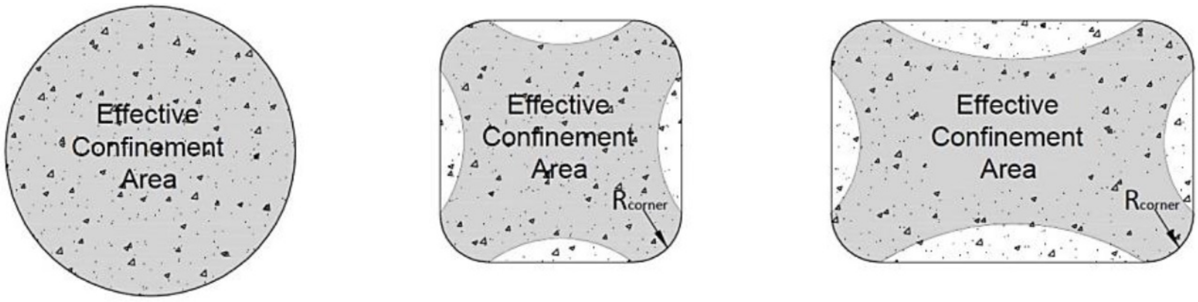


Figure 2: Effective confinement areas in circular, square and rectangular columns [25]

carbon, glass and aramid fibers. These fibers can be used together with various resins that have the task of transferring forces at the interface between concrete and fibers, as well as protecting fibers from environmental factors. Among the commonly used resins in civil engineering, we can mention vinyl ester, phenolic resins, polyester resins and epoxies. Compared to vinyl ester, epoxy resin has shown a higher position in adhesion properties, but the cost of using it is higher [3, 13, 19, 38].

The objectives of the research described in this article are to evaluate the behaviour of concrete confined by different types of FRP composite jackets under eccentric loading conditions on circular columns by finite element software.

2 Analysis

Confining RC columns using FRP with different mechanical properties is a conventional method for strengthening and rehabilitating RC columns. This study investigates the behaviour of FRP confined RC columns under eccentric load. The study focused on variables including shear reinforcement ratio (ρ_{ss}), longitudinal reinforcement ratio (ρ_{sl}), concrete cover, concrete strength, and eccentricity of the applied load. The effect of FRP fibers with different mechanical properties on the strength of the column, lateral strain, and axial strain of the column will be studied.

The basic geometry of the model consists of a concrete square column with one clamping support, to which a constant force is applied vertically. This force is applied with one-dimensional eccentricity.

The loading method for the infinite eccentricity is as shown in Fig. 3. When the eccentricity of the load is infinite, it means that the axial load is zero, and only the bending is applied to the specimen. According to Fig. 3, the specimens are tested in pure bending mode.

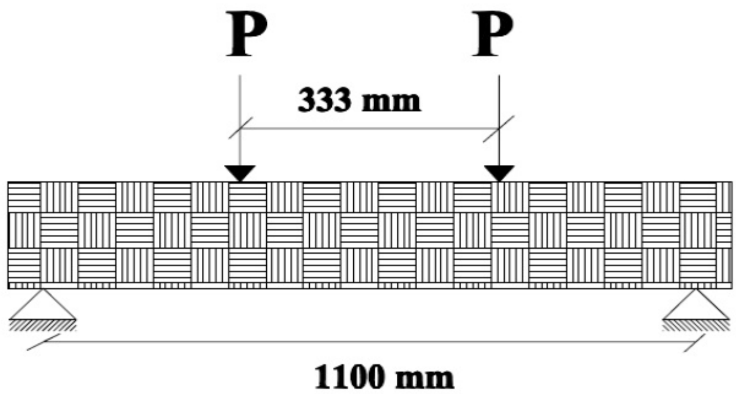


Figure 3: Loading method when $e = \infty$

RC is one of the most complex materials for finite element modelling. Appropriately defining the mechanical behaviour of reinforced concrete (elastic/plastic) in finite element modelling is one of the complex aspects of it. The strength of concrete under multidimensional stresses is a function of stress states and cannot be predicted by simple tensile, compressive, or shear ranges.

Usually, the yield of concrete occurs in two forms: tensile and compressive. Tensile yield happens with a major crack created in the concrete. On the other hand, numerous small cracks appear in the concrete in compressive yielding, which leads to loss of strength in the concrete element. Under small tensile and compressive stresses, concrete failure will be brittle with very little plastic flow. Under compressive stresses, concrete will yield like formable materials [7]. Three methods can define the nonlinear behaviour of brittle materials: smeared crack concrete model (SCCM), Brittle crack concrete model (BCCM), and concrete damage plasticity model (CDPM) in ABAQUS software. mentioned models have benefits that can be used as needed [33]. 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 are designed to model the failure of brittle materials so that it is possible to calculate stiffness changes during loading [35].

It is necessary to test the concrete sample under a uniaxial compression test and enter the stress and strain data obtained in ABAQUS software to use the CDPM. Since this is expensive and time-consuming, the data needed to define the CDPM have been extracted through the code written in MATLAB software in this study. In MATLAB software, a program has been written that can 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 1. The type of elements considered for concrete columns, FRP, and longitudinal and shear rebars are C3D8R, S4R, and T3D2, respectively.

Table 1: Characteristics of FRP sheets [17]

	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

3 Results

The resistance characteristics of each column are calculated using the program coded based on [2]. The obtained stress and strain data from Abaqus are transferred to MATLAB, and the strength characteristics of each column include maximum strength, yield strength, yield strain, ultimate strain, and ductility.

Figures 4 (a and b) show the effect of change in e and f'c on the stress-strain curve of the square column retrofitted by AFRP. According to these figures, increasing the e/d ratio decreases the maximum axial resistance and maximum axial strain, and the maximum lateral strain increases.

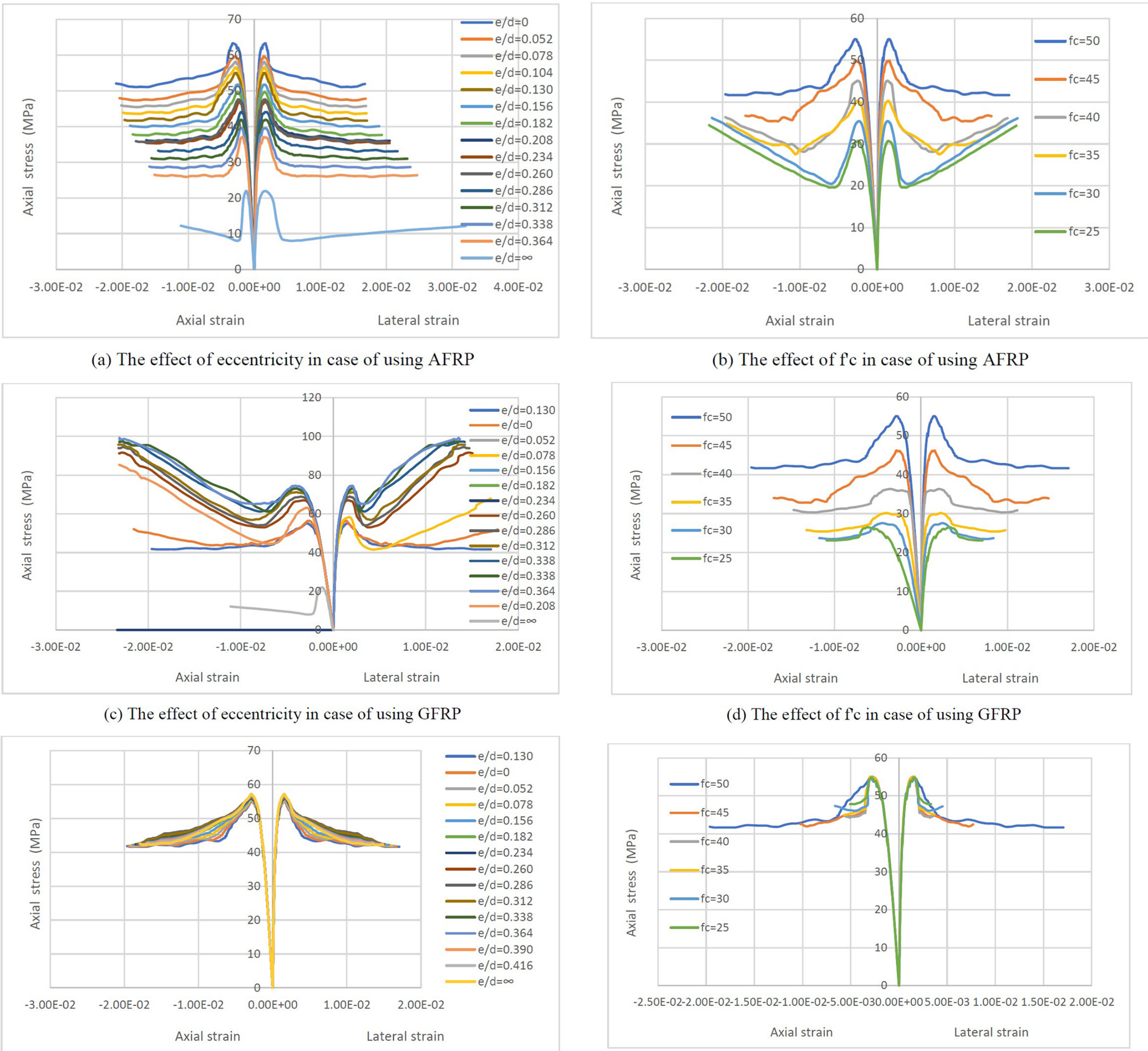
As the f'c decreases, the maximum strength of the column also decreases. Also, for each column, the maximum axial strain is much higher than the maximum lateral strain. Generally, the maximum axial and the maximum lateral strain are reduced and then increased by decreasing the f'c.

In the case of using GFRP, with increasing the e/d ratio, the concrete column's axial strength increases several times. Also, increasing the e/d ratio increased the axial strain of the column at first and was almost constant till the end. Nevertheless, the lateral strain of the column first increased slightly and then decreased. In other words, increasing the e/d ratio, in this case, reduces the lateral strain, which in turn reduces the effects of the $P-\Delta$ effect which will enhance the behaviour of the RC column. Also, with increasing f'c, the axial resistance of the column has decreased. Also, the maximum lateral and axial strain decreased with increasing f'c.

By increasing the e/d ratio, the axial strength, the axial strain, and the lateral strain of the concrete column increased in the case of using CFRP. As a result, the behaviour of the concrete column was enhanced. With increasing f'c, the axial resistance is almost constant and has not changed much. Also, the maximum lateral strain and the maximum axial strain have decreased sharply.

Strength parameters for square RC columns rehabilitated using different FRP sheets were calculated using analytic results from all models. The results computed using Matlab software are provided in Tables 2 to 7. The data in these tables are graphically illustrated in Figures 5 to 7.

Results show that by using AFRP, the maximum axial strength, maximum axial strain, yield strength, yield strain, and ductility under pure moment condition ($e/d = \infty$) relative to pure compression (e/d = 0) have decreased by 65.4%, 46.8%, 67.4%, 34.8% and 19.2%, respectively. Alternatively, the maximum lateral strain in pure moment state ($e/d = \infty$) has increased more than 90% compared to the pure compression (e/d = 0). With a decrease in f'c from 50 to 25 MPa, the maximum axial strength, yield strength, and yield strain decreased by 40.0, 61.3, and 55.9%,



(a) The effect of eccentricity in case of using AFRP

(b) The effect of f'c in case of using AFRP

(c) The effect of eccentricity in case of using GFRP

(d) The effect of f'c in case of using GFRP

(e) The effect of eccentricity in case of using CFRP

(f) The effect of f'c in case of using CFRP

Figure 4: The effect of different factors on the stress-strain curve of square column

respectively. With a decrease in f'c to 35 MPa, the yield strength and yield stress of the concrete column are uniformly reduced, but from compressive strength of 30 MPa onwards, both are abruptly reduced.

In the case of Using GFRP sheets with an increasing e/d ratio, 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.

An increase in f'c triggered 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.

An increase in e/d ratio in the case of using CFRP 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 f'c, 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. A decrease in f'c 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%.

Table 2: Square column strength parameters in terms of e/d ratio using AFRP sheets

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
∞	0.0101	18.58	0.0320	0.0111	21.90	1.09

Table 3: Square column strength parameters in terms of f'c using AFRP sheets

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
45	0.0148	45.70	0.0144	0.0170	49.92	1.15
40	0.0148	42.25	0.0168	0.0196	45.10	1.32
35	0.0143	37.30	0.0167	0.0194	40.27	1.35
30	0.0121	27.30	0.0181	0.0213	36.19	1.76
25	0.0108	22.70	0.0180	0.0217	34.47	2.01

Table 4: Square column strength parameters in terms of e/d ratio using GFRP sheets

e/d ratio	**yield strain**	**yield strength (MPa)**	**Maximum lateral strain**	**Maximum axial strain**	**Maximum axial strength (MPa)**	**Ductility**
0	0.0152	50.80	0.0171	0.0196	55.01	1.29
0.052	0.0160	52.90	0.0178	0.0216	56.41	1.35
0.078	0.0162	59.62	0.0177	0.0232	67.86	1.43
0.104	0.0159	68.66	0.0170	0.0234	74.86	1.47
0.130	0.0131	77.42	0.0161	0.0230	80.11	1.75
0.156	0.0112	82.70	0.0158	0.0232	85.42	2.07
0.182	0.0096	83.51	0.0158	0.0234	89.22	2.43
0.208	0.0087	87.74	0.0151	0.0231	91.60	2.65
0.234	0.0063	90.49	0.0147	0.0232	94.47	3.68
0.260	0.0057	92.14	0.0143	0.0232	95.73	4.07
0.286	0.0051	94.39	0.0142	0.0231	97.41	4.52
0.312	0.0045	95.66	0.0137	0.0232	99.22	5.15
0.338	0.0039	98.78	0.0136	0.0231	101.32	5.92
0.364	0.0037	99.68	0.136	0.231	103.25	6.23
∞	0.0033	100.02	0.134	0.232	104.88	7.76

4 Conclusions

This study investigated the effect of using FRP sheets with different characteristics, including GFRP, AFRP, and CFRP, and the results can be summarized as follows:

In case of using AFRP sheets, the eccentricity of the load has the most effect on the maximum lateral strain and

Table 5: Square column strength parameters in terms of f'c using GFRP sheets

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
45	0.0148	42.31	0.0148	0.0170	46.22	1.15
40	0.0132	27.41	0.0111	0.0147	36.33	1.11
35	0.0121	25.62	0.0097	0.0132	30.10	1.09
30	0.0115	24.32	0.0083	0.0118	27.60	1.03
25	0.0107	24.22	0.0071	0.0109	26.49	1.01

Table 6: Square column strength parameters in terms of e/d ratio using GFRP sheets

e/d ratio	yield strain	yield strength (MPa)	Maximum lateral strain	Maximum axial strain	Maximum axial strength (MPa)	Ductility
0	0.0152	50.80	0.0171	0.0196	55.01	1.29
0.052	0.0153	51.01	0.0167	0.0194	55.20	1.27
0.078	0.0153	51.25	0.0164	0.0193	55.30	1.26
0.104	0.0153	51.29	0.0160	0.0191	55.52	1.24
0.130	0.0153	51.20	0.0157	0.0189	55.75	1.23
0.156	0.0153	51.42	0.0152	0.0186	55.91	1.21
0.182	0.0153	51.38	0.0150	0.0185	56.00	1.20
0.208	0.0153	51.41	0.0147	0.0183	56.22	1.19
0.234	0.0153	51.42	0.0143	0.0181	56.32	1.18
0.260	0.0153	51.31	0.0144	0.0181	56.30	1.18
0.286	0.0157	52.53	0.0145	0.0181	56.33	1.16
0.312	0.0157	52.51	0.0146	0.0180	56.52	1.15
0.338	0.0157	52.59	0.0147	0.0180	56.76	1.15
0.364	0.0158	52.68	0.0148	0.0179	56.94	1.14
∞	0.0159	53.01	0.0148	0.0179	57.03	1.13

Table 7: Square column strength parameters in terms of f'c using CFRP sheets

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
45	0.0088	50.07	0.0077	0.0102	54.98	1.15
40	0.0053	50.15	0.0035	0.0057	54.91	1.08
35	0.0054	50.12	0.0037	0.0057	55.06	1.06
30	0.0061	50.10	0.0045	0.0066	54.68	1.09
25	0.0049	50.49	0.0033	0.0051	54.80	1.04

the least effect on the ductility of the square column. However, a decrease of f'c had the most significant effect on the ductility and yield strain of the column and the least effect on the maximum axial and lateral strain.

In the case of using GFRP sheets, the e/d ratio has a significant effect on the strength of the concrete column. Also, increasing the e/d ratio had the greatest effect on the ductility and strength of the column and the least effect on the maximum axial strain. Increasing the f'c 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.

Furthermore, finally with using CFRP sheets, the increase in the e/d ratio generally had a positive effect on the behavior of the concrete column. However, it was very small compared to other parameters. Also, increasing f'c had the most effect on reducing the column strain and the least effect on the strength of the concrete column.

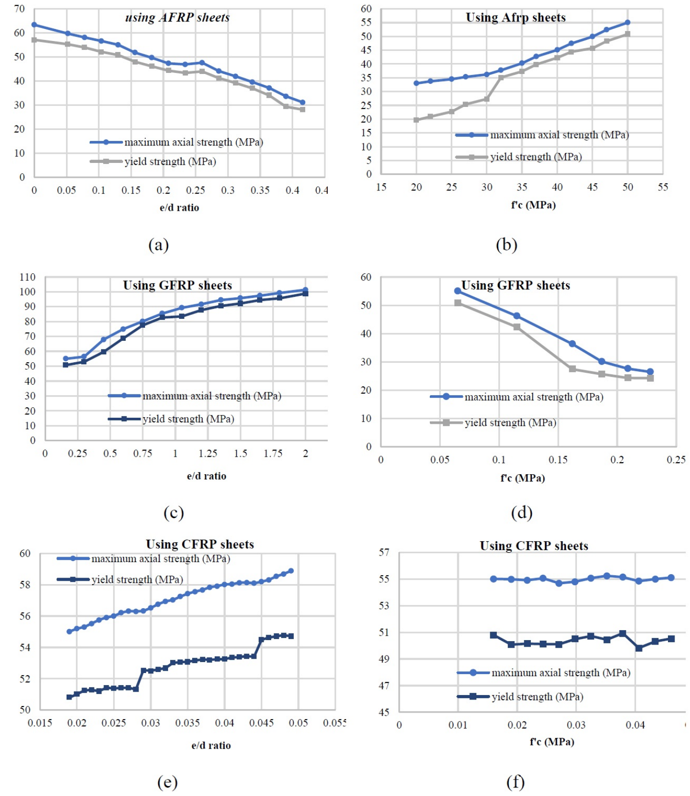


Figure 5: The effect of different factors on the maximum axial strength and yield strength of the square column

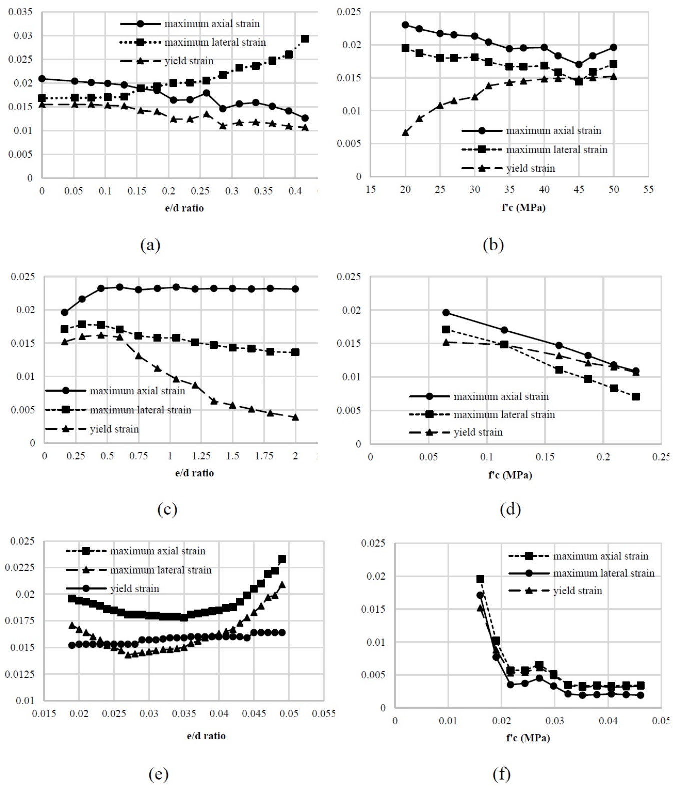


Figure 6: The effect of different factors on the maximum axial and lateral strain and the yield stress of square column

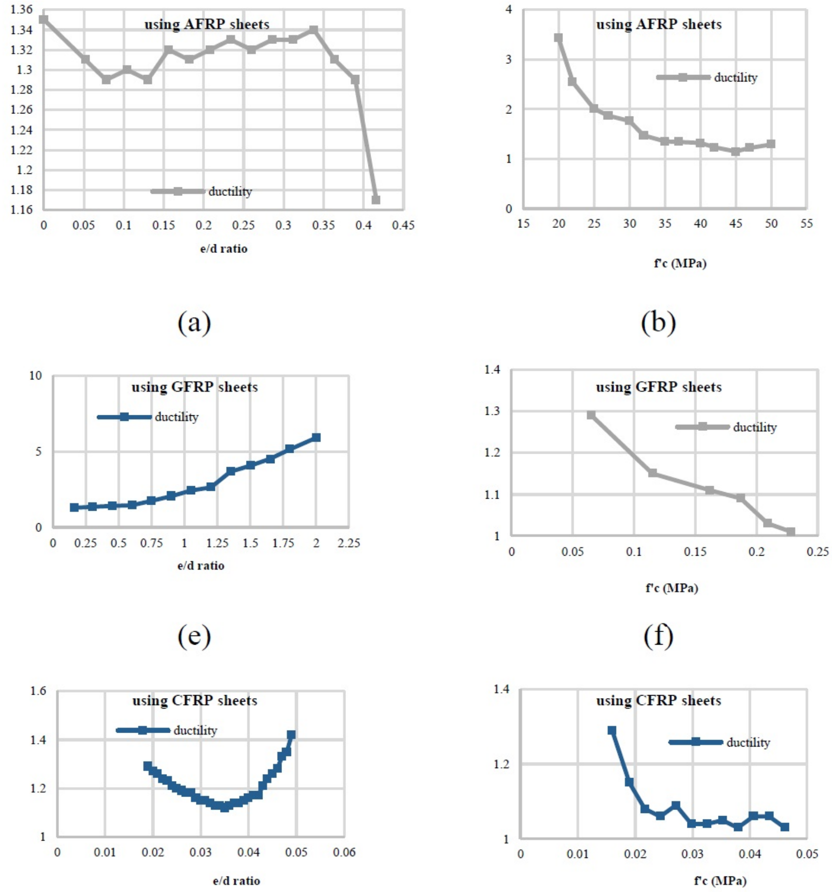


Figure 7: The effect of different factors on the ductility of square column

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