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BEHAVIOR OF REINFORCED CONCRETE SHORT COLUMNS WITH FIBER REINFORCED POLYMERS BARS

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This paper presents the results of an experimental investigation of the axial behavior of small scale square reinforced concrete columns with fiber reinforced polymer (FRP) bars, as a solution to overcome the corrosion problems, where this material represents a relatively new technology; therefore more research is needed to determine its characteristics and gain confidence to be accepted by engineers for practical applications. Eight columns were tested in a vertical position and under compressive axial static loading, where all columns had the same dimensions 250*250mm and 1250mm height, main reinforcement 4#12mm, 6#12mm, and 8#12mm, the transverse reinforcement was ø6@120mm closed stirrups along the columns. The major parameters included in this research were the main reinforcement ratios, the main reinforcement types, the transverse reinforcement ratios in the column, and the characteristic strength of the concrete. Results from a series of tests on small-scale specimens showed that increasing main reinforcement, transverse reinforcement ratios in the column ends and increasing characteristic strength of the concrete have a significant effect on the behavior of reinforced concrete columns with FRP.

Keywords: inelastic behavior, column, fiber, polymer, glass, and compression strength

1. Introduction

Deterioration of reinforced concrete structures has become a serious problem in the last decade; this situation is mainly due to corrosion of steel reinforcement embedded in concrete. Fiber reinforced polymer (FRP) is increasingly used for reinforcing new structures, and strengthening the existing structures. FRP composites, in the form of sheets, cables, rods, and plates, have

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proven to be a cost-effective alternative to steel reinforcements because of their low weight to strength ratio, corrosion resistance, and flexibility. The most common types of FRP are aramid, glass, and carbon; AFRP, GFRP, and CFRP respectively. There are many bridge structures all over the world with application of FRP as reinforcement: In China, there are now eight GFRP bridges. These bridges were generally constructed by hand lay-up of glass fibers in a polyester resin using a honeycomb form of deck structure, as the Miyun Bridge, the Xianyyong bridge, and Hulan River Bridge; In Germany, the Lünensche Gasse pedestrian bridge, the Ulenbergstrasse Bridge, and the Schiessbergstrasse Bridge; In Japan, the Shinmiya Highway Bridge, the Bachi-Minami-Bashir highway bridge, the Nagatsugawa pedestrian Bridge, Tochigi Prefecture Bridge, and Ibaraki Prefecture Bridge; In Canada, the Beddigton Trail Bridge, the Headingley Bridge, Wotton Bridge, and Magog Bridge; In the United States; the McKinleyville Bridge, and the Morristown Bridge (Nicholas, 2003; Halcrow, 1996; OU, 2003; and EL-Salakawy, 2003). Unfortunately, there was a lack of data about using FRP as reinforcement; the lack of a comprehensive database on FRP materials makes it difficult for the practicing civil engineers and designers to use FRP composites on a routine basis. Although a number of reviews have been published recently related to durability and test methods. The focus of each has been to summarize the state of knowledge in general without emphasizing or attempting to prioritize critical areas in which needs are the greatest for collection, assimilation, and dissemination of data (Karbhari, 2003). Fiber reinforced polymer bars (FRP) may used in reinforcement of sections which are exposed to flexural moment like slabs and beams (RC), and are not used in the reinforcement of sections which are exposed to compression forces like columns (Egyptian Code Committee, 2005).

Paramanantham (1993) tested 14 concrete beam-columns reinforced with glass fiber-reinforced polymer (GFRP) reinforcing bars. The study reported that the GFRP reinforcing bars would only be stressed up to 20 to 30% of their ultimate compression strength in pure axial compression, and up to 70% of their tensile strength in a pure flexure. Kawaguchi (1993) performed similar tests with concrete member reinforced with aramid fiber-reinforced polymer (AFRP) reinforcing bars. Both studies showed that concrete compression members reinforced with FRP reinforcing bars can be analyzed by applying the same principles and procedures used for concrete columns with steel reinforcement. Deitz et al. (2003) tested GFRP reinforcing bars that had an outside diameter of 15 mm (3/5 in.) in compression, and reported that the ultimate compression strength of the bars was approximately 50% of the ultimate tensile strength. In general, the compressive strength of FRP reinforcing bars is lower than tensile strength. In contrast to the vast database available on FRP-RC beams and slabs, literature on FRP-RC columns with FRP bars is infrequent and limited. So, this study aims to study the behavior of reinforced concrete columns with GFRP. The results and observations presented in this paper are useful to practicing engineers who have to predict the enhanced compressive strength of concrete columns reinforced with GFRP bars.

2. Experimental Program

2.1. Description of Test Program

In this research, tests were carried out on 8-column specimens, where all columns had the same dimensions 250*250mm and 1250mm height. Tested specimens were divided into four groups:

Group 1: contains three specimens with GFRP reinforcement 4#12mm, 6#12mm and 8#12mm, the transverse reinforcement was closed stirrups ø6mm@120mm spread all the specimens lengths, and f_{cu}=25N/mm^2;

Group 2: contains one specimen with steel reinforcement 4#12mm, the transverse reinforcement was closed stirrups ø6mm@120mm spread all the specimen length, and f_{cu}=25N/mm^2;

Group 3: contains two specimens with GFRP reinforcement 4#12mm, the transverse reinforcement was closed stirrups ø6mm@120mm spread all the specimens lengths, and fcu=30, 35 N/mm2;

Group 4: contains two specimens with GFRP reinforcement 4#12mm, and the transverse reinforcement was closed stirrups ø6mm@120mm spread at the middle third of tested specimen, and ø6mm@60mm spread at the other third of tested specimen. And the next specimen has transverse reinforcement was closed stirrups ø6mm@60mm spread all the specimen length.

Table 1 shows the details of tested specimens. Specimens were tested in a vertical position and under compressive axial static loading with pinned-pinned end-conditions up to failure, as shown in Figure 1. Figure 2 shows the details of reinforcement of columns.

Table 1. Details of tested columns specimens:

Group No.	Column No.	Dim (mm)		f_{cu} (N/mm^2)	Steel	Steel ratio (%)	Steel stirrups in the column ends	Notes
		dim	L					
1	C1	250*250	1250	25	4#12mm	0.723	(ø 6mm@120mm)	1-GFRP reinf 2-Stirrups shape (A)
	C2			25	6#12mm	1.08	(ø 6mm@120mm)	1-GFRP reinf 2-Stirrups shape (A)
	C3			25	8#12mm	1.45	(ø 6mm@120mm)	1-GFRP reinf 2-Stirrups shape (A)
2	C4			25	4#12mm	0.723	(ø 6mm@120mm)	1-Steel reinf 2-Stirrups shape (A)
3	C5			30	4#12mm	0.723	(ø 6mm@120mm)	1-GFRP reinf 2-Stirrups shape (A)
	C6			35	4#12mm	0.723	(ø 6mm@120mm)	1-GFRP reinf 2-Stirrups shape (A)
4	C7			25	4#12mm	0.723	(ø 6mm@60mm)	1-GFRP reinf 2-Stirrups shape (B)
	C8			25	4#12mm	0.723	(ø 6mm@60mm)	1-GFRP reinf 2- Stirrups shape (C)

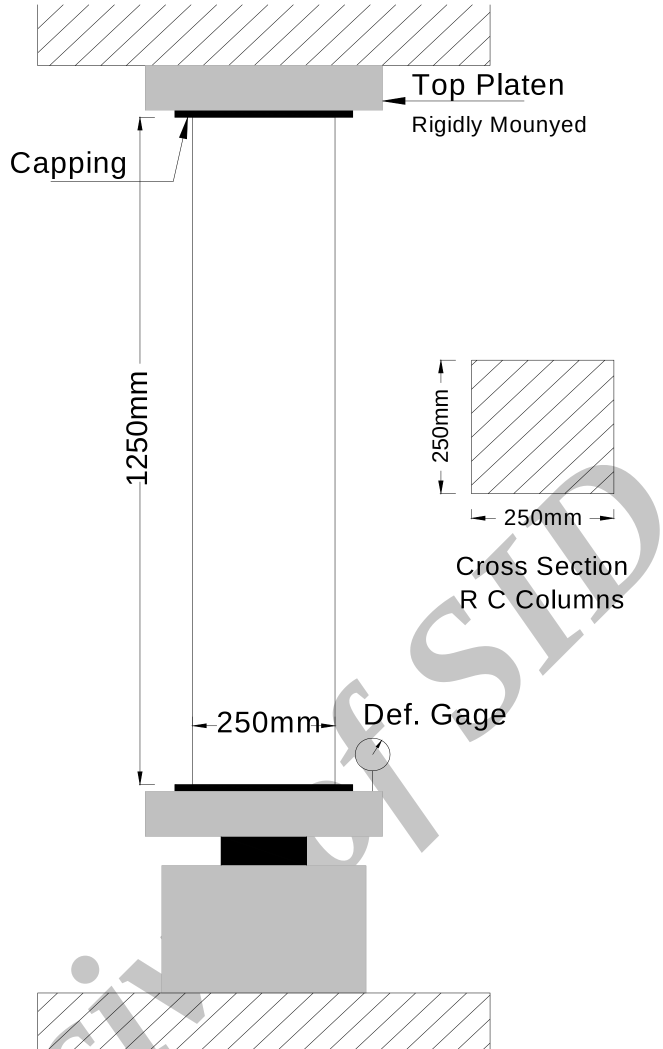
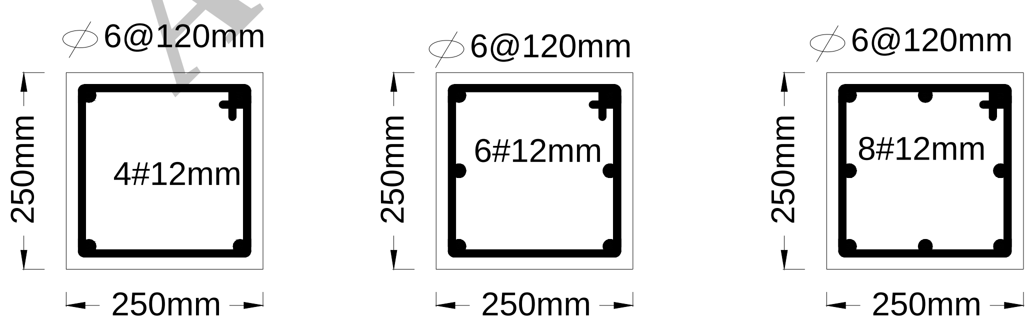
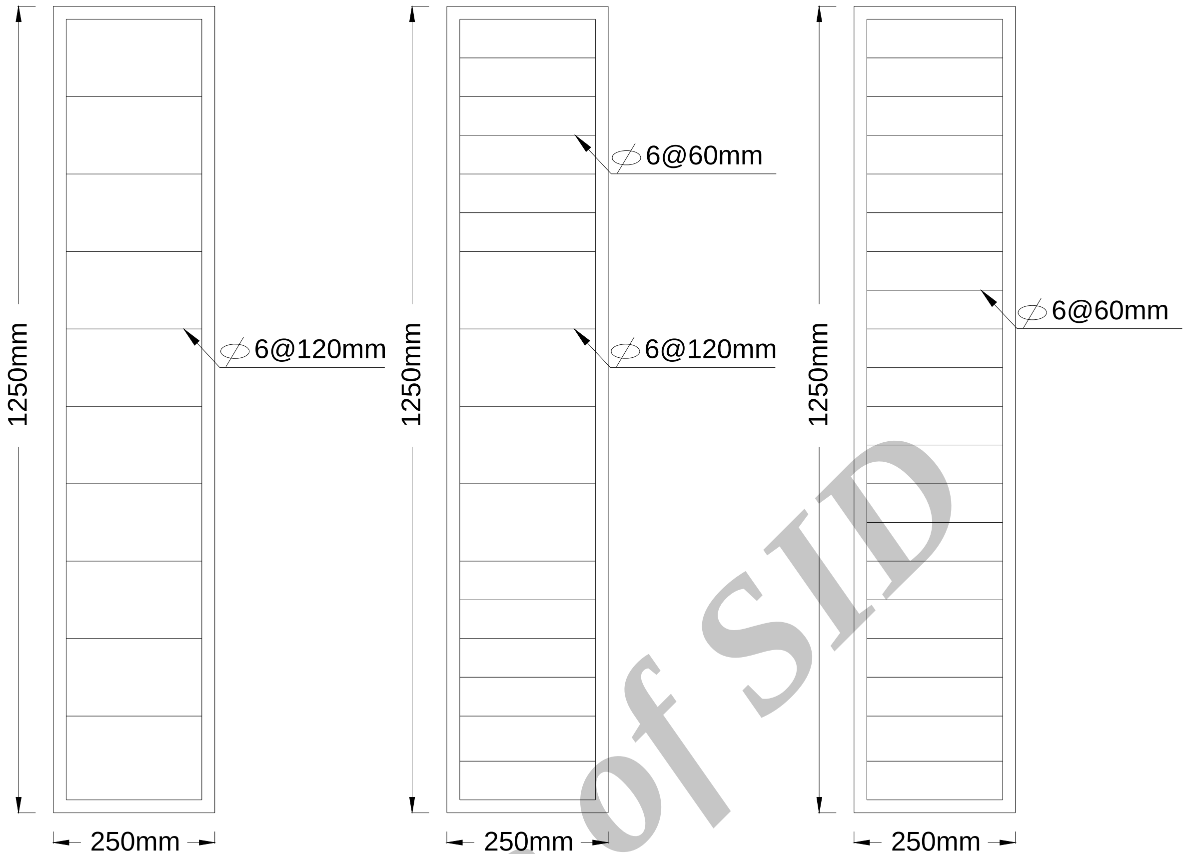


Figure 1. Loading arrangement on specimens



Cross Section (C1) Cross Section (C2) Cross Section (C3)

Figure 2. Details of reinforcement of tested columns



Stirrups Shape (A) Stirrups Shape (B) Stirrups Shape (C)

Figure 2 (continue). Details of reinforcement of tested columns

2.2. Material Properties

2.2.1. Material Used and Casting of Tested Columns

The materials used in this work were sand with fineness modulus 2.464, siliceous gravel with maximum nominal size 9.5 mm and them grading shown in Table 2, ordinary Portland cement; its testing results shown in Table 3, and tap drinking water was used.

Table 2. Grading of used gravel and sand

Sieve size (mm)	38	19	9.51	4.76	2.83	1.41	0.707	0.354	0.177
% Passing (by weight) gravel	100	99	95.5	20	5	0	0	0	0
% Passing (by weight) sand	100	100	100	100	98	75	50	9.5	0

Table 3. Results of tested concrete

No.	Test	Results
1	Time of setting	Initial = 0.0 hour, 50 min.
		Final = 6.0 hour, 15 min.
2	Soundness, cm	0.8 cm
3	Compressive strength, N/mm^2	At 3 days = 19.5
		At 7 days = 27.5

2.2.2. Steel Reinforcement Bars

High grade deformed steel bars of nominal diameter 12 mm was used for main reinforcement in this work, mild steel bars of nominal diameter 6 mm was used as stirrups. The relevant mechanical properties of reinforcement steel bars were obtained from a basic tensile test on universal testing machine; Table 4 shows the test results.

Table 4. Properties of used steel

Commercial Dia. (mm)	Actual Dia.(mm)	Yield strength (N/mm^2)	Ultimate Strength (N/mm^2)	Elongation (%)
ø 6	6	250	365	26
#12	12	415	535.5	18.7

2.2.3. Fiber Polymer Bars

Modern composites are usually made of two components, as fiber and matrix. The fiber is most often glass, Kevlar, carbon fiber, or polyethylene. A common fiber-reinforced composite is Fiberglass. Glass fiber Gun Roving RS240 was used in this work, where it is made of "E" glass fiber roving with uniform tax, good chop ability, stiffness, dispersion, anti-static and wet out. The fiber is embedded in the matrix; SIRE5TER FS 0993/T/I which is an unsaturated thixotropic orthophthalic Polyester based resin dissolved in styrene. Such a resin is characterized by medium/high reactivity. SIRESTER FS 0993/T/I is not accelerated but it is formulated in order to have a very short curing time even at low temperature. Table 5 shows the test results.

Table 5. Properties of used GFRP bars

No.	Diameter (mm)	Proof strength (N/mm^2)	Ultimate strength (N/mm^2)	Strain (%)
Sample No 1	12	458	576.5	4.58
Sample No 2	12	472	581	4.5
Sample No 3	12	451	560	4.5

2.2.4. Concrete Mix Design

The ACI method (ACI. Committee 211) was used in mix design proportion as given in Table 6. Cubes of 150×150×150 mm were casted at the same time and from the same batch of concrete used for the beams to determine the compressive strength of concrete.

Table 6. Weights of the used components in concrete mix design

Mixing No.	Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Water/cement	Slump value (mm)	f_{cu} (N/mm^2)
1	350	605	1211	0.58	85	26
2	375	595	1190	0.54	60	31.5
3	425	580	1160	0.48	50	36.5

2.3. Instrumentations and Detection of Cracks

Mechanical gauges with 0.01mm accuracy were used to measure the contraction at the end of columns, Figure 1 shows the location of installed instruments on the model. The initial cracks were detected using a magnifying glass with a lamp to improve lighting; the propagation of cracks was marked after each load increment. The development of cracks may be easily marked by pencil, which will be visible after the test.

3. Results and Discussions

The main parameters included in this research were the main reinforcement ratio, the main reinforcement types, the transverse reinforcement ratio in the column ends and the characteristic strength of concrete. Table 7 shows the results of the tested columns in this study, the table includes the values of the initial cracking loads (P_{cr}), the ultimate loads (P_u), and ultimate deformations.

Table 7. Results of the tested columns

Column No.	Steel Ratio (%)	Initial cracking loads P_{cr} (KN)	Ultimate loads P_u (KN)	Ultimate deformations def_u (mm)	Notes
C1	0.723	230	760	0.7	1-GFRP reinf 2-Stirrups shape (A)
C2	1.08	260	870	0.72	1-GFRP reinf 2-Stirrups shape (A)
C3	1.45	305	920	0.77	1-GFRP reinf 2-Stirrups shape (A)
C4	0.723	270	900	0.82	1-Steel reinf 2-Stirrups shape (A)
C5	0.723	320	960	0.75	1-GFRP reinf 2-Stirrups shape (A)
C6	0.723	340	1095	0.81	1-GFRP reinf 2-Stirrups shape (A)
C7	0.723	260	830	0.79	1-GFRP reinf 2-Stirrups shape (B)
C8	0.723	290	975	0.85	1-GFRP reinf 2- Stirrups shape (C)

Table 8. Comparison between predicted and experimental results (ACI 318-08)

Column No.	Steel Ratio (%)	Rebar type	Characteristic strength (KN/mm^2)	Experimental loads P_u (KN)	Predicted Loads P (KN)	P_{exp}/P_{pred}
C1	0.723	GFRP	25	760	750	1.01
C2	1.08	GFRP	25	870	810	1.07
C3	1.45	GFRP	25	920	870	1.06
C4	0.723	Steel	25	900	740	1.21
C5	0.723	GFRP	30	960	875	1.09
C6	0.723	GFRP	35	1095	1005	1.09
C7	0.723	GFRP	25	830	750	1.10
C8	0.723	GFRP	25	975	750	1.30

3.1. Main Reinforcement Ratio

Figure 3 shows the load-deformation of columns C1, C2 and C3 which reinforced by GFRP reinforcement 4#12mm, 6#12mm and 8#12mm (0.723, 1.08, and 1.45%) respectively; increasing GFRP reinforcement ratio leads to increase the toughness and ductility of tested columns. From Table 7, it can be seen that, ultimate loads, ultimate strain and initial cracking loads of C2 and C3 to C1 are (114,102 and113%), and (121,110 and132%) respectively. The increasing of the main reinforcement ratios with GFRP bars increase the ductility of cross section, so it has a significant effect on the initial cracking loads, ultimate strain, and ultimate loads that the columns resist. Figure 4 shows the effect of the main reinforcement ratios on the ultimate load that the columns resists, where the increasing of the main reinforcement ratios has a significant effect on ultimate loads, it is observed that load increasing corresponding to increasing reinforcement ratio from 0.723 to 1.08% is larger than that ratio from 1.08 to 1.45%.

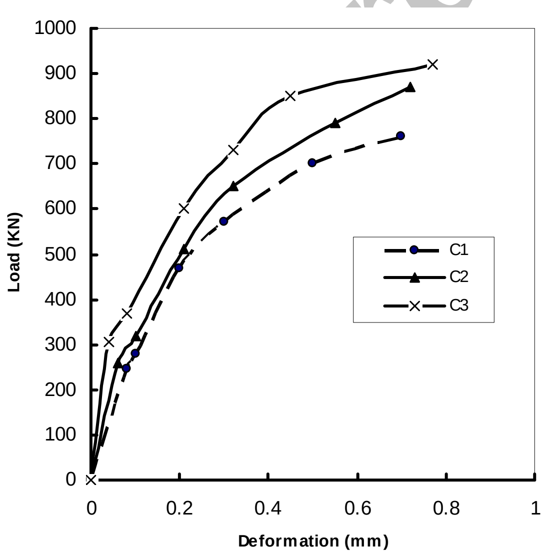


Figure 3. Load-deformation of C1, C2 and C3

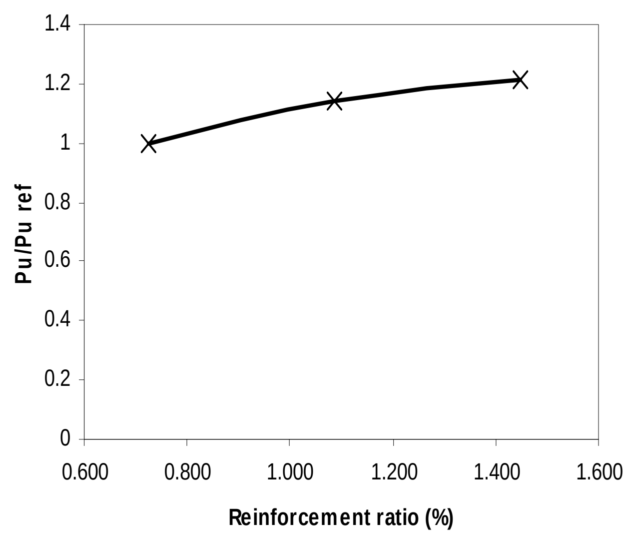


Figure 4. Ultimate load of C2, C3 to C1 and main reinforcement ratio

3.2. Main Reinforcement Types

Figure 5 shows the load-deformation of columns C1 and C4 which reinforced by GFRP and steel reinforcement with 4#12mm (0.723%); tested column with steel reinforcement has ductility more than column with GFRP reinforcement. From Table 7, it can be seen that, ultimate load, ultimate strain and initial cracking loads of C4 to C1 is 118, 117 and 117% respectively. Figure 6 shows that using steel as the main reinforcement has a significant effect on the ultimate load which the column resists. Using steel as main reinforcement has a significant effect on the initial cracking loads ultimate strain, and ultimate loads that the columns resist.

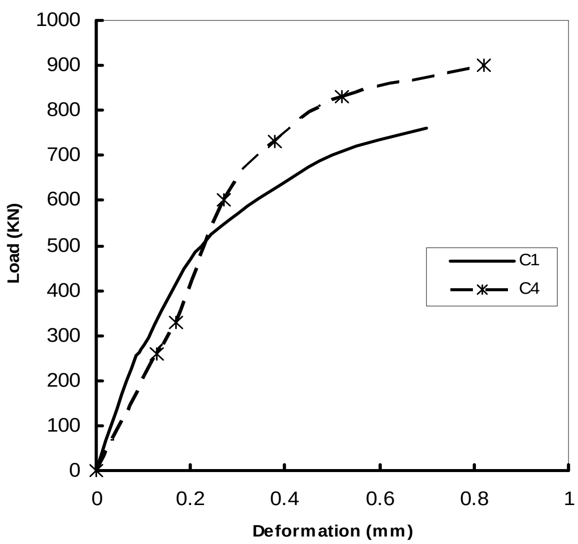


Figure 5. Load-deformation of C1 and C4

Figure 6. Ultimate load of C4 to C1 and reinforcement type

3.3. Transverse Reinforcement Ratio in Tested Columns

Figure 7 shows the load-deformation of columns C1, C7 and C8; increasing of transverse reinforcement ratio leads to increase the toughness and ductility of tested columns. From Table 7, it can be seen that, ultimate loads, ultimate strain and initial cracking loads of C7 and C8 to C1 are (109,112 and113%) and (128,121 and126%) respectively. Figure 8 shows the effect of the transverse reinforcement ratios in the column ends on the ultimate load that the columns resists, where the increasing of transverse reinforcement ratios has a significant effect on ultimate loads. The increasing of transverse reinforcement ratios confines the columns so it is lead to increase the ultimate loads which the columns resisted, hence increasing ultimate strain, and initial cracking loads.

As the increasing of the transverse reinforcement ratio leads to increase the toughness and ductility of tested columns with GFRP, so it will be compared with tested column with steel reinforcement and normal stirrups distribution. Figure 9 shows the load-deformation of columns C1, C7, C8 and C4, the increasing of stirrups with columns reinforced by GFRP increase the toughness and ductility of columns more than using steel bars with normal stirrups distribution, the behavior of column with steel bars C4 generate between the behaviors of C7 and C8. From Table 7, it can be seen that, ultimate loads, ultimate strain and initial cracking loads of C4, C7 and C8 to C1 are (118, 117 and117%), (109,112 and113%) and (128,121 and126%), respectively.

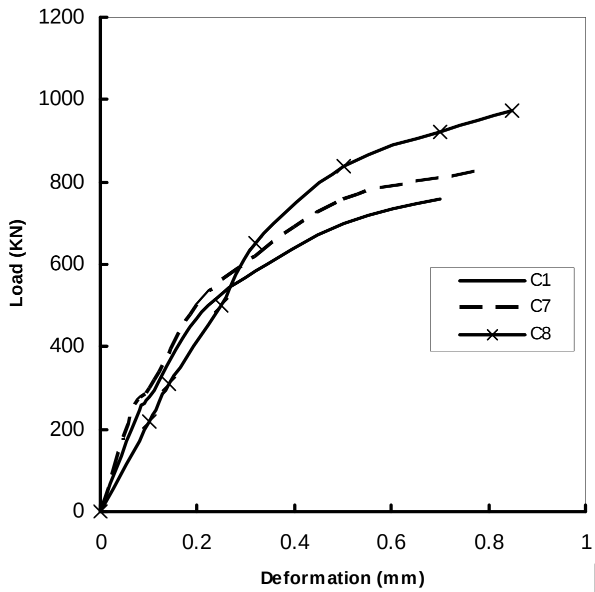


Figure 7. Load-deformation of C1, C7 and C8

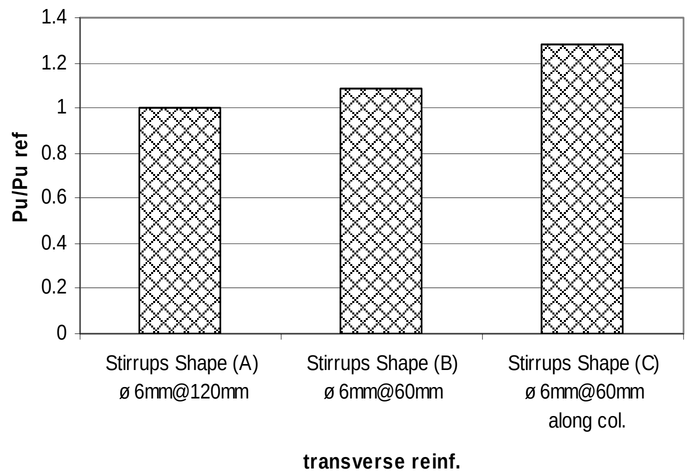


Figure 8. Ultimate load of C1, C7 and C8 and transverse reinforcement

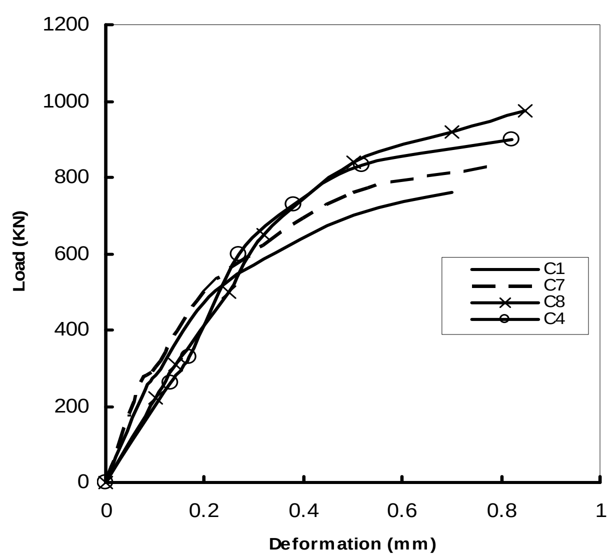


Figure 9. Load-deformation of C1, C4, C7 and C8

3.4. Characteristic Strength of Concrete

From Table 7, it can be seen that, ultimate loads, ultimate strain and initial cracking loads of C5 and C6 to C1 with (25, 30 and 35N/mm^2) are (126,107 and 139%) and (144,115 and 147%), respectively. Figure 10 shows the load-deformation of columns C1, C5 and C6; increasing of characteristic strength of concrete has significant effect on the behavior of tested columns where increases toughness and ductility of tested columns. Figure 11 shows the effect of the characteristic strength of concrete on the ultimate load that the columns resists, where the increasing of characteristic strength of concrete has a significant effect on ultimate loads.

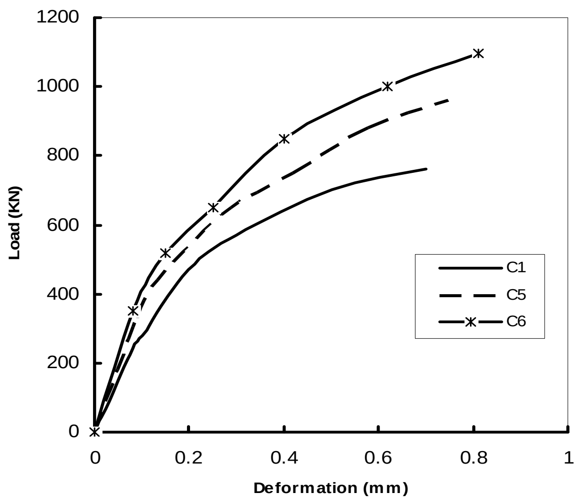


Figure 10. Load-deformation of C1, C5, C6

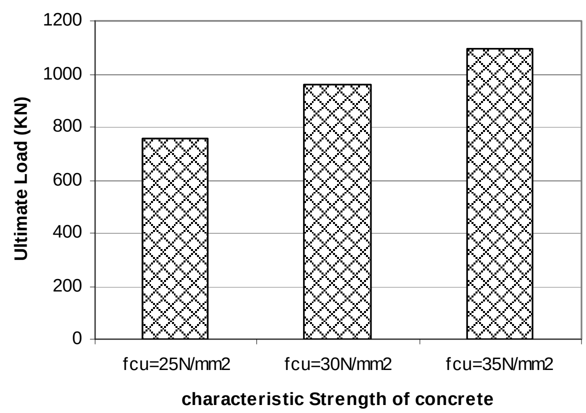


Figure. 11. Ultimate load of C1, C5 and C6 and characteristic strength of concrete

3.5. Theoretical Analysis

The ultimate strength of the tested specimens was calculated theoretically based on the first principles of the ultimate theory for design of reinforced concrete members. Computations of the strength of cross-sections should be performed based on the following assumptions:

(a) Strain in the concrete and the FRP reinforcement is proportional to the distance from the neutral axis (that is, a plane section before loading remains plane after loading);

(b) The maximum usable compressive strain in the concrete is assumed to be can be 0.003;

(c) The tensile strength of concrete is ignored;

(d) The tensile behavior of the FRP reinforcement is linearly elastic until failure;

(e) A perfect bond exists between the concrete and FRP reinforcement.

The ultimate strength of the steel and GFRP rebars were taken according to the material tests and all safety factors were considered equal to one.

Table 8 gives a comparison of theoretical and experimental results of the tested specimens. The increase in the experimental ultimate strength of specimens compared with the theoretical strength is related to the contribution of the external fabric mesh. Table 8 shows that the experimental results are approximately 1–9% higher than the theoretical values, apart from specimen C8 in which the difference was 30%.

4. Summary and Conclusions

The experimental results from eight reinforced concrete columns demonstrated the influences of the main reinforcement ratio, the main reinforcement type, the transverse reinforcement ratio, and characteristic strength of concrete on the ultimate loads, ultimate strain and initial cracking loads. Based on the experimental results presented in this study the following conclusions can be drawn:

1. Tested column with steel reinforcement has ductility more than column with GFRP reinforcement, where ultimate load, ultimate strain and initial cracking loads of column with steel reinforcement increase with 118, 117 and 117% respectively of column with GFRP reinforcement.
2. The increasing of main reinforcement ratios with GFRP bars increase the ductility of cross section, so it has a significant effect on the initial cracking loads, ultimate strain, and ultimate loads that the columns resists.
3. The increasing of GFRP reinforcement ratios from 0.723 to 1.08% has a noticeable significant effect on the all behavior of tested columns more than the increasing of reinforcement ratios from 1.08 to 1.45%.
4. Increasing of transverse reinforcement ratio leads in increasing the toughness and ductility of tested columns with GFRP bars, where the increasing of transverse reinforcement ratios confines the columns so it leads in increasing the ultimate loads which the columns resisted, hence increasing ultimate strain, and initial cracking loads. And the column with GFRP bars has toughness and ductility more than column with steel bars and normal transverse reinforcement distribution.
5. Increasing of the characteristic strength of concrete has significant effect on the behavior of tested columns where increases the toughness and ductility of tested columns.
6. Using the first principles of the ultimate theory for prediction of the ultimate loads capacity of tested columns that gives results in good agreement with the experimental results.

So, GFRP bars can be used as the main reinforcement in columns with increasing the transverse reinforcement along columns length and using high strength concrete.

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