Journal of Engineering and Sustainable Development
Vol.20, No.03, May 2016
ISSN 2520-0917
www.jeasd.org

BEHAVIOR OF HIGH-STRENGTH FIBER CONCRETE COLUMNS REINFORCED WITH GLASS FIBER-REINFORCED POLYMER BARS AND STRENGTHENED BY CARBON FIBER-REINFORCED POLYMER WRAP

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(Received:14/12/2015 ; Accepted 26/01/2016)

Abstract: The solution of using glass fiber reinforced polymer (GFRP) bars, as reinforcement in concrete structures to overcome the problems created by steel reinforcement, is now widely accepted because of both its low cost and good results shown by large investigation efforts. In this paper twelve tests had been conducted on reinforced concrete column specimens of (120 x 120 x 1000 mm effective dimensions) equally enlarged from both ends for the purpose of applying eccentric load, three specimens were made of high strength concrete , reinforced with traditional deformed steel bars and stirrups to be considered as references, while the remaining nine specimens were of high strength concrete with 0, 0.5, 1.0% steel fiber, reinforced longitudinally with GFRP bars and wrapped with carbon fiber reinforced polymer (CFRP) textile replacing the steel stirrups .In addition to the similarity in behavior under load and in the failure patterns of the specimens reinforced with GFRP bars and the specimens reinforced with traditional steel, the results show that Steel reinforced columns has 13% higher ultimate load than corresponding GFRP reinforced columns, also an approximate linear increase in the first crack and failure load with the presence of steel fiber in concrete in range from 20% to 42% for 1% fiber content and in range of 21% to 26 % for the first crack and ultimate load respectively . The ductility of the specimen reinforced with GFRP bars is 90% higher than that of steel reinforced specimens of $\boldsymbol{\rho}$=2.18% and 10% more for those of $\boldsymbol{\rho}$=5.58%.

Keywords: *Columns, GFRP Reinforcement, High Strength Concrete, Fiber Reinforced Concrete CFRP Wrapping Strengthener*

سلوك الاعمدة الخرسانية عالية المقاومة المسلحة بالقضبان الزجاجية والمقواة بألياف الكاربون

الخلاصة: يعتبر استعمال ماده الالياف الزجاجيه ,الممزوجه بالبوليمر والمعموله على شكل قضبان, كتسليح في المنشأت الكونكريتيه للتغلب وتلافي المشاكل المتولده من استعمال الحديد الاعتيادي حلا مقبولا على نطاق واسع هذه الايام وذلك بسبب قله كلفته والنتائج الجيده

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المتوفره من الابحاث . في هذه الدراسه تم فحص اثنا عشر عينه من اعمده بابعاد (120*120*1000)ملم مقواه من النهايين لغرض تسليط الاحمال اللامركزيه ولتجنب حدوث فشل جانبي. تم تسليح ثلاثه نماذج بالحديد الاعتيادي لاعبارها كمرجع وتم تسليح التسعه الباقيه بقضبان الالياف الزجاجيه و بثلاث نسب من الياف الحديد مع الكونكريت العالي المقاومه. اضافه الى التشابه في التصرف تحت الحمل و التشابه في شكل الفشل بالرغم من عدم وجود منطقه تصرف لدن للنماذج المسلحه بالياف الزجاج فان النتائج اظهرت نقص في تحمل النماذج المسلحه بالياف الزجاج عن مثيلاتها المسلحه بالحديد بنسبه 13% وكذلك زياده في حمل التشقق الاولي والحمل الاقصى بمقدار 42% و20% عند زياده نسبه الياف الحديد في الكونكريت الى1% في النماذج المسلحه بالالياف الزجاجيه وبنسبه 21% الى 26% على التوالي,كذلك زياده نسبه المطيليه بمقدار 90% للنماذج المسلحه بالياف الزجاج عن مثيلاها المسلحه بالحديد بنسبه2.18% بينما كانت الزياده 10% لذوات نسب التسليح 5.58% .

1. Introduction

In nowadays practice, using of high strength concrete is widely spread in compression members than in flexural those are mainly controlled by deflection criteria. Columns are of vital priority among the remaining structural elements, therefore their concrete and steel durability, protection against deterioration and degradation are of paramount importance for safety issues. Continuous trials, to improve the quality and performance of such members had been conducted on concrete, by using additives and different types of fibers to produce more firm matrices, and on reinforcement by replacing the traditional steel bars by the GFRP bars to eliminate the problem of steel corrosion which disintegrate the surrounding concrete due to volume change of corroded steel [1].

GFRP is a nontoxic material, with low hazard impact to human and environment can be used in concrete structures instead of the traditional steel reinforcement, the most important feature of GFRP is that its coefficient of thermal expansion is similar to that of concrete, which prevents cracking under temperature changes.

Recently, the trend is using FRP wraps to improve structural performance like strengthening of columns for enhancing load carrying capacities, shear strength and deformation properties. Carbon fiber reinforced polymer (CFRP) is high performance material that consist of high strength fiber embedded in a polymer matrix to combine the strength of the fibers with the stability of the polymer resin [2, 3].

CFRP has unique properties making them extremely attractive for structural applications. It offers better strengthening alternative to traditional steel jacketing because it is durable, noncorrosive, has high strength-to-weight and stiffness-to-weight ratios, possess good fatigue behavior and allow easy handling and installation [2, 4, 5, 6].

Although FRPs are materials with high tensile strength and exhibit a linearly elastic stress strain relationship until failure without any plastic behavior (yielding), but their anisotropic properties oriented the researches test done by (Mallick1988,Wu 1990,Ehsani 1993)[1] to support the reliability of GFRP bars to resist the compressive stresses, which conclude to that the compressive elastic modulus, of GFRP and CFRP (50-60% fiber volume), is 80% and 85% of its tensile modulus of elasticity and the compressive strength is 55%,78% of the tensile strength respectively.

Tests, on concrete structure elements reinforced and strengthen by those materials, are in continuous running to evaluate their contribution to the strength, stiffness and durability of elements, among them are the tests carried through this paper on column specimens loaded eccentrically and reinforced longitudinally by GFRP bars and strengthen externally by CFRP wrap.

2. Literature Review

Al Sayeed [7] reported a 13% decrease in load carrying capacity of concentric loaded columns (450 x 450 x 1200 mm) reinforced with GFRP main bars and stirrups replacing same area of traditional steel, whereas replacing steel ties with GFRP ones reduce the capacity by 10% only. Mirmiran [8] concluded from analytical study that the slenderness limit of 22 for steel reinforced columns should be reduced to 17 for GFRP reinforced columns in single curvature mode of failure.

De Luca, after tests of five 610x610x 1200 mm concrete columns reinforced with GFRP bars under concentric load concluded that GFRP bars can be used in columns but the contribution of GFRP bars in calculating the nominal capacity could be ignored.

3. Research Significance

This experimental study aimed to explore the mechanical behavior of the high strength steel fiber concrete columns reinforced longitudinally with GFRP bars and replacing tie steel reinforcement with external wrap of CFRP.

4. Experimental Program

This paper presents an experimental study of the behavior of eccentrically loaded fiber reinforced concrete columns reinforced with GFRP bars and wrapped with CFRP textile and compared to columns of traditional steel reinforcement, the specimens were denoted by (G) which stands for GFRP or (S) for steel, then by 0, 5, 1 stand for percentage of steel fiber in concrete 0%, 0.5%, 1% then 10, 12, 16 which are the diameter of the reinforcing bars.

4.1. Columns Specimens

Total of twelve reinforced concrete columns were tested to failure to assess the performance of the GFRP bars and CFRP wrap together with high strength concrete of steel fiber compared to traditional deformed steel bars and stirrups column cross section, three specimens (denoted by letter S for steel) were cast with high strength concrete of 66 MPa and reinforced longitudinally with three different bar diameters "(10, 12, 16mm)" sets of four bars at corners and ϕ 6 mm at 120 mm transverse stirrups.

All the remaining nine column specimens (denoted by G for GFRP bars) were wrapped with carbon fiber textile as a replacement of the transverse stirrups and grouped to threes of same longitudinal GFRP reinforcement but different ratios of steel fiber (0, 0.5, 1.0%), Table(1) shows specimens designation and test program matrix.

Table1. Test Program Details

Specimen	Longitudinal Reinforcement	ρ %	Transverse Reinforcement	Fiber Volume % in concrete	Concrete F_{cu} MPa
S010	4ϕ10 steel	2.18	Steel ϕ 6@120mm	0	66
S012	4ϕ12 steel	3.14	Steel ϕ 6@120mm	0	66
S016	4ϕ16 steel	5.58	Steel ϕ 6@120mm	0	66
G010	4ϕ10 GFRP	2.18	CFRP Wrap	0	66
G510	4ϕ10 GFRP	2.18	CFRP Wrap	0.5	70
G110	4ϕ10 GFRP	2.18	CFRP Wrap	1.0	73
G012	4ϕ12 GFRP	3.14	CFRP Wrap	0	66
G512	4ϕ12 GFRP	3.14	CFRP Wrap	0.5	70
G112	4ϕ12 GFRP	3.14	CFRP Wrap	1.0	73
G016	4ϕ12 GFRP	5.58	CFRP Wrap	0	66
G516	4ϕ12 GFRP	5.58	CFRP Wrap	0.5	70
G116	4ϕ12 GFRP	5.5	CFRP Wrap	1.0	73

The geometry and reinforcing details of the tested columns are shown in" Fig.1", "Plate 1" shows the tested specimens, where all columns have the same cross –sectional area and over all dimensions, the 500 mm middle portion of constant cross section (120 x 120 mm) is that under test consideration whereas the two 250 mm length tapered ends are designed to handle the load application assembly and to avoid local and immature failure.

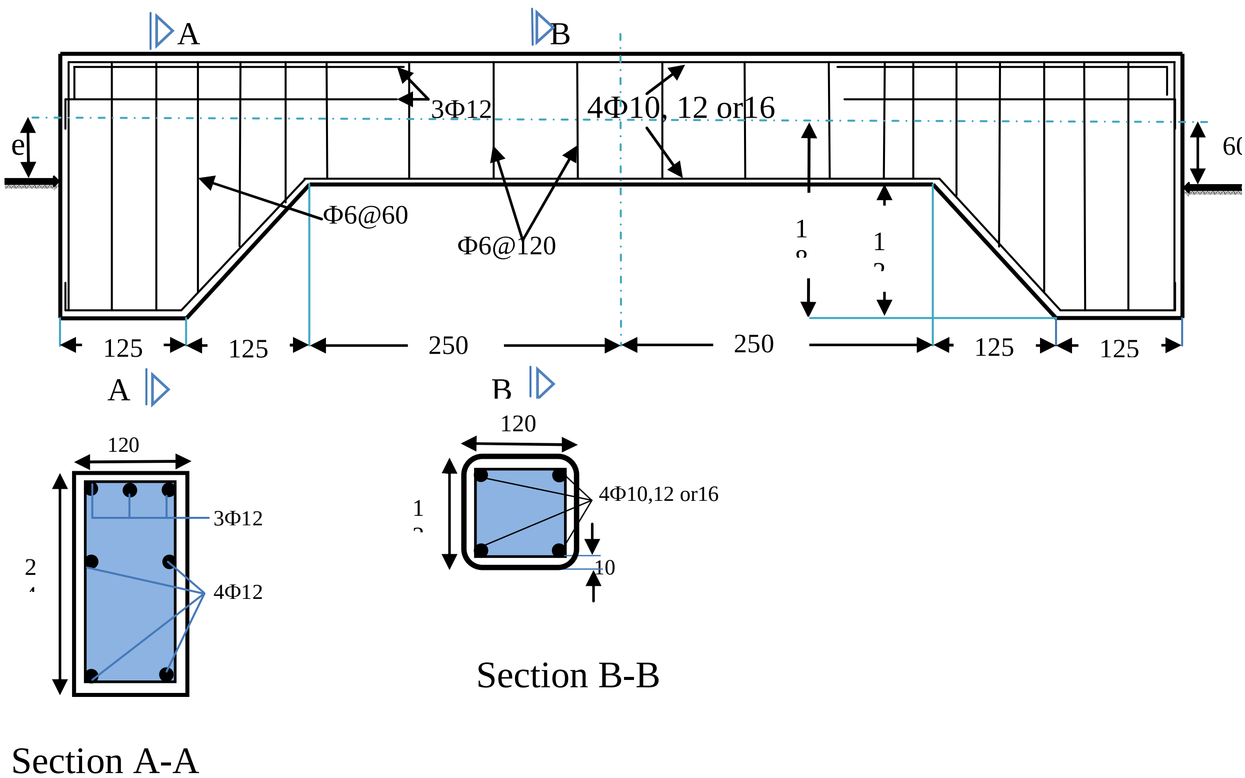

Figure 1. Specimen Geometry and Reinforcing detail

Plate 1. Test Specimens

4.2. Testing and Instrumentation

All column specimens were tested by application of static axial eccentric load using MFL 3000 kN universal testing machine “Plate 2”.Through a steel loading rig covered both ends, specimens were preloaded with 2 kN for adjustment ,then load application continued on the specimens in equal 10 kN increments start from zero to failure. Using 30 mm dial gauge of 0.01 division lateral mid height displacement was recorded for each load increment along with the compressive concrete edge strain which was recorded using electrical strain gauges, as well to the first crack load which was automatically detected by the machine the ultimate load was also fixed for each specimen.

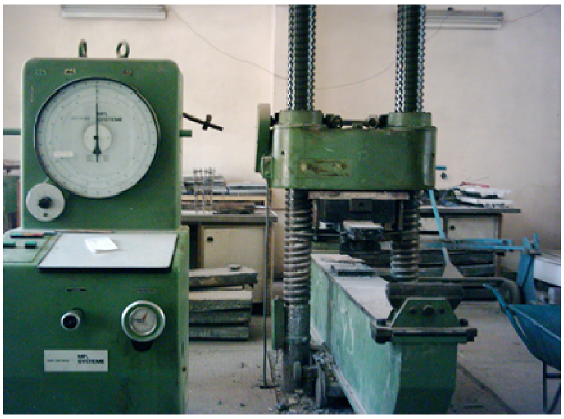

Plate 2. Testing machine

4.3. Materials

The high strength concrete used throughout this research was made from Portland cement type I comply with Iraqi standard no. 5/1984, crashed coarse aggregate with a specific gravity 2.65 and maximum size 14 mm, and fine aggregate sand with specific gravity 2.66 and fineness modulus 3. Modified polycarboxylate based polymer superplasticizer admixture in a dose of 3 to 4% by weight of cement was added to mixing water to achieve the required workability. High strength steel fiber of properties shown in “Table 2” was also used in two different ratios of 0.5 and 1.0% by volume of concrete.

Table 2. Properties of Steel Fiber*

Property	Value
Ultimate strength	2000 MPa
Strain at proportion limit	5650 x10^{-6}
Average length	30 mm
Nominal diameter	0.375 mm
Aspect ratio (L_f/D_f)	80

*By manufacturer

Implementing the ACI mix design procedure, the final proportions of the mixes with a stiff plastic slump were achieved for the required compressive strength as in “Table 3”.

Table 3. Concrete Mixes Proportions

Mix Type	Cement kg/m^3	Coarse Aggregate kg/m^3	Fine Aggregate kg/m^3	Water kg/m^3	Superplasticizer L/m^3	Steel Fiber kg/m^3
HC	525	1108	685	157	18	0
HC0.5%	525	1108	685	157	21	39
HC1.0%	525	1108	685	157	21	78

The characteristic strength values “Table4” were determined using standard cubes of (150mm), cylinders of (150x300mm) and prisms of (100x100x300mm) and tested by a calibrated testing machine as per the standard testing ASTM procedures.

Table 4. Properties of Hardened Concrete

Concrete Type	F_{cu} (MPa)	$F_{\mathbf{r}}$ (MPa)	$F_{\mathbf{t}}$ (MPa)
HC	66	7.80	7.1
HC0.5%	70	9.21	8.75
HC1.0%	73	9.83	9.21

The main relevant properties of both types of reinforcement used in the study are listed in “Table 5”

Table 5. Properties of Steel, GFRP Reinforcement*

FEATURE	STEEL	GFRP
Density g/cm^3	7.8	2
Ultimate tensile strength MPa	460	1200
Modulus of Elasticity MPa	200000	55000
Equivalent Replacement Rebar Φ mm	10	7
	12	8
	14	10
	6	12
	20	16
Coefficient of Thermal Expansion α x10^{-6}/C°	11.7	6 -10

* By manufacturer

5. Experimental Results and Discussion

5.1. Failure Mode and Strength

In General, and regardless the types of either the longitudinal and transverse reinforcement the modes of failure were same for all the twelve specimens. With the increase of load the lateral displacement at the mid height section increase toward the tension side, which accompanied with the appearance of the first transverse crack, tension failure occurs after excessive widening of the crack and increase in the curvature of the specimen. No evidence of failure had been shown on the compression side of the specimen although there is no transverse internal reinforcement in the specimens reinforced longitudinally with GFRP bars. This similarity in behaver under load indicates that crack pattern and tension failure modes were not affected by the reinforcement type. It had been noticed that the CFRP wrap maintains its initial condition till failure except at the tension side indicating that the compression side reinforcement did not experience any local lateral buckling due to the absence of internal ties. Tests results,”Table6”, shows variable percentage (average 13%) increase of ultimate load of steel reinforced specimens than the corresponding GFRP reinforced ones, also the ratios of the first crack load to ultimate load are in the range of 0.3 with a slight increase with the increase in main reinforcing ratio.

Table 6. Lateral Displacements Corresponding to Ultimate and Crack Load

Specimen	First Crack Load P_c (kN)	Lateral Deviation Δ_c (mm)	Ultimate Load P_u (kN)	Lateral Deviation Δ_u (mm)	P_c/P_u	Δ_u/Δ_c
S010	85	0.70	250	6.9	0.340	9.9
G010	70	0.50	240	9.4	0.291	18.8
G510	90	0.58	270	7.9	0.333	13.6
G110	100	0.59	300	6.0	0.333	10.2
S012	115	0.52	310	5.0	0.333	9.6
G012	100	0.59	280	7.3	0.357	12.4
G512	110	0.63	315	5.8	0.317	9.2
G112	120	0.64	340	5.0	0.353	7.8
S016	135	0.61	360	4.0	0.375	6.6
G016	120	0.67	325	4.92	0.369	7.3
G516	130	0.67	360	4.8	0.361	7.2
G116	150	0.73	410	4.5	0.366	6.2

"Fig.2" Shows that the percentage of fiber has no effect on the rate of increase of the ultimate load with the percent of GFRP reinforcing ratio, as this increase is 25% in GFRP specimens it is 76% in steel reinforced specimens of 0% fiber. "Fig.3" shows that 1% steel fiber in concrete increases the first crack load by 42% in specimens of $\boldsymbol{\rho}$=2.18%, 25% in those of $\boldsymbol{\rho}$=5.58% and the ultimate load by 25% regardless the reinforcing ratio.

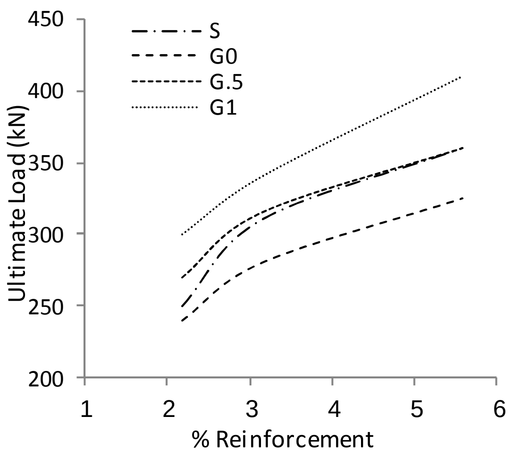

Figure 2. Influence of Reinforcing Ratio on Ultimate Load for Different % of Steel Fiber

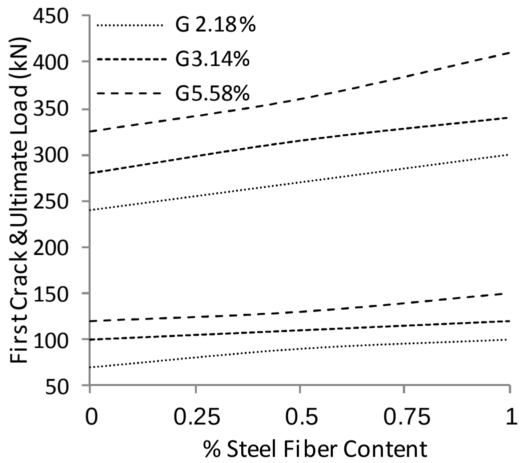

Figure 3. Influence of % Steel Fiber on Ultimate and First Crack Load

5.2. Load Displacement Behavior

The curves, relating applied load to lateral displacement, are shown in "Figs. 4, 5 and 6". All specimens reinforced with GFRP bars exhibit linear deformation response to the applied load at first stage, then a more inclined curve with a decreasing slope till failure. The curves did not show distinct yield point or a clear plastic range like those of specimens reinforced with steel bars, this is because the difference in behavior of GFRP bars, which don't possess a yield point in its stress strain behavior curve, than steel bars. Specimens of 0% steel fiber reinforced with traditional steel gives higher ultimate load (average 13%) with lower displacement (average 21%) than the corresponding specimens reinforced with GFRP bars due to higher modulus of elasticity of steel.

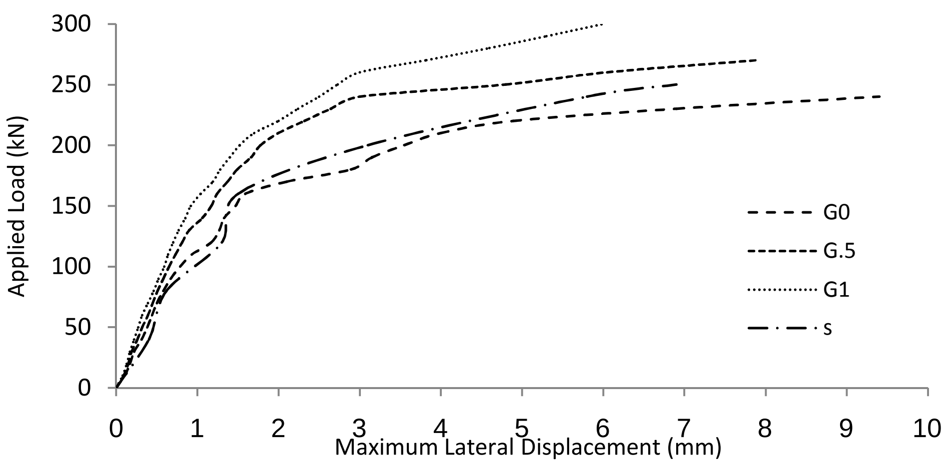

Figure 4. Load Displacement Curves for Specimens with $\boldsymbol{\rho} = 2.18\%$

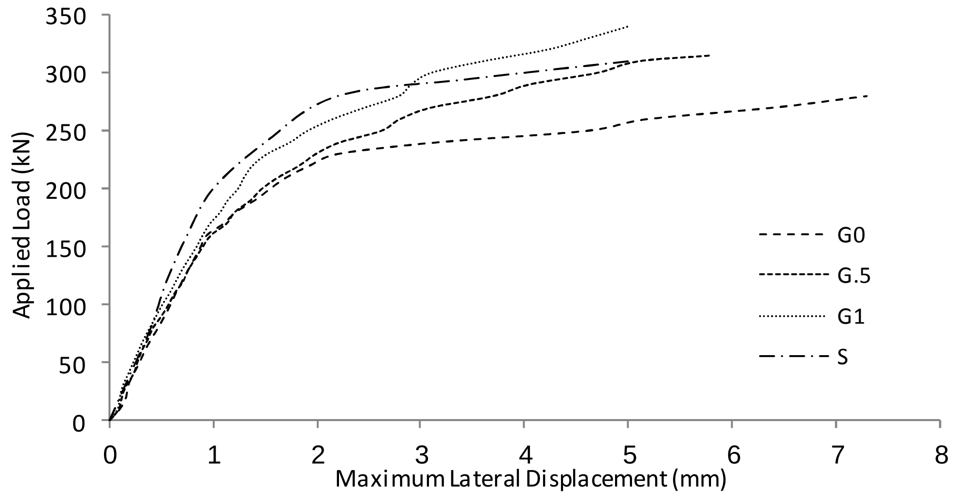

Figure 5. Load Displacement Curves for Specimens with $\boldsymbol{\rho}$= 3.14 %

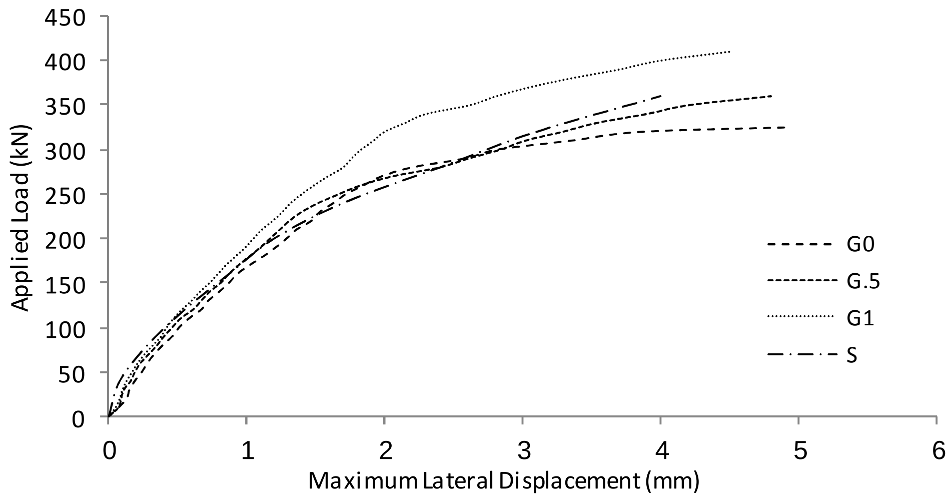

Figure 6. Load Displaceent Curves for Specimens with $\boldsymbol{\rho}$ =5.58 %

5.3. Ductility

Ductility in a structural member means the maintain of strength while sizeable deformation or deflection occurs. Physically it is the warning of overload presence in the form of excessive cracking and deflection. Many researchers [9, 10, 11, 12] define ductility ($\mu_u = \Delta_u/\Delta_y$) as a ratio based on the deflection of the member at yield of reinforcement, which can be seen clearly at the beginning of the nearly horizontal part of the load deflection curves (the plastic plateau), and since the GFRP reinforcing bars have no yield stress point and behave elastically till failure, the first crack deflection can be considered as a base to compare ductility of member as ($\mu = \Delta_u/\Delta_c$). “Fig.7” shows that columns reinforced with steel bars exhibit less ductility than those reinforced with GFRP of same reinforcing ratio (curves S and G0) in which 47% less for columns of $\boldsymbol{\rho}$=2.18% and 10% less for those of 5.58%. “Figs. 7&8” show that ductility of GFRP column decreases with the increase of the percent of fiber in concrete from zero to 1% and with the main reinforcement ratios ($\boldsymbol{\rho}$) from (2.18 to 5.58%) , the loss in ductility was of 46 % in specimens of ϕ 10 reinforcement ($\boldsymbol{\rho}$= 2.18%) where it was only 15% in specimens of ϕ 16 reinforcement ($\boldsymbol{\rho}$= 5.58%). On the other hand the loss in ductility was higher, (61%) in specimens of zero % of fiber, than (39%) in those of 1% of fiber.

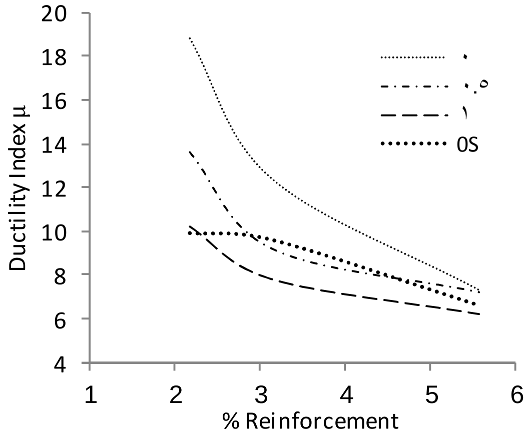

Figure 7. Infuence of Reinforcing Ratio on Ductility for Different % of Steel Fiber

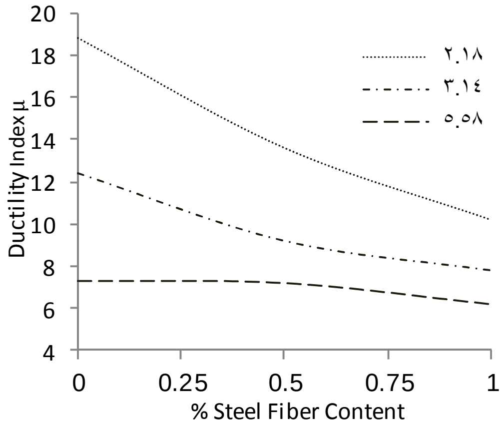

Figure 8. Infuence of Steel Fiber on Ductility for Different Reinforcing Ratios

5.4. Concrete Strain

The compressive strain, of the outer concrete fiber at the critical cross section, were measured at each load increment till failure which did not reach the ultimate strain of 0.002 for high strength concrete. “Table 7” and “Figs.9,10&11” show the concrete strain at compression face of the most stressed section; comparing the identical specimens with only difference in type of reinforcement like S010, G010 and S012, G012 and S016, G016 give that behaviors are almost same means that GFRP reinforcement acts as steel in handling the stress after the first crack occur ,and the strain at failure is higher in specimens reinforced with GFRP bars than in those reinforced with steel bars although the failure load was lower, because of the higher modulus of elasticity of steel than GFRP. Also, although failure load is higher but compression Strain at failure is lower in specimens of higher GFRP reinforcing ratio.

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Table 7. Concrete Strain at First Crack and Ultimate Loads

Specimen	First Crack Load (kN)	Comp. Strain x E^{-6}	Ultimate Load (kN)	Comp. Strain x E^{-6}
S010	85	-160	250	-980
G010	70	-104	240	-1101
G510	90	-108	270	-959
G110	100	-36	300	-803
S012	115	-200	310	-890
G012	100	-36	280	-898
G512	110	-58	315	-742
G112	120	-72	340	-810
S016	135	-211	360	-900
G016	120	-63	325	-915
G516	130	-119	360	-805
G116	150	-102	410	-770

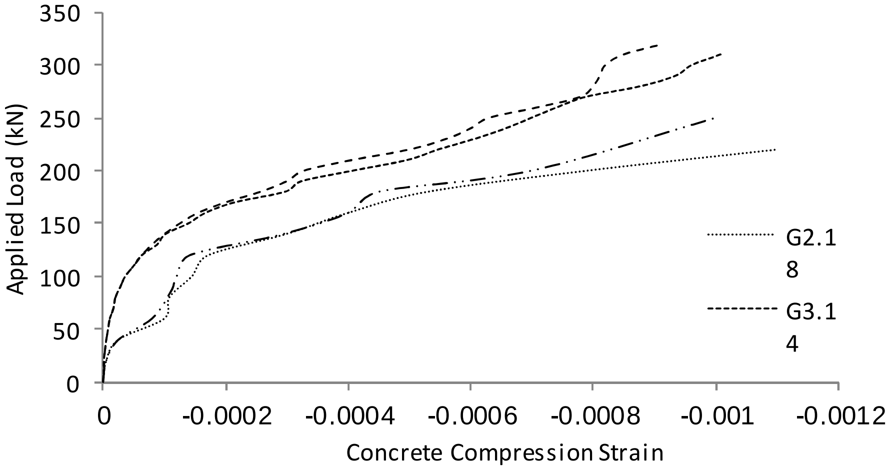

Figure 9. Influence of Reinforcing Ratio on compression Strain of Concrete of 0% Steel Fiber Content

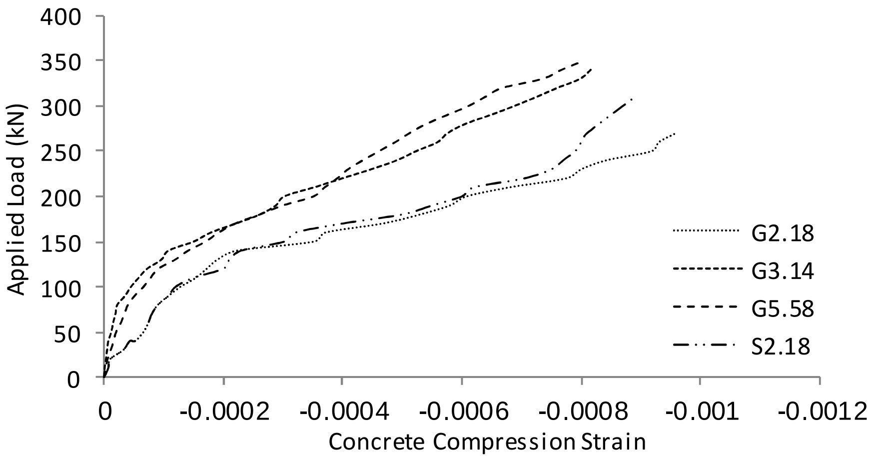

Figure10. Infuence of Reinforcing Ratio on Compression Strain of Concrete of 0.5% Steel Fiber Content

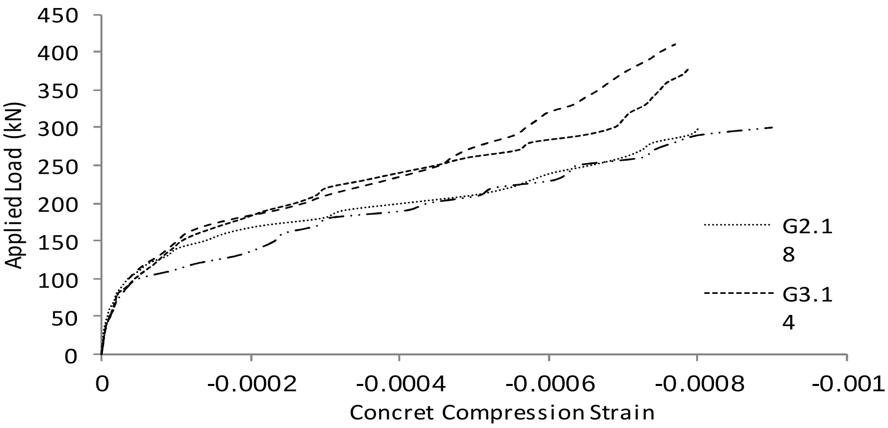

Figure 11. Influence of Reinforcing Ratio on Compression Strain of Concrete of 1% Steel Fiber Content

5. Conclusions

The results of twelve specimens tested through this study, to investigate and asses the behavior of the GFRP bars as a replacement of the traditional steel reinforcement in eccentrically loaded columns, were discussed and the main outcomes can be stated as below

1. In columns subjected to eccentric load, GFRP reinforcing bars act like steel ones regarding their effects on the mode of failure and the crack patterns, also no thermal cracks were observed since the coefficients of thermal expansion for concrete and GFRP are close to each other.
2. Steel reinforced columns show 13% higher ultimate load than corresponding GFRP reinforced columns.
3. 1% steel fiber in concrete increases the first crack load by 42%than in plain concrete specimens of ρ=2.18%, 25% in those of ρ=5.58% and the ultimate load by 25% regardless the reinforcing ratio.
4. The behaviors of the GFRP reinforced specimens under load are similar to those of steel reinforced specimens with no distinguished plastic plateau.
5. The ductility of the specimen reinforced with GFRP bars is 90% higher than that of steel reinforced specimens of ρ=2.18% and 10% more for those of 5.58%.
6. The ductility of GFRP specimens decreases with the increase of the percent of fiber in concrete from zero to 1% and with the main reinforcement ratios (ρ) from (2.18 to 5.58%.
7. Concrete strain at the compression side of the most stressed section of steel reinforced specimens is lower than that of GFRP reinforced specimens although the ultimate load is higher.

6. Abbreviations

CFRP Carbon fiber reinforced polymer
GFRP Glass fiber reinforced polymer
P_c First crack applied load
P_u Ultimate applied load
Δ_c deflection at first crack load
Δ_u Deflection at ultimate load
Δ_y Deflection at yield
μ_u Ductility Index

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