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Эльсаед Т.А. – доцент
Тел.: 0020129777360, e-mail: elsayedtarek@hotmail.ru
Хана Н.Ф. – доцент
Гханем Г.М. – профессор
Инженерный факультет Хельванского университета, Матария, Каир, Египет
Йехиа С. – ассистент
Высший инженерный институт, Академия Эшрук, Каир, Египет

ПОВЕДЕНИЕ НИЗКИХ ЖЕЛЕЗОБЕТОННЫХ КОЛОНН, УСИЛЕННЫХ СТЕКЛОПЛАСТИКОВОЙ СТЕРЖНЕВОЙ АРМАТУРОЙ

АННОТАЦИЯ

Коррозия стальной арматуры – один из наиболее серьезных дефектов армированного бетона. Для очистки железобетонных конструкций от коррозии необходимы огромные усилия и большие материальные затраты. Коррозия стали в железобетонных колоннах может привести к полному или частичному разрушению сооружения. Таким образом, вопрос решения проблемы коррозии стальных стержней в железобетонных колоннах актуален. В настоящей статье приводятся результаты исследования поведения железобетонных колонн, усиленных стеклопластиковыми стержнями, в сопоставлении с поведением стандартных колонн со стальной арматурой при деформации. Исследование содержит большинство критериев, которые могут повлиять на поведение колонн, усиленных стеклопластиком, таких как: способ размещения стальных анкеров, деформация продольной арматуры в колонне и деформация колонны снаружи. Также варьируется уровень воздействия на арматуру. Максимальная нагрузка, продольное укорачивание и напряжение продольного армирования фиксировались при каждом испытании. Данные проанализированы, сделаны выводы и приведены рекомендации по проектированию.

КЛЮЧЕВЫЕ СЛОВА: железобетонные низкие колонны, стеклопластиковая арматура.

Tarek A. Elsayed – associate professor
Tel.: 0020129777360, e-mail: elsayedtarek@hotmail.ru
Nagy F. Hanna – associate professor
Gouda M. Ghanem – professor
Faculty of Engineering, Mataria, Helwan University, Cairo, Egypt
Sameh Yehia – assistant
Higher Institute of Engineering, Ashrooq Academy, Cairo, Egypt

BEHAVIOR OF SHORT RC COLUMNS REINFORCED WITH FRP BARS

ABSTRACT

Corrosion of steel reinforcements is one of the most serious defects of reinforced concrete. A lot of money and efforts are needed for repairing corrosion of RC structures. Corrosion of steel in RC columns may lead to complete or partial failure of the building. Consequently, the issue of solving the problem of corrosion of steel rebars in RC columns is very demanding. In this paper the behavior of RC columns reinforced by GFRP bars is studied and compared to the behavior of the traditional steel reinforced columns. The study includes most of the parameters those may affect the behavior of the GFRP reinforced columns. This included replacing steel stirrups by GFRP sheets in two forms, warping the longitudinal reinforcement of the column, and warping the column from the outside. Also the reinforcement percentage was taken as a variable. Ultimate load, axial shortening, and strains in the longitudinal reinforcements were recorded for each test specimen. Data were analyzed and conclusions and design recommendations were drawn.

KEYWORDS: RC short columns, FRP rebars.

Introduction

Columns are the most important structural elements in RC structures. Corrosion of traditional steel reinforcements causes cracks in columns those may lead to failure in critical columns. This may cause partial or complete failure of structures. Nowadays, new materials are developed to enhance the performance of structural elements. Among these materials is the FRP reinforcing bars used in reinforcing different structural elements. The FRP materials are characterized by high resistance to corrosion, high strength-to-weight ratio, and fatigue resistance [1]. Consequently, in this paper, the behavior of RC columns reinforced by GFRP bars is studied and compared to the behavior of the traditional steel reinforced columns. Also

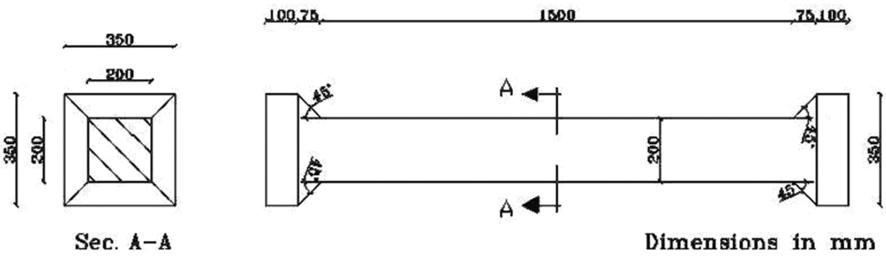


Fig. 1. Dimensions of test specimens

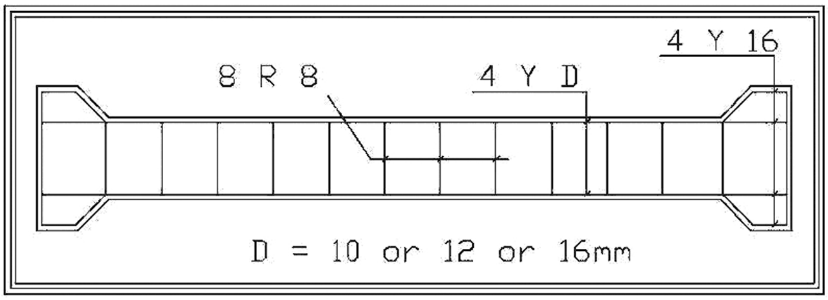


Fig. 2. Details of specimens A, B, and C with steel stirrups

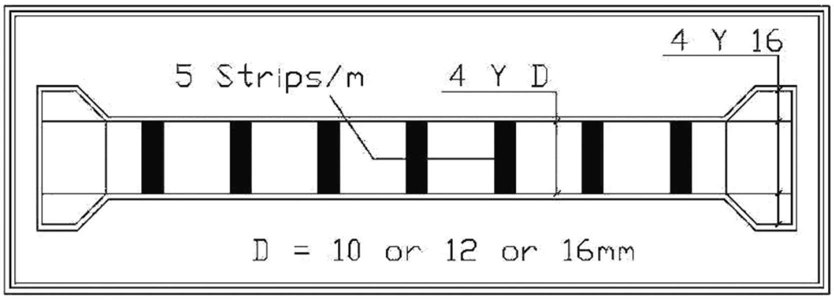


Fig. 3. Details of specimens D, E, and F with GFRP internal stirrups

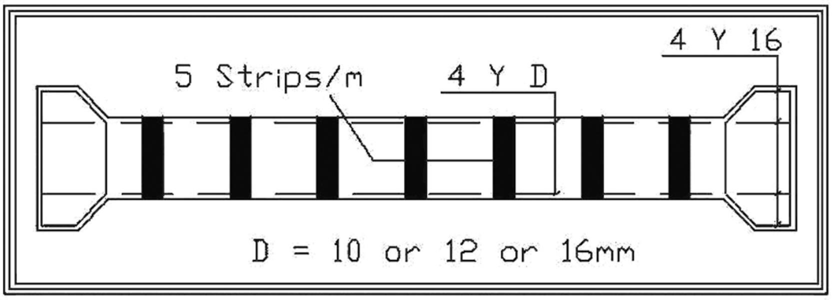


Fig. 4. Details of Specimens G, H, I, and K with external GFRP stirrups
(specimen K is the unreinforced column)

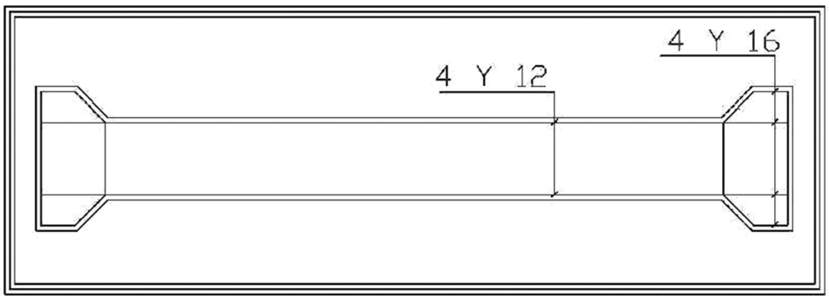


Fig. 5. Details of Specimen (J) without stirrups

most of the parameters those may affect the behavior of the proposed columns in this research were considered in the experimental program. The parameters considered in this research are, reinforcement percentage, the type and formation of stirrups; the used stirrups are traditional steel stirrups, GFRP sheet stirrups used in two forms; inside the concrete cover around the longitudinal reinforcements, outside the concrete cover at the surface of tested columns. The experimental program in this paper also included testing one column specimen reinforced with longitudinal GFRP bars, without stirrups, and one plain concrete column specimen with stirrups at the column' surface. All test column specimens were loaded axially until failure and the load-shortening, load-strain in longitudinal reinforcements, and the cracking and the ultimate loads were recorded. Analysis of test results showed that GFRP bars are effective in reinforcing RC columns in this research. The paper included analytical investigation that showed that the traditional equation used for predicting the axial compressive strength of steel reinforced columns warped with GFRP jackets, 3. ACI-440 2R-02 [2], predicts the axial compressive strength of the columns in this research with reasonable accuracy, but after introducing some modifications, regarding the properties of the used GFRP rebars, to the equation.

Research significance

In this work, the behavior of RC short columns reinforced by GFRP bars is studied under axial loading conditions. The variables considered in this research are, the reinforcement percentage, the type and formation of the stirrups. The study is expected to contribute in predicting the validity of reinforcing RC columns by GFRP bars and thus eliminating the steel corrosion problem of the steel reinforced columns and consequently providing more safety to RC structures and reducing their maintenance cost.

Test program

The experimental program in this research includes testing column specimens reinforced with steel and GFRP longitudinal rebars under axial load. The variables considered included the reinforcement percentage, 0.78, 1.13, and 2.01 %, these reinforcement percentages were done by reinforcing test columns by four longitudinal rebars 10, 12, 16 mm in diameter, respectively. The variables also included the type and formation of the stirrups. The used stirrups are three types. The first type is the traditional mild steel stirrups of yield and tensile strength of 2400 and 3600 kg/cm^2 respectively. The used steel stirrups are 8 stirrups per meter, 8 mm in diameter. The other two types of stirrups are 5 GFRP strip stirrups per meter, 5cm in width, installed internally in the transverse direction around the longitudinal rebars; or externally warping the outer surface of the tested columns. Also test program included testing one column specimen with GFRP longitudinal rebars, without stirrups and another specimen without reinforcement (plain concrete) and warped by external GFRP strip stirrups.

Test specimens

Eleven columns were tested in this research, specimens are coded A to K. All columns had the same dimensions, Fig. 1, Table 1, and were manufactured with column head at both ends to avoid failure by bearing stresses. Columns reinforced with steel rebars, specimens A, B, and C, are reference specimens, Fig. 2. Test specimens were manufactured in a way to include all variables considered in this research. For specimens reinforced with GFRP rebars, the used stirrups are GFRP strips, 5cm in width. Specimens D, E, and F, Fig. 3, were manufactured with GFRP stirrups installed around the longitudinal reinforcements, while the GFRP stirrups were installed around the surface of the columns, specimens G, H, I, and K, Fig.4. Figure 5 shows the details of specimen J without stirrups. Table 1 presents the details and dimensions of test specimens.

Fabricating test specimens

The fibers used in manufacturing the GFRP rebars are E-glass fibers with linear weight of roving 2400 g/km, and the used resin is polyester E.S 1319 mixed with cobalt in the ratio 1000:1, by weight. This ratio gives a setting time of about 2 hours at 160єC (320єF) which is enough for manufacturing process. The used volume fiber fraction is 60 %. The GFRP rebars used in this research were circular in cross-section, manufactured using the mechanical pultrusion process. Bars were then wrapped helically by fiber yarns in 1 cm pitch to roughen their surfaces to enhance their bond strength with concrete. Specimens were cast in anti-rust metal forms, Fig. 6. The reinforcements were first arranged, Fig. 7, and then installed in the forms. The inside surfaces of the forms were painted by thin film of hydraulic oil to ease removing specimens after hardening. The forms were manufactured in a way to provide the specimens with column head at both ends. The column head were reinforced with 4 bars 16mm diameter, in a way to make the heads capable to transfer load uniformly to the column' cross-section and to prevent failure by bearing stresses. All specimens were cast vertically for similarity with casting conditions in construction sites. A mechanical vibrator was used in the compaction of the columns. Specimens were removed from the forms after 3 days from casting, Fig. 8 and then they were cured by covering the specimens with wet canvas for complete 7 days. After 14 days age, GFRP stirrups were installed at the surface of the columns. Figure 9 shows the procedures of installing internal and external GFRP stirrups. All columns were capped using Gypsum paste at both ends, Fig. 10.

Test setup and instrumentation

All column specimens were tested using rigid steel loading frame. A compression hydraulic jack of 1000 kN capacity and a load cell of 1000 kN capacity with digital read out were used. For all test specimens, strains in longitudinal reinforcing bars were measured using electrical strain gauges, 5 mm length, electrical resistance

Table 1

Details of Column Specimens

Specimen	Section dimensions, cm	No of bars	Diameter	Main Reinforcement	Stirrups
A	20 x 20	4	10	Steel	Steel
B	20 x 20	4	12	Steel	Steel
C	20 x 20	4	16	Steel	Steel
D	20 x 20	4	10	GFRP	GFRP Sheets Internally
E	20 x 20	4	12	GFRP	GFRP Sheets Internally
F	20 x 20	4	16	GFRP	GFRP Sheets Internally
G	20 x 20	4	10	GFRP	GFRP Sheets Externally
H	20 x 20	4	12	GFRP	GFRP Sheets Externally
I	20 x 20	4	16	GFRP	GFRP Sheets Externally
J	20 x 20	4	12	GFRP	–
K	20 x 20	–	–	–	GFRP Sheets Externally

Fig. 6. Used metal model

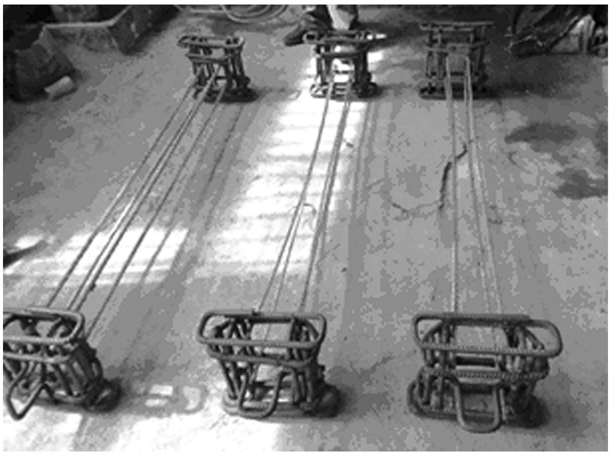


Fig. 7. Reinforcements Arrangement

Fig. 8. Test specimens

of 119.8 ± 0.20 ohms, and gauge factor (2.11±1 %). A vertical LVDT was used for measuring the linear shortening of columns during loading. Test setup was manufactured in a way to hold tested columns vertically and to prevent columns from lateral sway. Columns were plumbed vertically and adjusted to verify the axial loading conditions. Test setup is presented in Fig. 11.

Test Results and Discussion

In this research column specimens were tested to study the behavior of RC short columns reinforced with GFRP bars under axial loading. The parameters included are the reinforcement percentage and the type and formation of stirrups. The effect of these parameters was studied on, failure mode, cracking and ultimate loads, load-axial shortening in columns, and the load-strain in longitudinal reinforcements. This will be discussed in details in the following sections.

Failure Mode

Failure of steel reinforced columns is the traditional splitting ductile failure occurred at the upper or lower third of the column, Fig. 12a. The failure of all GFRP reinforced columns is splitting brittle failure, Fig. 12b, c, d. This is related to the linear brittle behavior of the GFRP stirrups compared to the ductile behavior of the steel stirrups used in the reference specimens. The plain specimen (column without reinforcement) with GFRP strip stirrups installed at the column surface, failed by crushing compression failure, Fig 12e it is clear from Fig 12 that, using GFRP strip stirrups installed internally or externally as described in this research, does not significantly affect the failure mode of tested GFRP reinforced short columns.

Cracking and Ultimate Loads

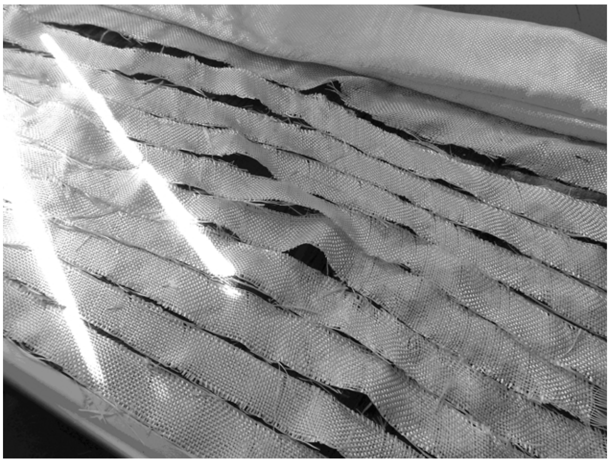
Table 2 presents the cracking and the ultimate loads of test specimens. It is shown in Table 2 that columns reinforced with GFRP reinforcements give higher cracking and ultimate loads than those given by steel reinforced columns by about 60, 25 % respectevely as an average. This is related to the effect of the confinement provided by the GFRP stirrups and the high strength of the GFRP rebars. Table 2 Also shows that using GFRP strip stirrups installed at the surface of columns as described in this research, increases their cracking and ultimate loads than using the GFRP stirrups installed aound the longitudinal reinfprcements inside the column, without singnificantely affecting their failure mode. This is related to the effect of the extra confinement provided by the GFRP stirrups intalled externally, as for specimens with internal GFRP stirrups, the stirrups were installed perior to casting concrete, Fig. 9b, and thus their confinement effect is low compared to that provided by the external stirrups those were installed on the surface of the hardened concrete of tested columns. Also it is shown that specimen without stirrups, specimen J, showed cracking and ultimate loads lower by about 50 % than cracking and the ultimate loads of similar specimens but with GFRP stirrups. Column with plain concrte and external GFRP stirrups showed ultimate load almost equal to that of specimen reinforced with 4 longitudinal 10mm-diameter bars and internal GFRP stirrups, but the ratio of the cracking to ultimate loads of the plain concrete specimen was almost close to 1. This is related to the confinement effect of the GFRP stirrups that increases the axial compressive strength of the concrete used in manufacturing this specimen without affecting the failure mode. This indicates the remarkable effect of the GFRP strip stirrups in increasing the load carrying capacity of the GFRP reinforced columns in this research.

Load-Axial Shortening in Column Specimens

A vertical LVDT was used to measure the axial shortening in tested columns. The load-shortening relationship is drawn for all test specimens. Figure 13 shows comparisons between the load-shortening relationships of tested columns. It is shown in Fig. 13 that steel reinforced columns showed higher axial stiffness than those for columns reinforced with GFRP reinforcements by about 30, 70 and 75 % as an average for reinforcement percentage 0.78, 1.31 and 2.01 % respectively. This is due to the higher stiffness of steel rebars than that for GFRP rebars. It is noticed from Fig. 13 that columns reinforced with GFRP rebars showed axial stiffness ranging in a narrow range corresponding to all reinforcement percentage considered. This is due to the effect of the high confinement provided by the GFRP stirrups that increases the apparent axial compressive strength of concrete in columns thus reducing the contribution of longitudinal reinforcements, and consequently the failure of columns is brittle mode due to the rupture of the GFRP stirrups. In Fig. 13b it is clear that the column specimen without stirrups showed axial stiffness about 1/3 that of columns with GFRP stirrups. This revealed that about 2/3 of the axial stiffness of columns reinforced with GFRP bars and GFRP stirrups in this research is achieved by the effect of the used GFRP strip stirrups.

Load-Axial Strain in Longitudinal Reinforcements

The strain in longitudinal reinforcements was recorded using strain gages and a digital readout. The load-strain relationships are drawn in Fig. 14. It is shown in Fig. 14 that steel rebars showed ductile behavior compared to the linear behavior of the GFRP rebars. Also steel rebars showed lower strains than the GFRP reinforcements. It is clear from Fig. 14 that the longitudinal reinforcements in all GFRP reinforced columns with internal or external GFRP stirrups showed identical load-strain behavior, but with different ultimate loads. This approves the conclusion revealed in the previous section in this paper that the high confinement provided by the GFRP stirrups that increases the apparent axial compressive strength of concrete in columns reduced the contribution of the longitudinal GFRP reinforcements thus the strains in rebars was controlled by the stirrups confinement.



a) b)

c) d)

Fig. 9. Column specimens with GFRP stirrups:
a) GFRP strip stirrups; b) GFRP stirrups installed internally; c) roughening the surface of the column;
d) installing the outside stirrups

a) b)

Fig. 10. Capping test columns:
a) capping upper end; b) capping the lower

Analytical investigation

The ACI-440 [2] specifies that the axial compressive strength of nonslender, normal weight concrete member confined with FRP jacket may be calculated using the confined concrete strength, Eq. 1.

For nonprestressed members with existing steel spiral reinforcement:

$$\phi P_n = 0.85\phi[0.85\psi_f f_{cc}^{/}(A_g - A_{st}) + f_y A_{st}] \quad (1a)$$

For nonprestressed members with existing steel tie reinforcement

$$\phi P_n = 0.8\phi[0.85\psi_f f_{cc}^{/}(A_g - A_{st}) + f_y A_{st}] \quad (1b)$$

The additional reduction factor in this equation, ψ_f, is recommended to be taken equal to 0.95. $f_{cc}^{/}$ is calculated using Eq. 2:

$$f_{cc}^{/} = f_c^{/}[2.25\sqrt{1 + 7.9\frac{f_l}{f_c^{/}}} - 2\frac{f_l}{f_c^{/}} - 1.25] \quad (2)$$

f_l is calculated using Eq. 3:

$$f_l = \frac{k_a \rho_f f_{fe}}{2} \quad (3)$$

k_a is calculated using Eq. 4:

$$k_a = 1 - \frac{(b-2r)^2 + (h-2r)^2}{3bh(1-\rho_g)} \quad (4)$$

and ρ_f is calculated using Eq. 5:

$$\rho_f = \frac{2nt_f(b+h)}{bh} \quad (5)$$

Where:

$f_{cc}^{/}$ = apparent compressive strength of confined concrete;

ψ_f = additional FRP strength-reduction factor;

A_g = gross area of section;

A_{st} = total area of longitudinal reinforcements;

f_y = specified yield strength of nonprestressed steel reinforcements;

f_l = confining pressure due to FRP jacket;

$f_c^{/}$ = specified compressive strength of concrete;

ϕ = strength reduction factor;

ρ_f = FRP reinforcement ratio;

f_{fe} = effective stress in the FRP, stress level attained at section failure;

k_a = efficiency factor for FRP reinforcement (based on the section geometry);

b = width of rectangular cross section;

r = 0.5 in. (13mm);

h = overall thickness of a member;

ρ_g = ratio of the area of longitudinal steel reinforcement to the cross-sectional area of a compression member;

n = number of plies of FRP reinforcement;

t_f = nominal thickness of one ply of the FRP reinforcement;

C_E = environmental-reduction factor.

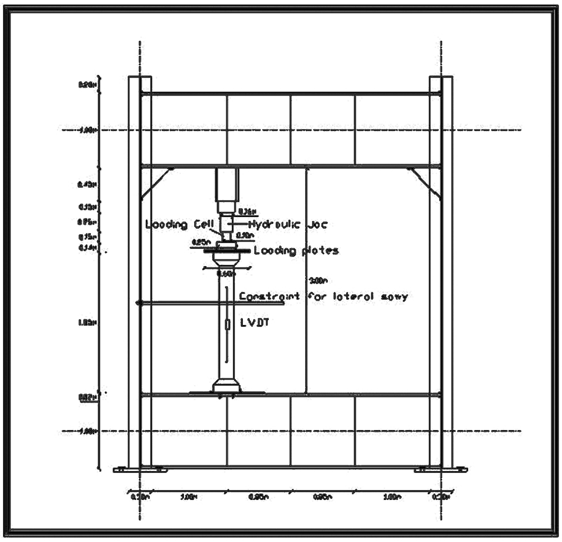
Equation 1 was used in estimating the compressive strength of column specimens with strip stirrups in this research. For this purpose, equations, 1a, and 1b were modified by replacing the yield strength of steel rebars, f_y, by the effective stress in the GFRP rebars, f_{fe}. Analytical study showed that, modified equation, Eq. 1a, predicts satisfactorily the axial compressive strength of columns reinforced with GFRP longitudinal bars and internal GFRP strip stirrups, while modified equation, Eq. 1b, predicts satisfactorily the compressive strength of columns reinforced with GFRP bars and external strip stirrups, Fig. 15, given that the environmental-reduction factor [3], C_E, is taken 0.65 for exterior GFRP stirrups, 0.8 for internal GFRP stirrups and GFRP rebars, and the strength reduction factor Φ is taken 0.8 for columns with exterior GFRP stirrups and 0.9 for columns with internal GFRP stirrups. Figure 15 shows a comparison between predicted and experimental axial compressive strengths.

Conclusions

In this paper short column specimens were tested to study the behavior of columns reinforced with GFRP reinforcements under axial loading conditions. Although Columns reinforced with GFRP reinforcements showed higher cracking and axial compressive strength than steel reinforced columns, they were characterized by lower axial stiffness and brittle failure mode. It is also shown that column specimens reinforced with external GFRP strip stirrups showed higher cracking and ultimate loads and slightly higher axial stiffness than columns reinforced with GFRP internal stirrups. Analytical investigation revealed that equation specified by the ACI 440.2R-02 for calculating axial compressive strength of nonslender, normal weight concrete member confined with FRP jacket, estimates the axial compressive strength of GFRP reinforced column in this research with reasonable accuracy.

Recommendation for futur research

Based on the experimental work and conclusions in this paper it is recommended that future research would be directed for studying the possibility of enhancing the failure mode of GFRP reinforced columns.



a) b)

Fig. 11. Loading frame and test setup:
a) column specimen in the loading frame; b) schematic diagram for test setup and instrumentation

a) b) c)

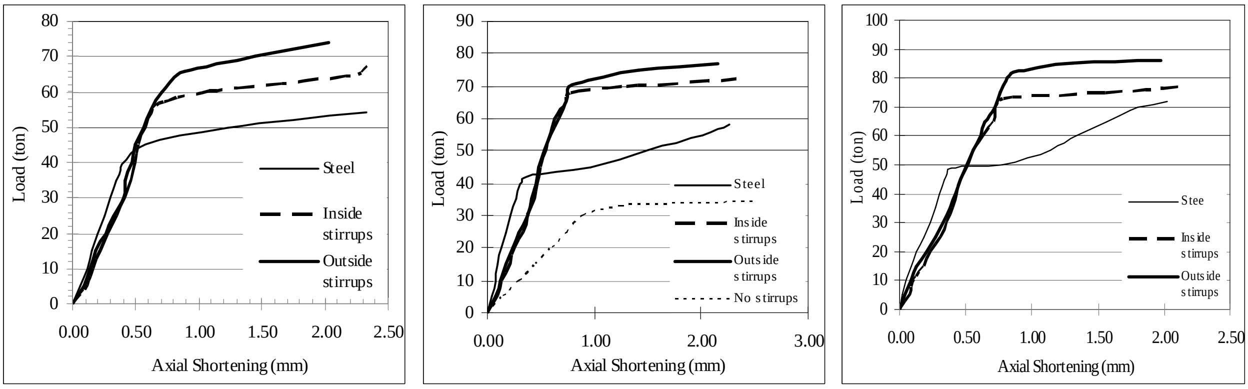
d) e)

Fig. 12. Failure mode of test specimens:
a) steel reinforced column; b) GFRP intenal stirrups; c) GFRP external stirrups;
d) column without stirrups; e) plain specimens with External GFRP

Table 2

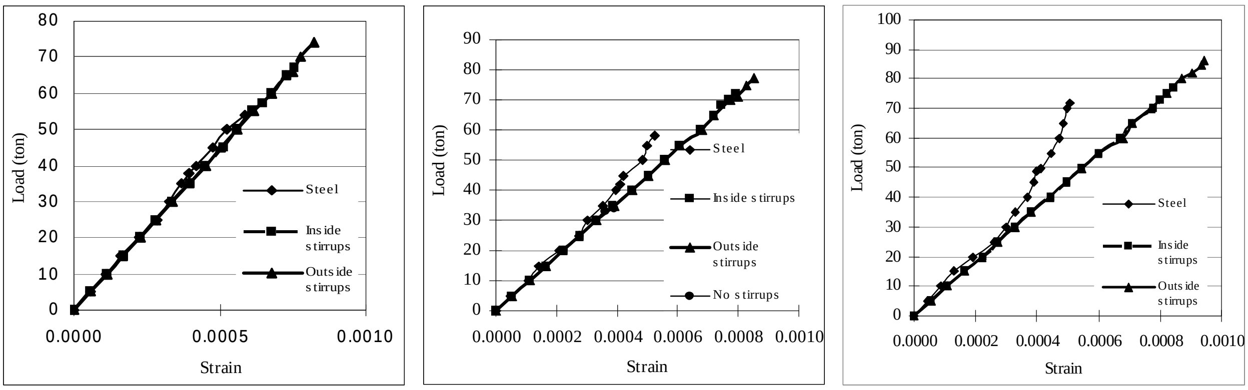
Cracking and ultimate loads

Specimen	Reinforcement	Cracking load (Ton)	Ultimate load (Ton)	P_{crak}/P_{ult}
A	Steel – 10 mm Steel stirrups	38	54	0.704
B	Steel – 12 mm Steel stirrups	42	58	0.724
C	Steel – 16 mm Steel stirrups	49	72	0.681
D	GFRP – 10 mm Internal sheets	57	67	0.851
E	GFRP – 12 mm Internal sheets	68	72	0.944
F	GFRP – 16 mm Internal sheets	73	77	0.948
G	GFRP – 10 mm External sheets	66	74	0.892
H	GFRP – 12 mm External sheets	71	77	0.922
I	GFRP – 16 mm External sheets	82	86	0.954
J	GFRP – 12 mm No stirrups	33	34	0.971
K	Plain concrete External sheets	64	65	0.985



a) b) c)

Fig. 13. Load-shortening relationships for tested columns:
a) reinforcement percentage 0.78 %; b) reinforcement percentage 1.13 %; c) reinforcement percentage 2.01 %



a) b) c)

Fig. 14. Load-axial strain in longitudinal reinforcements:
a) reinforcement percentage 0.78 %; b) reinforcement percentage 1.13 %; c) reinforcement percentage 2.01 %

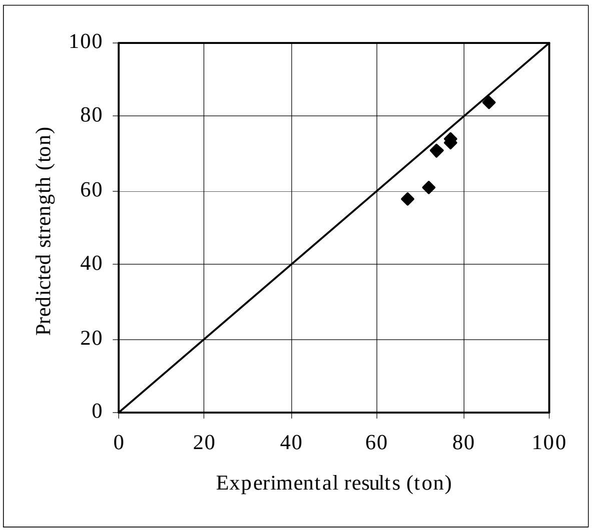


Fig. 15. Comparison of predicted and experimental axial compressive strength

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