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Axial behavior of FRP-wrapped circular ultra-high performance concrete specimens

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Abstract. Ultra-High Performance Concrete (UHPC) is an innovative new material that, in comparison to conventional concretes, has high compressive strength and excellent ductility properties achieved through the addition of randomly dispersed short fibers to the concrete mix. This study presents the results of an experimental investigation on the behavior of axially loaded UHPC short circular columns wrapped with Carbon-FRP (CFRP), Glass-FRP (GFRP), and Aramid-FRP (AFRP) sheets. Six plain and 36 different types of FRP-wrapped UHPC columns with a diameter of 100 mm and a length of 200 mm were tested under monotonic axial compression. To predict the ultimate strength of the FRP-wrapped UHPC columns, a simple confinement model is presented and compared with four selected confinement models from the literature that have been developed for low and normal strength concrete columns. The results show that the FRP sheets can significantly enhance the ultimate strength and strain capacity of the UHPC columns. The average greatest increase in the ultimate strength and strain for the CFRP- and GFRP-wrapped UHPC columns was 48% and 128%, respectively, compared to that of their unconfined counterparts. All the selected confinement models overestimated the ultimate strength of the FRP-wrapped UHPC columns.

Keywords: ultra high performance concrete with steel fibers; fiber reinforced polymer; ultimate strength; ultimate strain; confinement model

1. Introduction

Many existing reinforced concrete buildings have been exposed to severe seismic forces during and after construction. Recent major earthquakes around the world have proved that these types of existing buildings lack the appropriate seismic resisting characteristics and thus are very vulnerable to serious damage in structural elements such as columns, beams, walls, and beam-column joints. As a result of seismic impact, the strength and ductility capacities of these structural elements can significantly decrease which raises the concern that there is a need for seismic retrofitting. There are various retrofitting techniques such as reinforced concrete jacketing, steel jacketing and fiber reinforced polymer (FRP) jacketing to enhance the strength and ductility capacity of the structural elements. However, during the last two decades, there has been a substantial increase in the use of FRP composites, especially carbon, glass, and aramid sheets for retrofitting and repair of structural elements because of their distinctive characteristics such as low

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weight, high strength and stiffness, excellent corrosion resistance, design flexibility, ease of handling, and long-term durability under severe environmental conditions.

Until now a large number of studies have been conducted in order to understand the axial behavior of confined concrete. As a result of these studies, several confinement models are proposed in the literature. The early attempts on steel-based confinement models have been questioned by researchers (Fardis and Khalili 1982, Mander 1988, Saadatmanesh *et al*. 1994). Following these studies, due to the rapid increase in the use of FRP materials for repair and strengthening of the concrete, the gain in ultimate strength and strain capacity arising from FRP sheets for low and normal strength concrete columns was investigated by Shahawy *et al*. (2000), and Shehata *et al*. (2002). A total of 45 CFRP-wrapped concrete columns were tested by Shahawy *et al*. (2000). The average compressive strength of the concrete used in the tests was 19 and 49 MPa. When comparing the unconfined counterparts, the average increase in ultimate strength of the CFRP-wrapped columns with concrete compressive strength of 19 MPa and 49 MPa for the 1,2,3 and 4 layers was 74%, 139%, 223%, 290%, and 21%, 56%, 102%, and 130% respectively. In total 12 circular 1 and 2 layers of CFRP-wrapped columns with the average compressive strength of concrete varying between 25 and 30 MPa were tested by Shehata *et al*. (2002). The average increase in ultimate strength was 81% and 138% for columns wrapped with 1 and 2 layers of CFRP sheets, respectively. In addition to these studies, various experimental and analytical studies on FRP- wrapped low and normal strength concrete columns have been conducted by many researchers (Mirmiran and Shahawy 1997, Kono *et al*. 1998, Samaan *et al*. 1998, Purba and Mufti 1999, Demers and Neale 1999, Toutanji 1999, Miyauchi *et al*. 1999, Theriault *et al*. 2000, Lam and Teng 2003).

In the last two decades, there has been substantial progress in the technology to produce superior concrete with high compressive and tensile strength, as well as characteristics of high durability and low permeability. Ultra High Performance Concrete (UHPC) is now a pioneer product with outstanding properties for the construction industry and other structural applications, such as a compressive strength of 150–200 MPa and a tensile strength of 8-15 MPa (Sun *et al*. 2000, Sorelli *et al*. 2008). UHPC is a fiber-reinforced, superplasticized, silica fume-cement mixture with very low water-cement ratio (*w/c*) characterized by the presence of very fine quartz sand (0.15-0.40 mm) instead of ordinary aggregate (Lubbers 2003).

Although there have been many studies on low and normal strength concrete columns wrapped with FRP sheets, there has been relatively little research on high and ultra–high strength concrete columns wrapped with FRP sheets. Mandal *et al*. (2005) examined the behavior of 59 FRP-wrapped circular concrete columns with concrete strength ranging from 26 to 81 MPa under axial load. The test results indicated that the normal strength concrete columns wrapped with FRP sheets showed a substantial increase in ultimate strength and ductility compared with the unwrapped counterparts. However, for high strength concrete, the enhancement in strength and ductility is limited due to its low dilation capacity.

Cui and Sheikh (2010) tested 112 cylindrical concrete columns with concrete strength varying from 45 MPa to 112 MPa wrapped with different types of FRP sheets under monotonic axial compression. The test results show that with an increase of the strength of the unconfined concrete, the strength enhancement, energy absorption capacity, and ductility factor at the rupture of the FRP jackets all diminish significantly.

Zohrevand and Mirmiran (2011) investigated the behavior of sixteen UHPC-filled FRP tubes with different fiber types (CFRP and GFRP) under uniaxial compression. The 28-day compressive strength of the UHPC with 2% in volume steel fiber was 189 MPa. Contrary to the high strength

Table 1 Test program and specimen properties

Specimen group	Number of identical specimens	Type of FRP	Core diameter (mm)	Height (mm)	Number of FRP layers	Thickness of FRP (mm)
P	6	None	100	200	N/A	N/A
C2	3	HTA 40	100	200	2	0.7
C3	3				3	1.05
C4	3				4	1.4
C5	3				5	1.75
G2	3	Hybon 2026	100	200	2	0.7
G3	3				3	1.05
G4	3				4	1.4
G5	3				5	1.75
A2	3	HM Aramid	100	200	2	0.64
A3	3				3	0.96
A4	3				4	1.28
A5	3				5	1.6

concrete, the test results revealed that a substantial increase in ultimate strength and strain of UHPC was obtained up to 98% and 195%, respectively.

1.1 Objective

The use of UHPC in bridge columns and high-rise buildings is becoming increasingly common nowadays. However, information about the confinement effect exerted by the FRP sheets on the UHPC is still limited. It remains unclear whether there is any increase in the ultimate strength and strain capacity arising from FRP sheets wrapped UHPC columns. The current study was carried out to fill the gap in the literature. To this end, firstly, the gain in axial strength and axial strain and the failure modes were investigated for the Aramid (AFRP), Glass (GFRP), and Carbon (CFRP)-wrapped UHPC columns. Secondly, to determine the reliability of the selected four confinement models that have been developed, generally, for low and normal strength concrete columns are compared with the experimental results. Finally, a simple confinement model is proposed and compared with the experimental results and selected confinement models.

2. Experimental program

2.1 Specimen layout

A total of 36 CFRP, GFRP and AFRP-wrapped and 6 unconfined control UHPC cylinders with a diameter of 100 mm and a height of 200 mm were prepared and tested under monotonic axial compression. Three different types of fibers were considered, Carbon, Glass, and Aramid, all of which are unidirectional and wrapped only in the hoop direction. The unidirectional Carbon, Glass and Aramid FRP sheets are HTA 40, Hybon 2026, and HM Aramid produced by Tohotenax, PPG, and the Du Pont Corporation, respectively. The adhesive used was epoxy laminating resin MGS-L285 produced by the Hexion Corporation. Carbon and Glass FRP sheets with ply thickness of

Table 2 Geometrical and Mechanical properties of FRP sheets as reported by the Manufacturer

	Carbon Fibers	Glass Fibers	Aramid Fibers	Epoxy resin (L285)
Tensile Strength (MPa)	3950	2790	2926	70-80
Tensile modulus (GPa)	238	82.7	110	3-3.3
Ultimate Elongation (%)	1.7	3.2	2.5	5-6.5
Density (g/cm^3)	1.76	2.6	1.44	1.18-1.20
Thickness (mm)	0.35	0.35	0.32	-
Weight per unit area (g/m^2)	245	280	170	-

Table 3 UHPC mix proportion

Mix proportions kg (for 1 m^3 concrete)							
Cement	Siliceous Sand (0.5-1.5mm)	Siliceous Powder (0-0.5mm)	Silica fume	Super Plasticizer	Water	Steel Fiber	Total
1000	251	377	250	31.75	230	500	2640

0.35 mm, Aramid FRP sheets with ply thickness 0.32 mm, were used to provide the external confinement. The concrete cylinder specimens were wrapped with two, three, four and five (2, 3, 4, and 5) FRP layers. Three specimens were prepared and tested for each thickness of CFRP, GFRP and AFRP. The test program and specimen properties are given in Table 1.

2.2 Concrete

The UHPC is produced by using very fine sand, cement, silica fume, super plasticizers and steel fibers. Six plain concrete cylinders (100 mm × 200 mm) were tested under monotonic axial compression to determine the standard 28.day concrete strength of the concrete, f_{co}, and its corresponding strain, ε_{co}, at 28 days. The 28-day average compressive strength of the concrete cylinders was 159 MPa. Regular CEM I PÇ 42.5R was used as cement material in the mix. Two different steel fibers, OL 6/16 and Dramix ZP 305, were added at six percent (6%) by volume to the mix. Steel fibers were used in the mix. The water-binder (cement+silica fume) ratio was kept constant at 0.18. The typical mix composition of the UHPC used in this study is given in Table 3.

2.3 Specimen preparation

The plastic pipes with length of 200 mm and diameter of 100 mm were cut and prepared for the casting of the concrete. The UHPC is produced and cast into the plastic pipes. The specimens were kept in the molds for 24h at a temperature of 20℃. After demolding, the specimens were exposed to steam curing at 90℃ for 4 days. The heating rate of the steam cure treatment is 11℃/h. After completion of the curing periods, the specimens were kept in the laboratory atmosphere for cooling, and then cleaned and prepared for the wrapping. Epoxy resin, MGS-L285, and hardener were used to bond the FRP jackets onto the concrete columns. The specimens were wrapped by the FRP jackets (2, 3, 4, and 5 layers) in transverse direction with 0-degree orientation. The last FRP layer was wrapped around the cylinder with an overlap of the diameter of the column to prevent the sliding or debonding of the FRP sheets during tests. Carbon, Glass and Aramid fiber sheets were cut and impregnated with epoxy resin using the hand lay-up technique. The top and

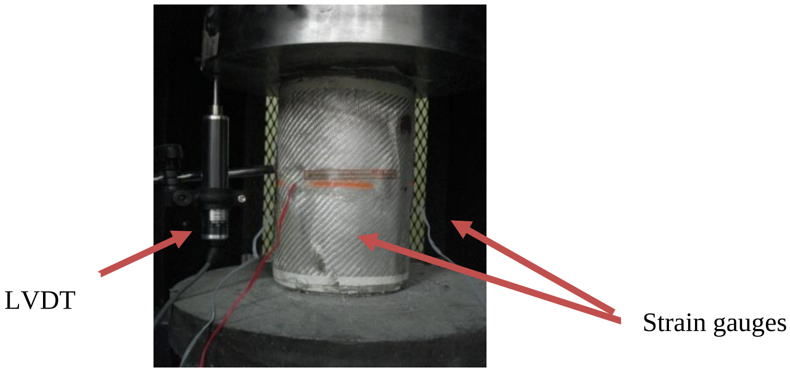


Fig. 1 Test setup

bottom surfaces of all the columns were ground smooth for the compression tests. Then for the epoxy to harden sufficiently before testing the wrapped concrete columns were left at room temperature for one week.

2.4 Test setup

A total of 6 unconfined and 36 different types of FRP-wrapped UHPC columns were tested under monotonic axial compression in the Structural and Earthquake laboratory of Istanbul Technical University (ITU). This research program was supported by scientific research project BAP-ITU and the Istanbul Concrete Production Corporation (ISTON).The monotonic compressive load was applied to the specimens using an Instron testing machine with a capacity of 5000 kN. All the specimens were loaded at a constant rate of 0.01 mm/s under displacement control. The axial load and strains were monitored for every 50 kN increment of load until failure. A linear variable differential transducer ($LVDT_s$) with a gauge length of 25 mm was used in axial direction to measure the axial deformation. For each specimen, two axial strain gauges and one hoop strain gauges, axial strains with a gauge length of 30 mm (PL-30-11) and lateral strains with a gauge length of 60 mm (PL-60-11), were installed at the mid-height of the specimens. The test setup is shown in Fig. 1.

3. Experimental results and discussions

3.1 Test observations and specimen behavior

All the specimens were loaded in monotonic axial compression until failure. Failure of the unconfined UHPC specimens was brittle with a rapid load decrease after the peak load was reached. As shown in Fig. 2(a), a great number of distributed cracks were observed due to the randomly oriented steel fibers in the mix. On the other hand, the CFRP and AFRP- wrapped UHPC columns exhibited more brittle behavior compared to the GFRP-wrapped UHPC columns after the peak load. The failure of the CFRP, AFRP-wrapped UHPC columns was gradual, ending with a sudden and explosive noise. However, the failure of the concrete columns GFRP-wrapped UHPC columns was more gradual and much less explosive than that observed for the CFRP and

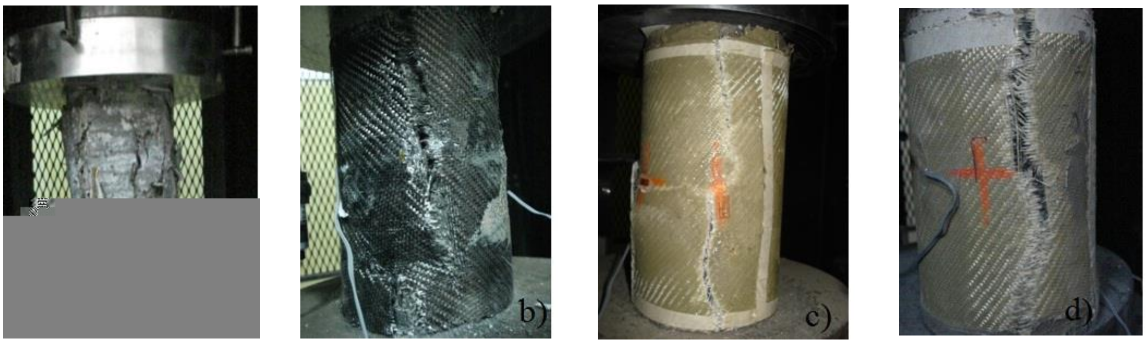


Fig. 2 (a), (b), (c), (d) Typical failure modes of specimens

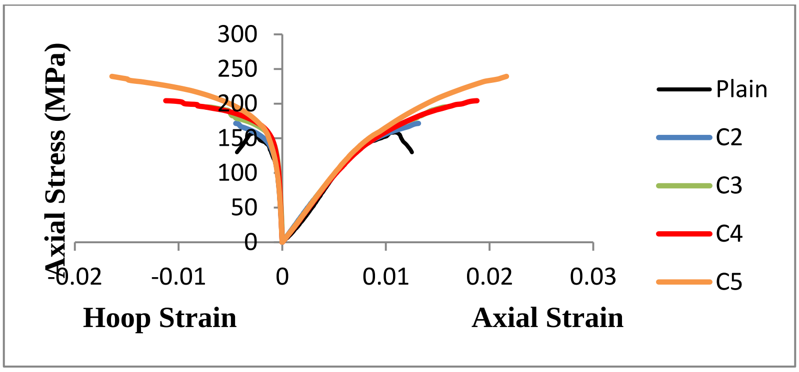


Fig. 3(a) Average stress-strain curves for CFRP-wrapped UHPC columns

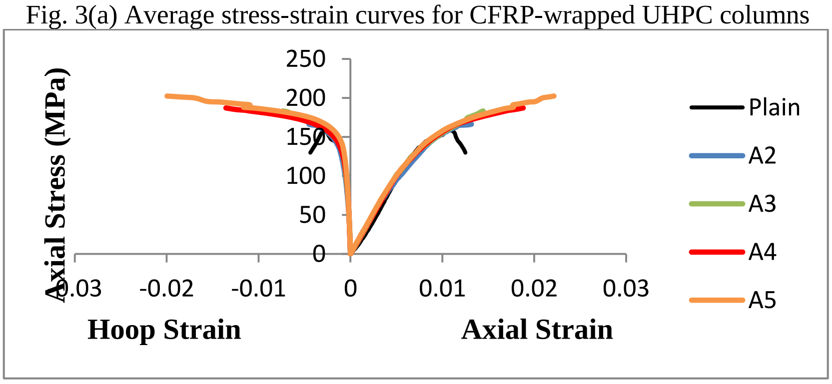


Fig. 3(b) Average stress-strain curves for AFRP-wrapped UHPC columns

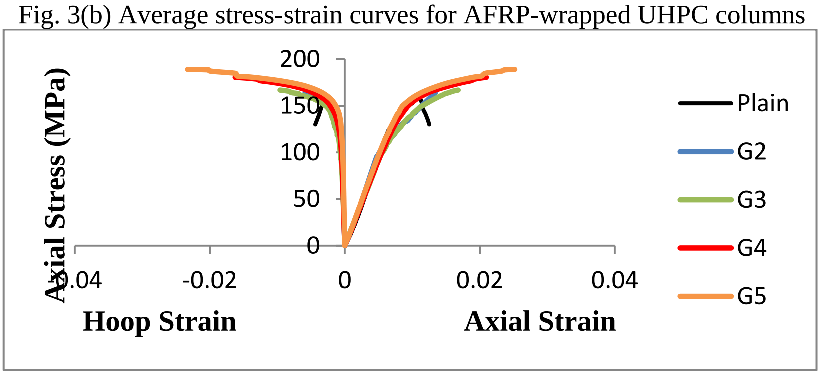


Fig. 3(c) Average stress-strain curves for GFRP-wrapped UHPC columns

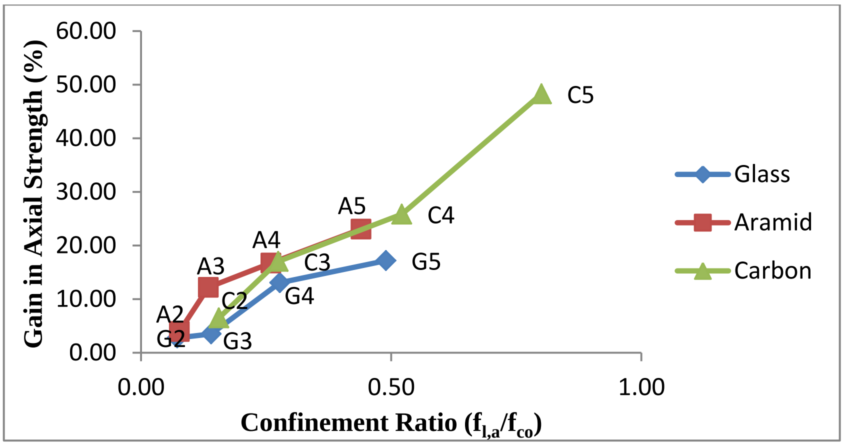


Fig. 4 Gain in axial strength vs. confinement ratio ($f_{l,a}/f_{co}$)

AFRP counterparts. Before failure, cracking noises were frequently heard. The failure of the FRP sheets was initiated away from the overlap region at the mid-height of the specimen and propagated to the top and bottom surfaces of the specimen. The typical failure of the column specimens wrapped with CFRP, GFRP, and AFRP sheets is shown in Figs. 2(b),(c),(d), respectively.

3.2 Stress-strain relationship

The average axial stress-axial and hoop strains relationships for the FRP-wrapped UHPC columns with 2, 3, 4, and 5 layers of FRP and the unconfined concrete specimens are shown in Fig. 3.

From the results, it can be clearly seen that the confinement of the UHPC columns with different type of FRP materials enhanced the axial strength, and the axial and lateral strain capacity of the unconfined UHPC columns. In addition, the greater the number of FRP layers used, the greater the gain observed in axial strength and axial strain capacity with respect to unconfined UHPC columns. However, this increase, over 10%, was seen to be more effective in the GFRP-wrapped UHPC columns with a higher confinement ratio (4 and 5 layers of FRP), while this increase is seen for the CFRP-and the AFRP-wrapped UHPC columns with smaller confinement ratio (3, 4, and 5 layers of FRP). The gain in the average ultimate strength was 2.4, 3.2, 12.7 and 16.8% for the specimens G2, G3, G4 and G5; 3.6, 11.8, 16.4, and 22.7% for the specimens A2, A3, A4, and A5; 6.2, 16.7, 25.5, and 48% for the specimens C2, C3, C4, and C5, respectively. Similarly, the gain in average axial strain was 24.8, 47.4, 92.6, and 128% for the specimens G2, G3, G4, and G5; 18.6, 30.1, 66.5, and 96.9% for the specimens A2, A3, A4, and A5; 18.6, 33.7, 62.8, and 88.9% for the specimens C2, C3, C4, and C5, respectively. The gain in axial strength and axial strain for the FRP-wrapped UHPC columns with regard to the confinement ratio are shown in Figs. 4-5, respectively.

3.3 Analytical investigation

3.3.1 Ultimate strength and strain of FRP-wrapped UHPC columns

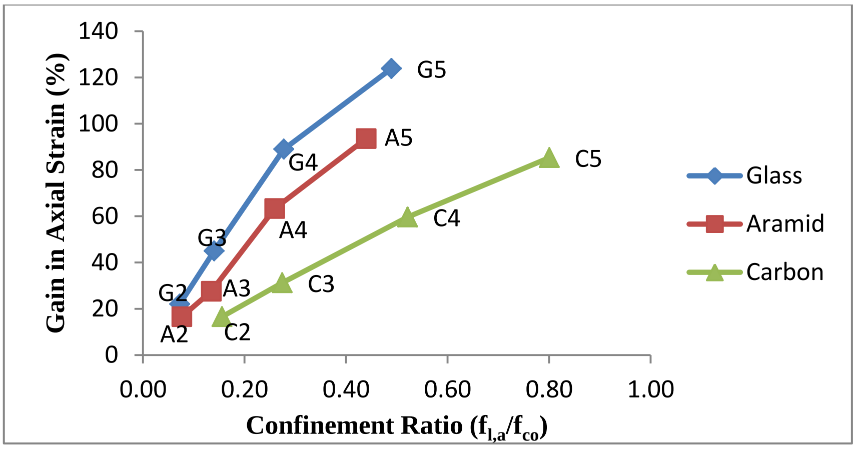


Fig. 5 Gain in axial strain vs. confinement ratio

Most of the existing confinement models in the literature are derived from the confinement model proposed by Richard *et al*. (1928) using concrete specimens confined with active hydrostatic fluid pressure

$$f_{cc} = f_{co} + k_1 f_l \tag{1}$$

$$\varepsilon_{cc} = \varepsilon_{co}\left(1 + k_2 \frac{f_l}{f_{co}}\right) \tag{2}$$

Here, f_{cc} and ε_{cc} are the compressive strength and corresponding strain of confined concrete; f_{co} and ε_{co} are the compressive strength and corresponding strain of unconfined concrete; f_l is the lateral confinement pressure; k_1=4.1 and k_2=5k_1.

For the circular specimens, the lateral confinement pressure (f_l), by equilibrium considerations, can be depicted as Eq. (3)

$$f_l = \frac{2t}{D} f_{frp} \tag{3}$$

Here, t is the thickness of the FRP; D is the diameter of the concrete core; and f_{frp} is the ultimate tensile strength of the FRP.

However, in most cases, the strains measured in the hoop direction are smaller than the ultimate strain of the FRP sheets given by the manufacturer. This phenomenon is emphasized by various authors (Lam and Teng 2003, De Lorenzis and Tepfers 2003). Thus, the actual hoop rupture strengths are used in the next analysis. The lateral confinement pressure given by Eq. (3) can be considered as a nominal value. The actual lateral confinement pressure ($f_{l,a}$) is given in Eq. (4)

$$f_{l,a} = \frac{2tE_{frp}\varepsilon_{h,rup}}{D} \tag{4}$$

Here, E_{frp} is the tensile elastic modulus of FRP; and $\varepsilon_{h,rup}$ is the measured hoop rupture strain of FRP. The values of the average ultimate strengths and strains, ultimate confinement pressure are obtained from the test results given in Table 4.

Table 4 Data and results of FRP-wrapped UHPC columns

Specimen group	Ultimate load (kN)	$f_{l,a}$ (MPa)	Confinement ratio ($\frac{f_{l,a}}{f_{co}}$)	f_{cc} (MPa)	ε_{cc}	$\varepsilon_{h,rup}$	$\frac{f_{cc}}{f_{co}}$	$\frac{\varepsilon_{cc}}{\varepsilon_{co}}$
P*	1245	-	-	-	-	-	-	-
G2	1279	11.46	0.07	162.89	0.0133	0.0099	1.03	1.22
G3	1288	22.23	0.14	164.04	0.0158	0.0128	1.03	1.45
G4	1407	44.00	0.28	179.19	0.0206	0.0190	1.13	1.89
G5	1459	77.57	0.49	185.72	0.0244	0.0268	1.17	2.24
A2	1294	12.11	0.08	164.76	0.0127	0.0086	1.04	1.17
A3	1397	21.33	0.13	177.83	0.0139	0.0101	1.12	1.28
A4	1453	41.11	0.26	185.00	0.0178	0.0146	1.17	1.63
A5	1532	69.70	0.44	195.06	0.0211	0.0198	1.23	1.94
C2	1326	24.66	0.16	168.79	0.0127	0.0074	1.06	1.17
C3	1457	43.48	0.27	185.51	0.0143	0.0087	1.17	1.31
C4	1567	82.63	0.52	199.47	0.0174	0.0124	1.26	1.60
C5	1846	126.89	0.80	235.04	0.0202	0.0152	1.48	1.85

* Average for identical specimens in each group
$f_{l,a}$: Actual confinement pressure
P: Plain concrete samples

Table 5 Summary of passive confinement models for FRP wrapped concrete

Model	Confined Strength (f_{cc})	Cylinder compressive strength (f_{co})	Confinement Type
Mander	$\frac{f_{cc}}{f_{co}} = 2.254\sqrt{1+7.94\left(\frac{f_l}{f_{co}}\right)} - 2\left(\frac{f_l}{f_{co}}\right) - 1.254$	Parametric	Passive-by steel hoops
Miyauchi *et al.*	$\frac{f_{cc}}{f_{co}} = 1+3.485\left(\frac{f_l}{f_{co}}\right)$	33 to 45 MPa	CFRP sheets
Kono *et al.*	$\frac{f_{cc}}{f_{co}} = 1+0.0572\, f_l$	32 to 35 MPa	CFRP sheets
Toutanji	$\frac{f_{cc}}{f_{co}} = 1+3.5\left(\frac{f_l}{f_{co}}\right)^{0.85}$	31 MPa	CFRP, GFRP sheets

3.3.2 Proposed equation for FRP-wrapped UHPC columns

A large number of confinement models have been proposed by many researchers in the literature. Most of these confinement models have been developed to predict the ultimate strength of the FRP-wrapped low and normal strength concrete columns. In this study, the selected four confinement models (Table 5) were examined whether or not they could be applied to the FRP-wrapped UHPC columns.

A simple equation is proposed to predict the ultimate strength of the FRP-wrapped UHPC columns based on the regression of test data reported in Table 4. Based on experimental results, by means of regression analysis, the relation between actual confinement ratio ($f_{l,a}/f_{co}$) and strengthening ratio (f_{cc}/f_{co}) can be obtained by Eq. (5) and shown in Fig. 6.

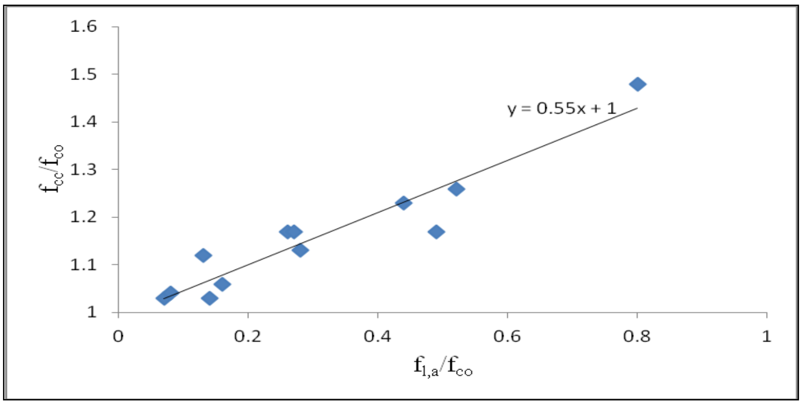
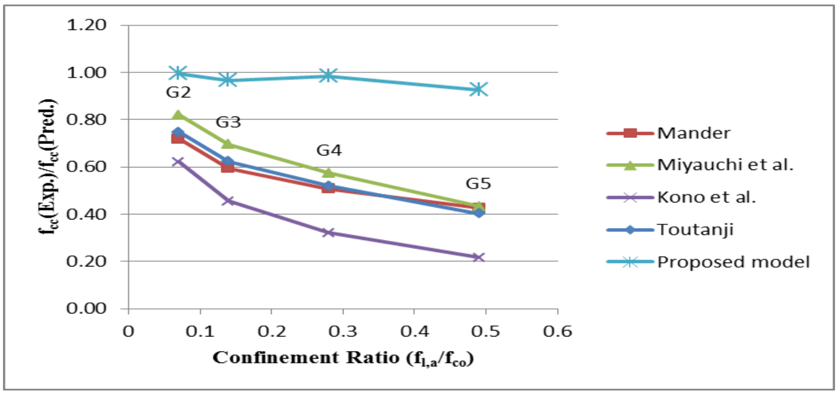
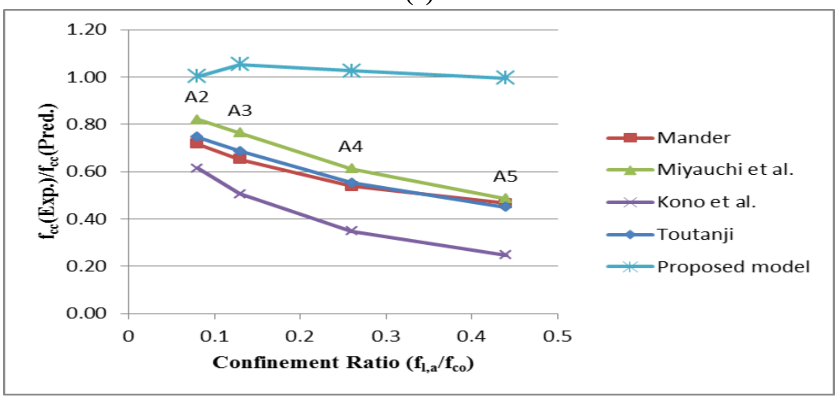


Fig. 6 Strengthening ratio vs. actual confinement ratio



(a)



(b)

Fig. 7 Comparison of confinement models for predicting ultimate strength (a) GFRP (b) AFRP (c) CFRP

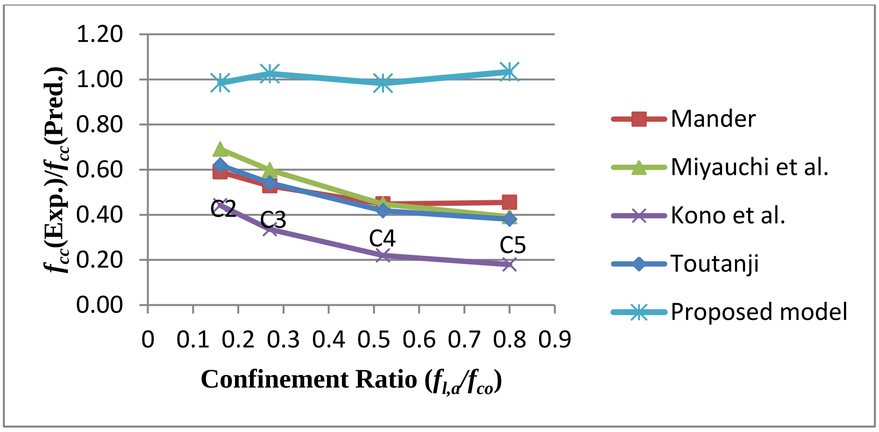


Fig. 7 Continued

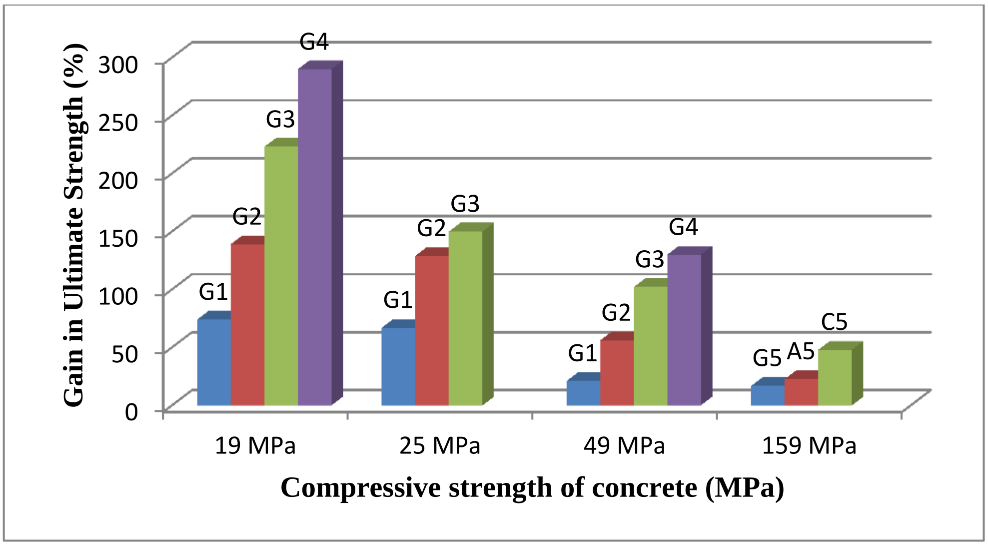


Fig. 8 The gain in ultimate strength for different range of concrete strength

$$\frac{f_{cc}}{f_{co}} = 1 + 0.55\frac{f_{l,a}}{f_{co}} \tag{5}$$

The efficiency and reliability of each confinement model in predicting the ultimate strengths of each group of specimens is shown in Fig. 7. The average experimental results were used for each group of specimens with the same FRP confinement. As seen in Fig. 7, all the confinement models overestimated the ultimate strength of the AFRP, GFRP, and CFRP wrapped UHPC columns.

As seen in Fig. 8, the main reason for this is that while a valuable increase occurs in the ultimate strength and strain capacity arising from the FRP sheets for the low and normal strength concrete columns, this increase is not as effective in UHPC columns, when compared with the results of Shahawy *et al*. (2000), and Sheheta *et al*. (2002).

In addition, by increasing the confinement ratio, the ultimate strength predicted by the confinement models is very unsafe for the FRP-wrapped UHPC columns. The most appropriate confinement model to predict the ultimate strength of all the types of the FRP-wrapped UHPC columns is the model proposed by Miyauchi *et al*. (1999). However, the ultimate strengths obtained from the test results in the current study were on average smaller 39% than those found by Miyauchi *et al*. (1999). Furthermore, it seems that the proposed model is quite reasonable and consistent with the experimental results to predict the ultimate strength of the all types of the FRP-wrapped UHPC columns. The greatest difference in the ultimate strength between the experimental results and the proposed model was 7% for the GFRP-wrapped UHPC columns with 5 layers of FRP sheets.

4. Conclusions

Based on the results obtained through the experimental investigation and the regression analysis, the following conclusions can be drawn:

• Generally, UHPC fails under axial compressive load through lateral tensile expansion. Thus, the ultimate strength and strain capacities of the UHPC columns can be significantly enhanced by the FRP-confinement. However, the gain in ultimate strength and ultimate strain were effectively seen for the FRP-wrapped UHPC columns with higher confinement ratios. In particular for this study, the increase in ultimate strength is nearly negligible for all the types of the FRP-wrapped UHPC columns using 2 layers of FRP sheets. The effective confinement exerted by the FRP sheets is only valid for the CFRP and AFRP wrapped UHPC columns wrapped with 3, 4, 5 layers of FRP sheets, while a greater confinement ratio is required for the GFRP wrapped UHPC columns with 4 and 5 layers of FRP sheets.

• As seen in Figs. 4-5, in comparison with the increase of the same confinement level, the greatest increase in ultimate strength is obtained for the CFRP wrapped UHPC columns due CFRP sheets having a higher tensile elastic modulus. This produces a greater improvement in stiffness, than the in the GFRP and the AFRP sheets. The greatest increase in ultimate strength is 48% for the CFRP-wrapped UHPC columns, however, this increase is only 16.8% and 22.7% for the GFRP and the AFRP wrapped UHPC columns, respectively.

• The greatest increase in the ultimate strain is seen in the GFRP wrapped UHPC columns due to the GFRP sheets having more ductile properties such as a lower tensile elastic modulus and a higher elongation capacity than the AFRP and CFRP sheets. The greatest increase in ultimate strain is 128% for the GFRP wrapped UHPC columns, while this increase is 96.9% and 88.9% for the AFRP and the CFRP wrapped UHPC columns, respectively.

• A simple analytical equation is obtained as a part of this study to predict the ultimate strength of the FRP-wrapped UHPC columns. As seen in Fig. 7, the proposed model predictions are reasonable and in good agreement with the experimental results in terms of predicting the ultimate strength of all the types of the FRP-wrapped UHPC columns. The greatest difference of the ultimate strength between the experimental results and the proposed model was 7% for the GFRP wrapped UHPC columns with 5 layers of FRP sheets. Furthermore, those results clearly prove that there is a need for much more test data to develop an appropriate confinement model considering several parameters such as fiber types, orientation and thickness of the composites for the FRP wrapped UHPC columns.

• When comparing four selected confinement models, all the models developed for low and normal strength concrete columns overestimate the ultimate strength of the FRP wrapped UHPC columns. Moreover, the predictions of these confinement models are very unsafe at higher confinement ratios for the FRP wrapped UHPC columns. However, the confinement model proposed by Miyauchi *et al*. (1999), compared with the other three models, can be applied more safely to estimate the ultimate strength of the FRP wrapped UHPC columns.

References

Cui, C. and Sheikh, S.A. (2010), “Experimental study of normal and high-strength concrete confined with Fiber-Reinforced Polymers”, *J. Compos. Constr.*, **14**(5), 553-561.

Demers, M. and Neale, K.W. (1999), “Confinement of reinforced concrete columns with fibrereinforced composite sheets-an experimental study”, *Can. J. Civ. Eng.*, **26**(2), 226–241.

De Lorensiz, L. and Tepfers, R. (2003), “Comparative study of models on confinement of concrete cylinders with fiber-reinforced polymer composites”, *J. Compos. Constr.*, **7**, 219-237.

Fardis, M.N. and Khalili, H. (1982), “RP-encased concrete as a structural material”, *Mag. Concrete Res.*, **34**(122), 191-202.

Kono, S., Inazumi, M. and Kaku, T. (1998), “Evaluation of confining effects of CFRP sheets on reinforced concrete members”, *Proceedings, ICCI’98*, 343-355.

Lam, L. and Teng, J.G. (2003), “Design-oriented stress-strain model for FRP-confined concrete”, *Construct. Build. Mater.*, **17**(6-7), 471-89.

Lubbers, A.R. (2003), “Bond performance between ultra-high performance concrete and pre-stressing strands”, Master Thesis, Ohio University.

Mandal, S., Hoskin, A. and Fam, A. (2005), “Influence of concrete strength on confinement effectiveness of fiber-reinforced polymer circular jackets”, *ACI Struct. J.*, **102**(3), 383-392.

Mander, J.B. (1988), “Theoretical stress-strain model for confined concrete”, *J. Struct. Eng.*, **114**(8), 1804-1826.

Mirmiran, A and Shahawy, M. (1997), “Dilation characteristics of confined concrete”, *Mech Cohes.-Frict. Mater.*, **2**(3), 237-249.

Miyauchi, K., Inoue, S. and Kuroda, T. (1999), “Strengthening effects of concrete column with carbon fiber sheet”, *Trans. JC*, **21**(3), 143-150.

Purba, B.K. and Mufti, A.A. (1999), “Investigation of the behavior of circular concrete columns reinforced with carbon fibre reinforced polymer (CFRP) jackets”, *Can. J. Civil Eng.*, **26**(5), 590-596.

Richard, F.E., Brantzaeg, A. and Brown, R.L. (1928), “A study of de failure of concrete under combined compressive stresses”, Bulletin 185, Engineering Experiment Station, University of Illinois.

Richard, P. and Cheyrezy, M. (1994), “Reactive powder concretes with high ductility and 200- 800 MPa compressive strength.”, *ACI Spring Convention*., **144**, 507-518.

Saadetmanesh, H., Ehsani, M.R. and Li, M.W. (1994), “Strength and ductility of concrete columns externally reinforced with fiber composite straps”, *ACI Struct. J.*, **91**(4), 434-447.

Samaan, M., Mirmiran, A. and Shahawy, M. (1998), “Model of concrete confined by fiber composites”, *J. Struct. Eng.*, **124**(9), 1025-1031.

Shahawy, M., Mirmiran, A. and Beitelman, T. (2000), “Tests and modeling of carbon-wrapped concrete columns”, *Compos.: Part B.*, **31**(6), 471-480.

Sun, M.Q., Liu, Q.P. and Li, Z.Q. (2000), “A study of piezoelectric properties of carbon fiber reinforced concrete and plain cement during dynamic loading”, *Cement Concrete Res.*, **30**, 1593-159.

Sorelli, L., Constantinides, G. and Ulm, F.J. (2008), “The nano-mechanical signature of Ultra High Performance Concrete by statistical nano indentation techniques”, *Cement Concrete Res.*, **38**(12), 1447-1456.

Thériault, M. and Neale, K.W. (2000) “Design equations for axially loaded reinforced concrete columns strengthened with fibre reinforced polymer wraps”, *Can. J. Civil Eng.*, **27**(5), 1011-1020.

Toutanji, H. (1999), “Stress-strain characteristics of concrete columns externally confined with advanced

composite sheets", *ACI Mater. J.*, **96**(3), 397-404.
Zohrevand, P. and Mirmiran, A., (2011), "Behavior of ultrahigh-performance concrete confined by fiber-reinforced polymers", *J. Mater. Civil Eng.*, **23**(12), 1727-1734.