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Evaluation and comparison of GRP and FRP applications on the behavior of RCCs made of NC and HSC

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Abstract. This paper presents the results of axial pressure testing on reinforced concrete columns (RCCs) filled with confined normal concrete (NC) and high-strength concrete (HSC) using glass-fiber reinforced plastic pipes (GRP) casing as well as fiber reinforced polymer (FRP). This study aims to evaluate the behavior and mechanical properties of columns confined with GRP casing and FRP wrapping under pressure loads. The major parameters in the experiments were the type of concrete, the effect of GRP casing and FRP wrapping, as well as the number of FRP layers. 12 cylindrical RCCs (150*600) mm were prepared and divided into two groups, NC and HSC, and each group was divided into two parts. In each part, one column was without FRP strengthening layer, a column was wrapped with one FRP layer and another column with two FRP layers. All columns were tested under concentrated compression load. The results of the study showed that the utilization of FRP wrapping and GRP casing improved compression capacity and ductility of RCCs. The addition of one and two layers-FRP wrapping increased compression capacity in the NC group to an average of 18.5% and 26.5% and to an average of 10.2% and 24.8% in the HSC group. Meanwhile, the utilization of GRP casing increased the compression capacity of the columns by 4 times in the NC group and 3.38 times in the HSC group. The results indicated that although both FRP wrapping and GRP casing result in confinement, the GRP casing resulted in increased compression capacity and ductility of the RCCs due to higher confinement. Furthermore, the confinement effect was higher on columns made with NC.

Keywords: Reinforced Concrete Columns (RCCs); GRP casing; FRP wrapping; axial force; ductility

1. Introduction

The degradation of concrete structure over time is inevitable due to environmental factors (corrosion, freezing and melting), structural damage (caused by casual loading such as earthquake, wind and flood) and heavy traffic loads (Toghroli *et al.* 2017, Nosrati *et al.* 2018, Shariat *et al.* 2018, Toghroli *et al.* 2018, Ziaei-Nia *et al.* 2018, Abedini *et al.* 2019, Li *et al.* 2019). It is very important and necessary to develop scientific and applicable methods for strengthening or repairing structures with weakness in design or implementation (Li *et al.* 2019). In the first method of strengthening columns, steel jackets were used to encircle the column. Despite that this method improved compressive and shear strength of the columns, its disadvantages included high weight of steel sheets, their corrosion, high installation and maintenance cost. With the advent of FRP and its expansive use in civil engineering, there have been significant developments in the repair and strengthening of concrete columns (Sinaei *et al.* 2011, Sinaei *et al.* 2012, Ashour and Kara 2014, Luo *et al.* 2019, Sajedi and Shariati 2019, Xie *et al.* 2019). This is due to the special properties of these materials, such as the high ratio of tensile strength to weight, corrosion resistance and optimal durability, ease of application, as well as insignificant geometric effects on reinforced members. The use of FRP composites to repair and protect damaged concrete columns of bridges has been common, since 1980s. More studies have shown that FRP improves bearing characteristics, in addition to protecting columns against environmental degradation factors. When the wrapped column is placed under compression load, FRP prevents the lateral expansion of the cross section, which is due to compressive cracks, hence a kind of passive confinement compression is applied. In this way, the bearing of the concrete core continues, and the column is destroyed at higher compression stresses (Dundar *et al*. 2015). Similar to any other reinforcement method, reinforcement by using FRP also has negative aspects. In the record, not only are some of the positive aspects of using CFRP, but also some of its negative aspects. Among these negative aspects, we can mention the following:

Increase the likelihood of a crunch failure, separation of sheet from concrete substrate, fire damage / fire damage against high temperatures, unavailability of FRP fibers on rough surfaces, weakness against pressure tension, lack of proper bonding between reinforced sheet and concrete surface, problem of durability and reversibility (Abedini *et al.* 2017).

HSC is considered a rather novel material and has recently been used in the construction of various structures such as high-rise buildings, bridges, and dams (Hamidian *et al.* 2011, Shariati *et al.* 2011, Shariati *et al.* 2012, Mohammadhassani *et al.* 2014a, Mohammadhassani *et al.* 2014b, Shariati *et al.* 2014, Shariati *et al.* 2016, Davoodnabi

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et al. 2019). The advantages of HSC include high compression strength, higher modulus of elasticity and lower porosity. The factors that affect achieving high strength in concrete are the utilization of strong and fine shape sand and gravel, increasing the amount of cement consumption, limiting the size of the largest aggregate, using sand with best fineness modulus and proper sand to cement ratio for more concrete homogeneity. In addition, using fine-grained material of <0.01 µ such as micro silica, a compact set of matrixes with very low porosity can be provided. In HSC, the water to cement ratio should be reduced as much as possible. Hence, super-plasticizers (SP) are required in order to provide plasticity and efficiency in such mixtures prepared with less water (Tokgoz *et al*. 2012). Many studies have been conducted on strengthening RCCs by wrapping their external surfaces. Most of the studies agreed that using FRP increases the compressive capacity and ductility of the confined concrete columns by providing the confinement effect of the concrete core under pressure loadings (Shahawy *et al*. 2000, Wu *et al*. 2006, Wong *et al*. 2008, Jiang *et al.* 2014, Pan *et al.* 2017, Shariati *et al.* 2017). Moreover, studies on sections shape of reinforced columns showed that unlike circular sections, square and rectangular sections are not influenced by confinement effect because the confining pressure is uniform in circular sections (Mirmiran *et al*. 1998, Ozbakkaloglu 2013, EL Maaddawy *et al*. 2010, Ozbakkaloglu and Xie 2016). Moreover, studies on hollow RCCs using FRP fiber showed that these columns perform better in tolerating axial loads (Mirmiran and Shahawy 1996, Kusumawardaningsih and Hadi 2010). In addition, many studies have also been conducted on the number of FRP strengthening layers applied on concrete column surfaces. All of the studies have reported similar findings that using more and thicker layers increase compressive capacity in the strengthen columns. Moreover, type of fiber and fiber tissue, glue volume, and other factors influence strengthening (Rahai *et al*. 2008, Kumutha *et al*. 2007, Parvin and Jamwal 2005). On the other hand, studies have shown that the strengthening percentage using FRP layers for columns made with low and medium-strength concrete is greater than HSC probably because the strength provided by the confining layer is less than the concrete compressive strength (Almusallam 2007, Vincent and Ozbakkaloglu 2013). All of the studies about eccentric axial loading agree that eccentric axial loading and imposing flexural moment reduce the pressure load bearing, and FRP also improves compressive capacity and ductility (Hadi 2006, Hadi, 2007a, b).

The filled concrete columns in GRP casings are the composite columns and in recent times, many studies have been conducted on concrete columns using these casings. In these columns, GRP casings act as the framework and provide radial confinement for the column core and limitation of micro-cracks extension and, concrete core prevents GRP casing buckling simultaneously. Studies on concrete columns with GRP casing showed that these columns have higher performance based on compressive capacity, stiffness, and ductility (Hadi *et al.* 2015, Xiao *et al.* 2014, Wang *et al*. 2017, Ozbakkaloglu and Oehlers 2008, Park *et al*. 2011). Moreover, using this casing type in columns was examined under axial impact and it was observed that the confinement provided by GRP casing application has a desirable effect on increasing the capacity of such columns under axial impact loads (Huang *et al.* 2017).

The purpose of this experimental study was to evaluate individual and simultaneous effects of GRP casing and FRP wrapping on RCCs made of NC and HSC. This was achieved by placing a 12 cylindrical RCCs (150*600 mm) with and without the presence of GRP casing in either NC or HSC. The aim of the study was achieved by the performance of compressive strength test and determining axial and lateral deformations.

2. Mechanical properties of FRP and GRP used in research

The used composite layers in this research are uniaxial CFRP made by TORAY Co. of Japan. The mechanical properties of FRP material was provided based on the manufacturing company's information and the tests based on ASTM D7565 and ASTM D2996 standards are presented in Table 1. The used epoxy glue was made by Paya Co. in two-partials of resin and stiffener, which are combined in the ratio of 1:3 and mixed manually for 5 min. The necessary time for the evolving of resin and its protection is influenced by the temperature of the environment and is between 5-7 days under normal condition based on the recommendation of the manufacturing company. The tolerable tensile stress of glue is 30 MPa and the tensile rapture strain is 3.6%. The characteristic of the mentioned glue was obtained based on the reports of the manufacturing company and the conducted tests were based on ASTM D638 standard.

GRP composite casings are made in Mashhad Sadra Shargh factory by imbrue glass fiber to the resin. These casings are classified based on the tolerable internal pressure. In this research, GRP casings with 10 bar internal pressure tolerance were used. The characteristics of GRP casings recognized from the conducted tests based on ASTM D2996 standard are presented in Table 1 based on the information of the manufacturer. GRP casings with 600 mm height, 150 mm internal diameter, and 8 mm thickness were used.

Table 1 The mechanical properties of FRP material and GRP composite casings

Composite characteristics	FRP material	GRP casing
Thickness (mm)	0.166	8
Density (kg/m^3)	-	1800
Weight in surface unit (g/m^2)	300	-
Weight in length unit (g/m)	-	6786
Tensile stress (MPa)	4900	75
Modulus of Elasticity (GPa)	230	120
Poisson ratio	0.3	0.4
Ultimate strain (%)	2.5	1.3

3. Experimental program

3.1 Preliminary tests

The cylindrical specimen from the used concrete for the columns was prepared with 150*300 mm to determine the concrete compressive strength based on ACI-211 recommendation (ACI 211.1, 1991), and compressive strength test was conducted on them after curing in water at 7 and 28-day ages. In HSC micro-silica gel was used for making dense and low porosity concrete, also, to increase compressive strength of concrete, the water - cement ratio (w/c) decreased to 0.2, and in order to maintain the workability of concrete, SP was used. Concrete slump during the construction of columns was 80 mm for NC and 210 mm for HSC. The details of mixture designs of the used concretes are presented in Table 2.
The results of compressive strength tests at 28-day ages are presented in Table 3. The mean compressive strength at 28-day ages of the cylindrical specimens was obtained as 32.7 MPa for NC and 63.1 MPa for HSC.

3.2 Specimens' characteristics

The experimental specimens of this research included 12 RCC with circular section having 150 mm diameter and 600 mm height. All columns were reinforced concrete and divided into two groups, NC and HSC, and each group was divided into two parts with and without GRP casing. In each part, one column was without FRP strengthening layer, a column was wrapped with one FRP layer and another column with two FRP layers.
Columns were named according to their components as follows: For column with HSC H, column with NC N, column with FRP wrapping F and column with GRP casing G was considered. Number after (F) shows the number of FRP layers in columns having FRP wrapping. Table 4 presents the name and characteristics of columns.

Table 2 Details of concrete mixture designs

Mix Constituents	NC (kg/m$^{3)}$	HSC (kg/m$^{3)}$
Cement type 2	350	495
Water	157.5	111.5
Gravel	932	930
Sand	932	720
Micro-silica gel	-	55
SP	-	2.5
w/c	0.45	0.20

Table 3 Results of the compressive strength for the standard cylindrical specimen at 7 and 28-day ages (MPa)

Specimen	NC	HSC
Specimen 1	31.2	61.7
Specimen 2	33.1	63.4
Specimen 3	33.8	64.2
Mean	32.7	63.1

Table 4 Characteristics of the research columns

Spe.	D. (mm)	H. (mm)	CT	GRP	FRP	FRP L.
N	150	600	NC	NO	NO	0
NF1	150	600	NC	NO	YES	1
NF2	150	600	NC	NO	YES	2
GN	150	600	NC	YES	NO	0
GNF1	150	600	NC	YES	YES	1
GNF2	150	600	NC	YES	YES	2
H	150	600	HSC	NO	NO	0
HF1	150	600	HSC	NO	YES	1
HF2	150	600	HSC	NO	YES	2
GH	150	600	HSC	YES	NO	0
GHF1	150	600	HSC	YES	YES	1
GHF2	150	600	HSC	YES	YES	2

3.3 Preparing test specimens

The experimental specimens of this research included 12 RCCs (150*600 mm); in addition, two specimens were considered to be used as storage in the experiments. The used longitude reinforcement were considered as 2.7% of the gross cross-section of the column in all columns which were supplied using 6 ribbed bars with a diameter of 10 mm. The longitude bars were cut at a distance of 20 mm at both ends of the column to prevent stress concentration on them. Thus, the considered length of the longitudinal bars was 560 mm. Moreover, spiral bars with 80 mm pitch and 6 mm diameter were used on each network. The concrete coverage on the bars was considered as 25 mm. Spacer was used to provide the mentioned coverage for the longitude and spiral bars. The yield stress of 400 MPa for longitudinal bars was determined by rebar tensile test and obtained as and 300 MPa for the spiral bars. Fig. 1 shows the longitudinal and transverse sections of the research columns.

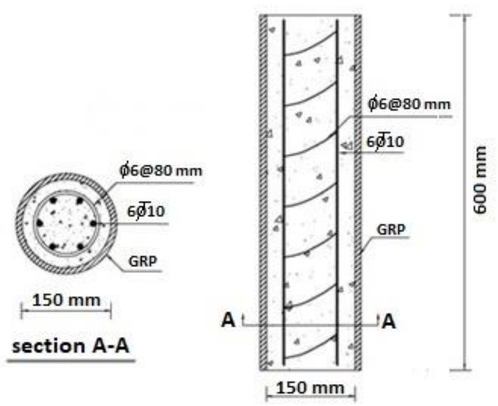


Fig. 1 Longitudinal and transverse sections of the research columns

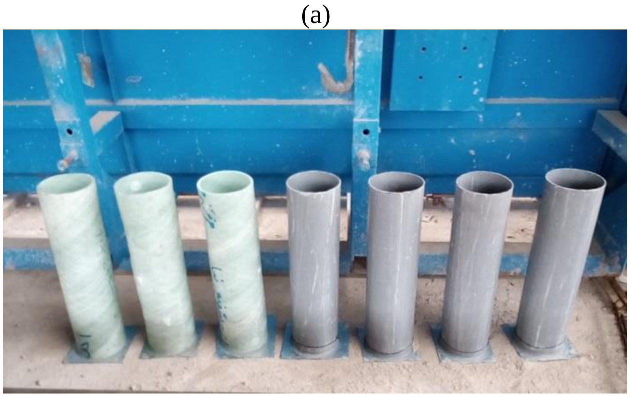
Fig. 2 Strain-gage installation on bars

To measure the strain of bars during columns compressive testing, digital strain-gage was used to examine the columns' behavior. Therefore, the strain-gages were installed on the bars before casting of each column. Fig. 2 shows the installment of strain-gages.

The next step was preparing 6 GRP casings and 8 PVC casings to cast the columns without casing with circular sections having 150 mm internal diameter and 600 mm height. Then, casings were installed on the metal sheets. Fig. 3 presents the GRP casings and PVC frames.

Then, oil was sprayed on the internal surface of the framework for easy separation from concrete surface and reinforcement was put in the framework.

(a)



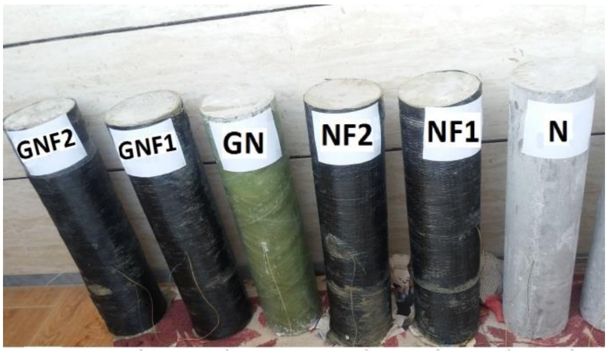
(b)

Fig. 3 GRP casings and PVC frames, (a) NC group and (b): HSC group

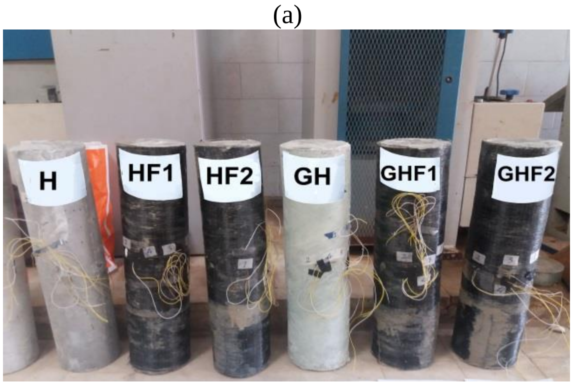
Fig. 4 Placement reinforcement inside CFRP casings and PVC framework

Fig. 4 shows the reinforcement placement inside GRP casing and PVC framework. NC was used for casting of NC group and HSC for HSC group. For curing, columns were put in water for 28 days and then were CFRP wrapped.

To prepare the concrete columns for installation of the CFRP layers before applying epoxy glue, the external surface of columns were completely smoothened, cleaned, and dried. The used epoxy glue was 2 partial and made of resin and stiffener which were mixed manually in a ratio of 1:3 for 5 min, then the thin layer of glue was rubbed on the concrete cylindrical surface and CFRP layer was carefully wrapped around the column. The end edge of CFRP wrapping was overlapped at 100 mm to ensure non-separation.



(a)



(b)

Fig. 5 Columns after installing CFRP wrapping and strain-gages, (a) NC group and (b) HSC group

The second layer was wrapped 2 hours after installation of the first layer for columns with 2 CFRP layers. All columns was wrapped with zero angle and were kept in room temperature for 7 days to cure the epoxy glue. Fig. 5 presents the studied columns after installing CFRP wrapping and strain-gages.

3.4 Testing the columns

The columns of this research were tested under uniaxial pressure loading by hydraulic jack with 500-ton capacity in the soil mechanic laboratory of the Road and Transportation office of Khuzestan state, in Iran. Specimens were tested by displacement control method and a loading rate of 10 kN/s. Two axial strain-gages and one lateral strain-gage were installed in the middle of each column to determine the axial and lateral strains which are presented in Fig. 6. Strain data for columns and bars was recorded using electronic data-logger attached to the computer in each second. In addition, load was recorded automatically using a 500-ton dynamometer to determine the load-strain diagram of specimens. Precision and care was taken to ensure that the columns were located in the center of the jack when placed in the machine. Fig. 7 presents the 500-ton laboratory jack and placement of specimens.

Fig. 6 Two Axial and one lateral strain-gage installation place

(a) (b)

Fig. 7 Test setup and columns placement in jacks column NF2, (B) column HF2

Table 5 Ultimate strains and capacity of columns

Column name	Ultimate Capacity (kN)	Mean axial strains (10^{-6} mm/mm)	Lateral strain (10^{-6} mm/mm)
N	566	* -3848	1356
NF1	715	-4144	1579
NF2	763	-5432	2022
GN	2485	-15229	4051
GNF1	2765	-18738	5347
GNF2	2940	-22075	5993
H	727	-3848	1745
HF1	815	-4451	1861
HF2	1014	-5196	2304
GH	2672	-16429	4642
GHF1	2897	-19622	5419
GHF2	3076	-23029	6336

* the negative sign means strain is negative (length reduces)

4. Analysis of test results

4.1 Ultimate capacity of columns

Columns were loaded by 500-ton capacity hydraulic jack at the rate of 10 kN/s until the moment of failure. The ultimate strains and capacity of columns are presented in Table 5.

Table 5 and Fig. 8 show that using single and double layer FRP in columns without GRP casing ultimately increased capacity by 26% and 35% for NC group columns and 12% and 39% for HSC group columns. In addition, with the use of single and double layer FRP in columns with GRP casing, ultimate capacity was increased by 11% and 18% for NC group columns and 8% and 15% for HSC group columns. Therefore, it is confirmed that using FRP wrapping can have positive effects on increasing the ultimate capacity of RCCs. Moreover, using FRP in columns with GRP casing does not result in a significant increase in columns ultimate capacity due to the high confinement effect of this casing. Therefore, the simultaneous use of casing and FRP is not economical to strengthen RCCs.

On the other hand, Fig. 9 shows that using GRP casings is significantly more effective than FRP wrapping because with GRP casing, average RCC compressive capacity increased by 4 times in the NC group and 3.38 times in HSC group. With the addition of one and two layers of FRP, the average compressive capacity increased by 18.5% and 26.5% in the NC group, and 10.2% and 24.8% in the HSC group, respectively.

A comparison between the ultimate capacity of NC and HSC groups shows that HSC group has higher compressive capacity. On the average, the use of HSC in columns with and without GRP casing increased ultimate capacity by 5.63% and 25.1%, respectively.

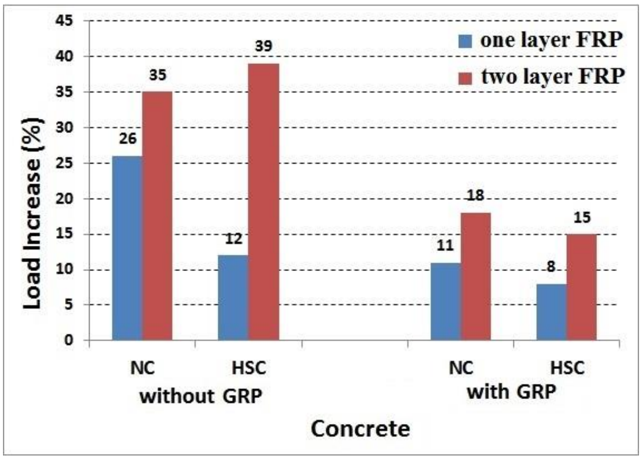


Fig. 8 FRP effect on compressive capacity of columns

This comparison showed that the effect of concrete compressive strength on ultimate capacity of columns with GRP casing was not significant because of high confinement of this casing. Fig. 10 shows the comparison between columns compressive capacity and percentage increase in ultimate capacity with the use of HSC with respect to NC.

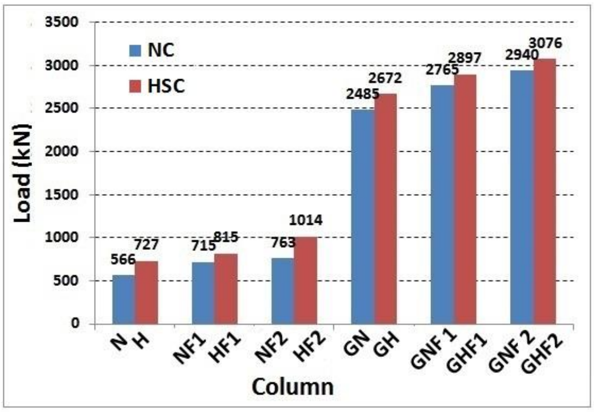


Fig. 9 Compressive capacity of columns

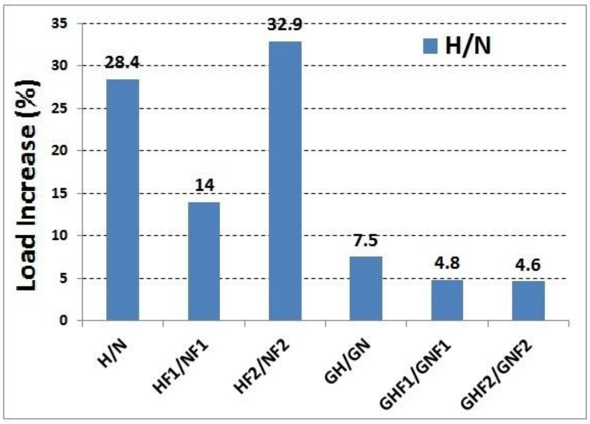


Fig. 10 Compressive capacity ratio of HSC group to NC group

Comparing the ultimate strains in columns without GRP casing showed that using single and double FRP wrapping layers increased the ultimate axial strain of columns by 16% and 34%, respectively, while these values are 19% and 40% in columns with GRP casing. Therefore, it is observed that using FRP wrapping to confine the concrete columns increased the ultimate axial strain of the RCCs, this effect is more visible in columns with GRP casing because of the casing confinement effect. Moreover, comparing the effect of casing confinement of GRP casing with FRP wrapping showed that in the ultimate axial strain of the RCCs, these casings are very effective. For example, using GRP casing without FRP wrapping increased the ultimate axial strain of the reinforced concrete column by 295% and 269% in the NC group and HSC group, respectively; while using single and double FRP layer increased the ultimate strain by 8% and 41%, in the NC group, and 16% and 34% in the HSC group, respectively. The high efficiency of GRP casing on axial strain can be attributed to the presence of fiber in their structure. Therefore, using GRP casing in regions requiring ductile design can be very useful.

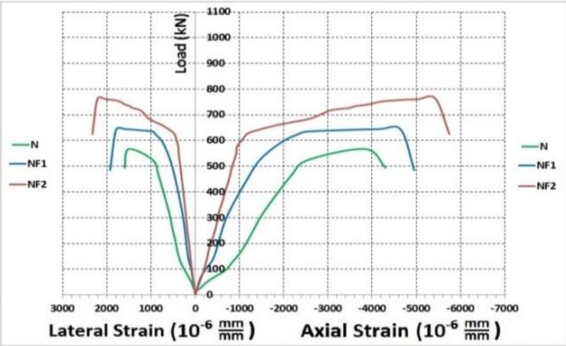
4.2 Load-strain diagram for columns

For comparing columns behavior, the load-strain diagram for axial and lateral strains are presented in Figs. 11 and 12.

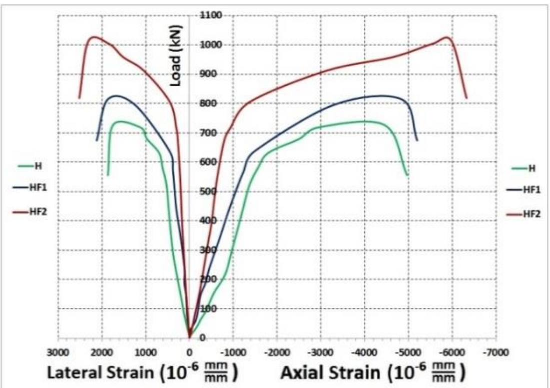
It is seen from the load-strain diagram that wrapping the reinforced concrete columns with FRP material increases their radial and axial strains which shows an increase in ductility of columns with FRP. Furthermore, there was a significant increase in the pressure tolerance in these columns.

More precise study of load-strain diagram of columns without GRP casing showed that this curve is made of two parts, including linear hardening and non-linear softening; change in column behavior is sudden and exhibits pressure crack in concrete, with the commencement of the use of FRP wrapping, and this strength was maintained under the pressure loads. In addition, load-strain diagram of columns with GRP casing are also made of two parts, including linear hardening and non-linear softening, but a change in column behavior is gradual because of the complete integration and more confinement of GRP casing with concrete column. Moreover, it was observed that wrapping columns with FRP increases column stiffness and reduces axial ductility because of the resulted confinement by wrapping.

For comparing columns behavior with different concrete, the load-strain diagram for axial and lateral strains is presented in Fig. 13. It is seen that HSC group has higher compressive capacity, and this effect is more common in columns without GRP casing, the reason maybe reduction concrete compressive strength effect in compressive capacity of column with GRP casing because of the high confinement effect of casing. HSC is also seen to increases the axial and lateral strains.

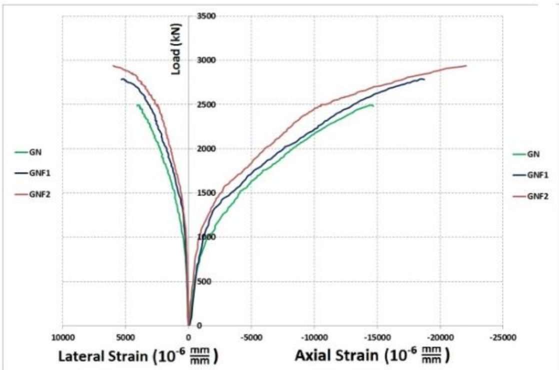


(a)



(b)

Fig. 11 Load-strain diagram for columns without GRP casing, (a) NC group and (b) HSC group



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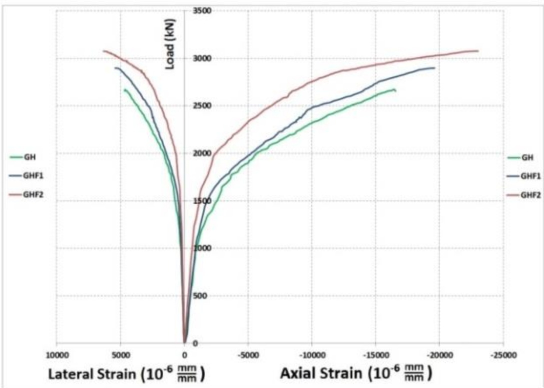
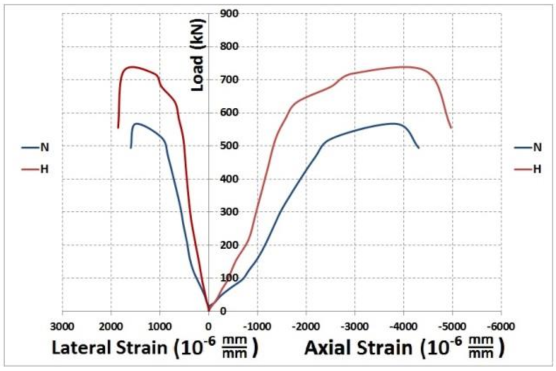
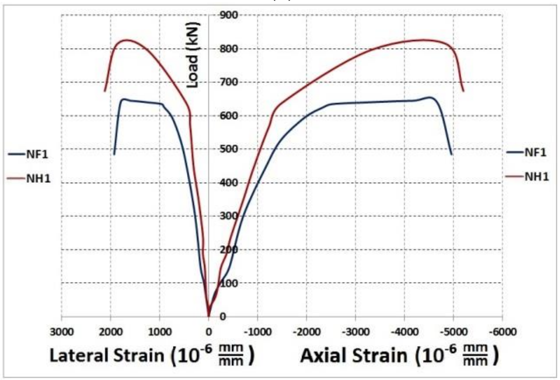


(b)

Fig. 12 Load-strain diagram for columns with GRP casing, (a) NC group and (b) HSC group



(a)



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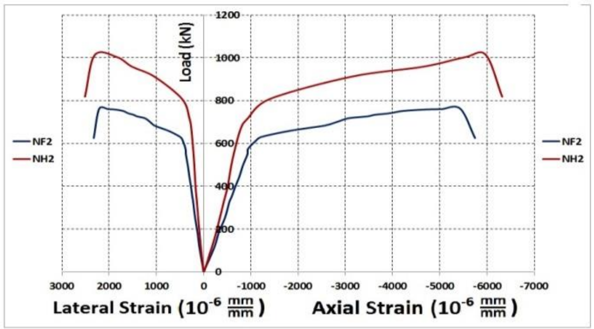

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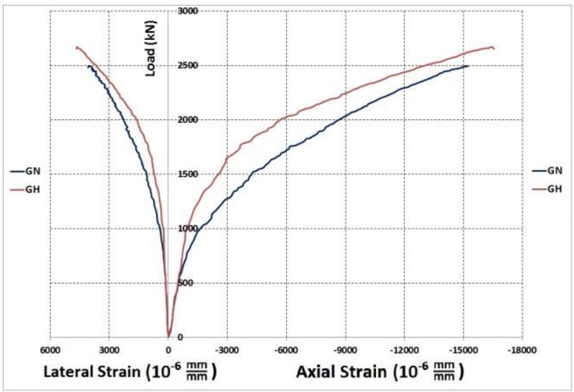

(d)

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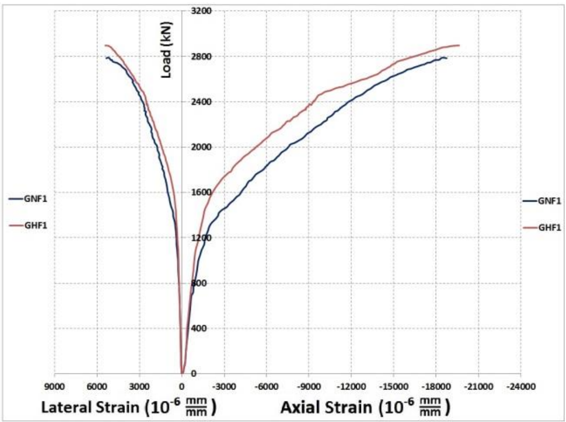

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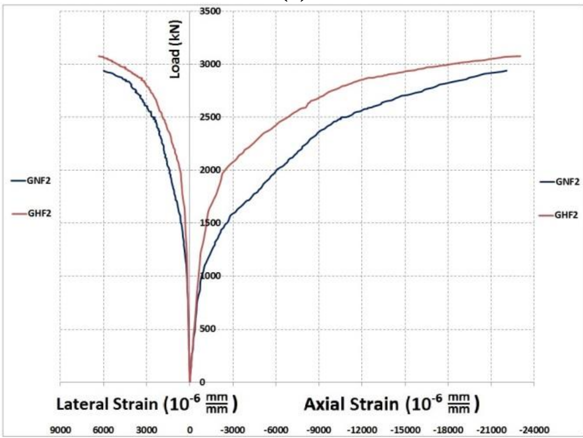

(f)

Fig. 13 Load-strain diagram for NC and HSC groups, (a) N and H columns, (b) NF1 and HF1 columns, (c) NF2 and HF2 columns, (d) GN and GH columns, (e) GNF1 and GHF1 columns (f) GNF1 and GHF1 columns

4.3 Study of columns rupture

Columns rupture is presented in Fig. 14. As observed, failure of most columns happens because of bars buckling of columns (Mehrmashhadi *et al.* 2019). In columns without GRP, most ruptures occurred locally and gradually, while in columns with GRP casing, the overall failure and the destruction of the entire column occurred. The reason for this is probably the difference in the confinement rate caused by the FRP wrapping and GRP casing. As the confinement of the FRP was smaller and the rupture occurred when the first stress occurred (usually at both two ends of the column), the confinement of the GRP casing was much higher and until all the points of the column reached all their tolerable strain, the yield of bars will not fail, so rupture in columns with GRP casing was brittle and with explosion sound, while in columns without GRP casing rupture occurred softly forming compressive cracks in the concrete and fracture in the confining FRP. Fibers may also change the damage pattern and failure modes in fiber-reinforced polymers (Mehrmashhadi *et al.* 2018, Abedini *et al.* 2019).

N **NF1** **NF2**

GN **GN1** **GN2**

Fig. 14 Rupture of NC group of columns after loading

H **HF1** **HF2**

GH **GHF1** **GHF2**

Fig. 15 Rupture of HSC group of columns after loading

Table 6 Technical and economic comparison of the studied columns

column name	The cost of framing, reinforcement and casting ($)	GRP casing (m)	Cost of GRP casing ($)	CFRP (m^2)	CFRP cost ($)	Column construction cost ($)	ratio of column making cost to column N cost	ratio of column ultimate capacity to column N capacity
N	13	-	-	-	-	13	1	1
NF1	13	-	-	0.4	8.6	21.7	1.65	1.26
NF2	13	-	-	0.8	17.1	30.2	2.31	1.34
GN	10.7	0.6	14.3	-	-	25	1.91	4.39
GNF1	10.7	0.6	14.3	0.4	8.6	33.6	2.56	4.88
GNF2	10.7	0.6	14.3	0.8	17.1	42.1	3.22	5.19
H	15.4	-	-	-	-	15.4	1.18	1.28
NH1	15.4	-	-	0.4	8.6	24	1.84	1.44
NH2	15.4	-	-	0.8	17.1	32.5	2.49	1.79
GH	13	0.6	14.3	-	-	27.3	2.09	4.72
GHF1	13	0.6	14.3	0.4	8.6	35.9	2.74	5.19
GHF2	13	0.6	14.3	0.8	17.1	44.4	3.40	5.43

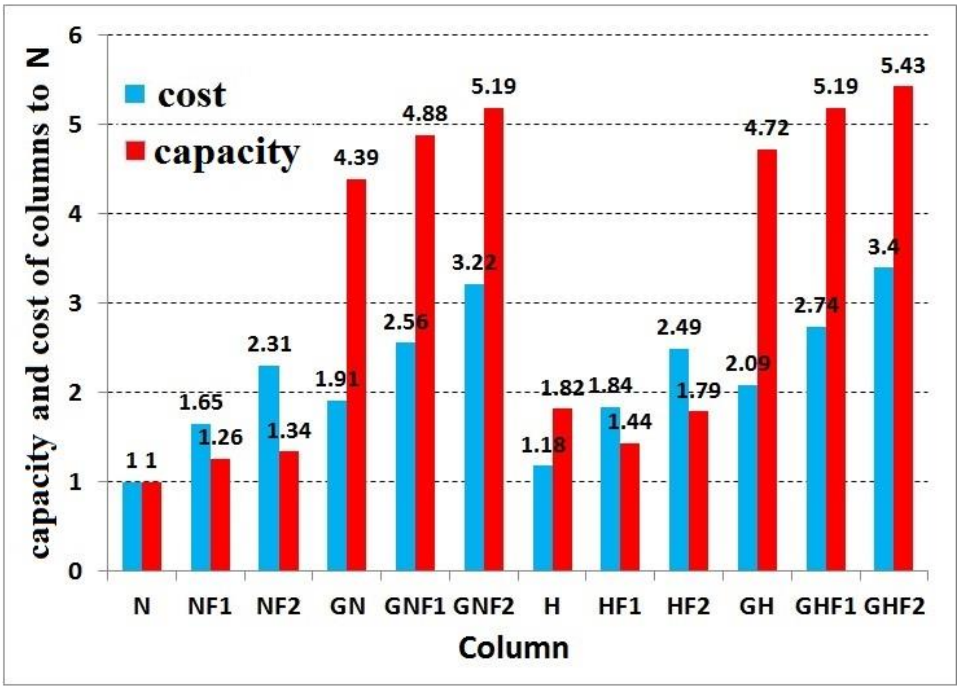

Fig. 16 Comparison of the percentage increase in capacity and cost of columns to column N

4.4 Technical and economic comparison

Later, the costs of preparing the columns, ultimate capacity of each column, and their technical and economic comparison were studied. Cost of framing, reinforcement, and casting of each studied columns with and without casing were calculated as 10.7$ and 13$ in NC group and 10.7$ and 13$ in HSC group. The GRP casing pipes had 150 mm internal diameter and a tolerable 10 bar internal pressure such that their supplement cost was 23.8$ per m. Moreover, the used CFRP wrapping was uniaxial which was supplied at a cost of 14.3$ per m^2 and cost of glue and resin used per m^2 of CFRP was 7.2$. Table 6 presents the consumed GRP casing and CFRP wrapping, their cost for the columns and their effects on the ultimate capacity.

The capacity and cost ratio of columns to the column N are presented in Fig. 16. Comparison capacity and cost of the columns shows that the ratio of strengthening by CFRP wrappings in columns without casing is less than its cost ratio, while the increased capacity in columns with GRP casing than column N is more than the cost of its strengthening. On the average, in column with casing capacity increase was about 1.9 times in NC group and 1.71 times in HSC group more than its initiation cost. Therefore, using GRP casing for strengthening the RCCs is economical. Among the columns studied, GN has the highest of capacity-cost ratio as 2.3. Therefore, these columns can be proposed as the most economical column for construction.

5. Conclusions

1- The use of GRP casing as molds in reinforced concrete columns caused a significant increase in compressive capacity; compressive capacity in columns having casing compared to columns without casing, was 4 and 3.38 times, respectively. These values were, for columns made of conventional concrete and high-strength concrete, respectively.

2- Strengthening the columns without casing and with use of CFRP significantly increased the compressive capacity of the columns. The use of a single layer and two-layered CFRP with conventional concrete increased 26% and 35%, respectively; this increase with high-strength concrete was 12% and 39%. This effect is less in the columns having casing due to higher confinement effect of casing; the use of a single layer and two-layer CFRP in columns with conventional and high-strength concrete resulted in increase in compressive capacity as 11%, 18% and 8%, 15%, respectively.

3. The increase in the number of CFRP layers increased the compressive strength of the columns, so that the mean increase in strength due to the use of a single layer and two-layer CFRP compared to similar columns without CFRP and made with conventional concrete were as 18.5% and 26.5%, and for columns with high-strength concrete were as 10.2% and 24.8%. These results indicate that the effect of CFRP on the columns made with conventional concrete is more.

4. The ultimate axial strain of reinforced concrete columns with CFRP is more than that of non-CFRP columns. The use of a single-layer and two-layer CFRP increases the ultimate strain in conventional concrete columns as 15.5% and 44.5%, respectively, and in columns with high-strength concrete are as 18% and 37.2%. The use of GRP casing resulted in increase in ductility of reinforced concrete columns in a large amount, such that the mean axial strain increase in columns with casing compared to the columns without casing and made of conventional concrete was 322% and 278% for columns made of high-strength concrete. These results indicate that the effect of CFRP on the columns made of conventional concrete is higher.

5. The rupture in the columns with GRP was brittle and explosive, while the rupture in the columns without GRP and with CFRP was soft and caused the formation of compression cracks in the concrete and rupture in the CFRP.

6. Technical and economic comparison of the research columns showed that the use of GRP casing to retrofit columns is much more cost effective than CFRP application, so that the increase in strength of the columns is more than cost for strengthening them; the ratio of the increased strength due to using CFRP to the cost spent to strengthen the column was lower in columns with and without casing. The greatest increase in the compressive strength to the cost of building the column is related to columns with casing and without CFRP (columns GN and GH), so these columns can be proposed as the most economical columns for execution.

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