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A Comparative Study on the Efficiency of CFRP and GFRP in the Improvement of Compressive Strength, Acoustic Impedance and Bracing of Filled and Hollow Concrete Columns in Different Layers and Ages

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Abstract

FRP technique is growing in popularity as a modern strengthening method. When it comes to FRP, concrete surface strength plays a determining role in the bond between FRP and concrete. This paper aims to compare the efficiency of CFRP and GFRP in the improvement of compressive strength, acoustic impedance and bracing of filled and hollow concrete columns in different layers and ages. In doing so, we carried out various tests on 18 samples in the ages of 3, 7, 14, 28, 42 and 90 days. According to the results, the strength of un-braced carbon and glass increased by 19-40% and 8-43% respectively and the strength of braced carbon and glass increased by 17-25% and 10-82% respectively. The compressive strength increased by 66% in one-layer CFRP hollow column, 96% in two-layer CFRP hollow column, 123% in three-layer CFRP hollow column, 36% in one-layer GFRP hollow column, 63% in two-layer GFRP hollow column, 105% in three-layer GFRP hollow column, 71% in one-layer CFRP filled column, 138% in two-layer CFRP filled column, 154% in three-layer CFRP filled column, 45% in one-layer GFRP filled column, 79% in two-layer GFRP filled column, and 144% in three-layer GFRP filled column. The ultimate strength of the beams with flexural-shear strengthening was higher than other beams. Also, the increased percentage of fiber resulted in the increased speed of ultrasonic waves.

Keywords: GFRP, CFRP, FRP, flexural strength, shear strength, hollow column, filled column

1. Introduction

In the modern age, strengthening the main structural elements is crucially important because the restoration of deteriorated structures would impose huge cost. With the emergence of FRP materials and powerful epoxy resins, a modern strengthening method has been introduced in response to the growing need for repairing and strengthening steel and concrete structures [Klees, M. 2004; Arduini, M., & Nanni, A. 1997; Barros, J. A., & Sena-Cruz, J. 2002; Wambold, J. C., Henry, J. J., & Hegmon, R. R. 1982; Abu-Tair, A. I., Lavery, D., Nadjai, A., Rigden, S. R., & Ahmed, T. M. A. 2000]. FRP sheet may be adhered to tension side of concrete beam to provide additional reinforcement. This sheet increases beam performance under service loads, reduces the displacements and cracks, and increases ultimate flexural strength [Talbot, C., Pigeon, M., Beaupré, D., & Morgan, D. R. (1995); Gao, B., Kim, J. K., & Leung, C. K. (2004);

Ueda, T., & Dai, J. (2005); Benyoucef, S., Tounsi, A., Bedia, E. A., & Meftah, S. A. (2007); Kang, T. H. K., Howell, J., Kim, S., & Lee, D. J. (2012)].

Since the early 1990s, a lot of studies have been done about the structural behavior of FRP-reinforced beams under ultimate conditions. These studies indicate that while composite materials can be successfully used during strengthening operations, some failures occur in the majority of such structures before reaching the ultimate capacity determined for the structure. Such failure, called premature failure, may limit the advantages of this method and lead to disastrous events [Naderi, M. (2011)]. There are three materials (FRP, glue and concrete) and two interfaces (FRP/glue and concrete/glue) in the bond between FRP and concrete. The failure may occur in the materials or in the interfaces. Seven failures have been identified in FRP-reinforced beams: FRP sheet fracture, concrete crushing under pressure, shear failure, concrete cover fracture, detachment of the end of FRP sheet at FRP-concrete interface, and development of flexural or flexural-shear crack at the middle of the beam [ASTM, C. (2005); Seo, S. Y., Feo, L., & Hui, D. (2013); Yuan, H., Lu, X., Hui, D., & Feo, L. (2012); Chen, D., & El-Hacha, R. (2013); Correia, J. R., Branco, F. A., & Ferreira, J. (2009); Neagoe, C. A., & Gil, L. (2014)]. The most common types are concrete cover fracture and concrete-FRP interface detachment. Premature failures mainly start with the development of flexural and shear cracks. The detachment proceeds further due to concentration of stress at the end of FRP sheet or in the area between FRP sheet and flexural reinforcements inside the concrete [Sekijima, K., Ogisako, E., Miyata, K., & Hayashi, K. (2001)]. These failures mainly occur due to concentration of shear and normal stresses of concrete-FRP interface at the points of FRP fracture and flexural cracks along the beam. Since the premature failure prevents an element from reaching its ultimate capacity and reduces ductility, it is essential to predict the ultimate load at the moment of premature failure [Mendes, P. J., Barros, J. A., Sena-Cruz, J. M., & Taheri, M. (2011); Mutsuyoshi, H., Shiroki, K., Hai, N. D., & Ishihama, T. (2011); Gonilha, J. A., Correia, J. R., & Branco, F. A. (2014); Correia, J. R., Branco, F. A., & Ferreira, J. G. (2007); Dalalbashi, A., Eslami, A., & Ronagh, H. R. (2012); Belarbi, A. (2011)].

While researchers have suggested the use of bracing systems to prevent the detachment of FRP sheet and the use of furrowing methods (external reinforcement by longitudinal furrows, EBROG) to postpone the failure, such methods are not still used in structures [Saraswathy, M. T., & Dhanalakshmi, M. K. (2014); Ronagh, H. R., & Eslami, A. (2013); Sen, T., & Reddy, H. J. (2013); Hamid, N. A. A., Thamrin, R., & Ibrahim, A. (2013); El-Nemr, A., Ahmed, E. A., & Benmokrane, B. (2013); Safan, M. A. (2013); Belarbi, A., & Acun, B. (2013); Attari, N., Amziane, S., & Chemrouk, M. (2012); Parikh, K., & Modhera, C. D. (2012); El Maaddawy, T., Soudki, K., & Topper, T. (2005)]. Furthermore, a considerable cost would be imposed if an optimal way is not determined for the use of FRP. The prediction of premature failure requires a good understanding of detachment process. Studies indicate that the strength of adhesive in FRP-concrete interface is one of the important factors in the behavior of reinforced structures. Therefore, a series of laboratorial studies have been done about the behavior of bond layer using a combination of tests such as shear tests, double shear tests and modified beams [Chen, G. M., Teng, J. G., & Chen, J. F. (2012); Antonopoulos, C. P., & Triantafillou, T. C. (2003); Chitsazan, I., Kobraei, M., Jumaat, M. Z., & Shafigh, P. (2010); Tavares, D. H., Giongo, J. S., & Paultre, P. (2008); Esfahani, M. R., Kianoush, M. R., & Tajari, A. R. (2007); Barros, J. A., & Fortes, A. S. (2005); Systèmes, D. (2011)]. In the recent years, some researchers have focused on adhesive layer modeling. They have defined the mechanical behavior of adhesive layer in a linear elastic form in order to simulate the behavior of FRP-concrete interface. The disadvantage of this method is the lack of a parameter for the failure of adhesive layer [Hu, H. T., Lin, F. M., & Jan, Y. Y. (2004); Almusallam, T. H., & Al-Salloum, Y. A. (2005); Pendhari, S. S., Kant, T., & Desai, Y. M. (2008); Bakis, C. E., Ganjehlou, A., Kachlakev, D. I., Schupack, M., Balaguru, P. N., Gee, D. J., ... & Kliger, H. S. (2002)]. This paper aims to compare the efficiency of CFRP and GFRP in the improvement of compressive strength, acoustic impedance and bracing of concrete filled and hollow columns in different layers and ages.

2. Method

First, we prepared the surface of element for FRP composite bonding. As the bond between FRP and element was vital to the final result, we exercised sufficient care in this step. Surface preparation included the removal of additional materials such as cement juice and chemicals from the surface and polishing the surface by a polisher so that the roughness reached below 1 mm. Finally, FRP was mounted on beam surface in laboratorial temperature (20°C) by epoxy resin.

Considering the limited laboratorial equipment, we selected a few beams with the length of 1.2m and cross section of 10m as our samples, in which a Ø10 bar was used to strengthen the tensile part, a 1Ø8 bar was used to strengthen the compressive part, and a Ø6 reinforcement was used as collar. We continued loading with a fixed speed until beam destruction and recorded the results in the form of force-displacement curve. The displacement was measured using the strain gauge with the accuracy of 0.001 at the middle of the beam. FRP fabrics with the width of 10 cm and length of 90 cm were installed 5 cm away from the support. Before loading, the samples were kept in laboratorial environment for one week. The concrete had a compressive strength of 25mpa and the steel has a failure resistance of 400mpa. The elasticity modulus ($^{KN}/_{mm^2}$) was 240 for carbon and 70 for glass. Thickness (mm) was 175 for carbon and 17 for glass. Ultimate strain was 1.50 for carbon and 3.2 for glass. Tensile strength ($^{N}/_{mm^2}$) was 3650 for carbon and 2280 for glass. Special weight ($^{g}/_{m^2}$) was 290 for carbon and 425 for glass. All beams were designed in accordance with ABA standards and in compliance with minimum and maximum reinforcement in beam.

The beams were made by concrete mixture with water-to-cement ratio of 0.50, using coarse aggregates with maximum grain size of 16 mm and sand with fineness modulus of 209 based on ASTM standard. After 24 hours, the beams were demolded and processed in water tank for 28 days. The non-reinforced beam, called R, was set as the reference sample. This sample was reinforced by only putting steel inside the beam. In order to study CFRP, we used three beams with 1-3 carbon layers with a thickness of 0.0165 mm. For the purpose of GFRP, we used three beams with 1-3 glass fiber layers with a thickness of 0.0165 mm. In addition to beams with unbraced ends, another group of beams were braced by glass fiber with the size of 15*25cm in *u* form. This group of beams are marked E (Table 1).

Hollow and filled columns were made by concrete mixture using Abadeh type 2 cement, washed sand and pea gravel with the strength of 20mpa. The small-sized cylindrical columns had the height of 30 cm and diameter of 15 mm. All samples were processed in steam bath for 28 days. After the samples dried, we filled the corrosions by a special epoxy resin and leveled the surfaces of all samples. In each group of seven samples, one was set as control sample, three were wrapped in CFRP and three were wrapped in GFRP with one, two and three layers.

Ultrasonic wave test was carried out using Pandit device based on 83-597ASTM C on cubic samples in the ages of 3, 7, 14, 28, 42 and 90 days. We performed this test to determine ultrasonic wave speed passing the concrete and depict compressive strength-wave speed correlation curve.

Table 1. Abbreviations of samples

No	Symbol	Description
1	R	Reference beam
2	C_L_1	Single-layer CFRP cover
3	C_L_2	Two-layer CFRP cover
4	C_L_3	Three-layer CFRP cover
5	G_L_1	Single-layer GFRP cover
6	G_L_2	Two-layer GFRP cover
7	G_L_3	Three-layer GFRP cover
8	$C\_L_1\_E$	Single-layer CFRP cover with end brace
9	$C\_L_2\_E$	Two-layer CFRP cover with end brace
10	$C\_L_3\_E$	Three-layer CFRP cover with end brace
11	$G\_L_1\_E$	Single-layer GFRP cover with end brace
12	$G\_L_2\_E$	Two-layer GFRP cover with end brace
13	$G\_L_3\_E$	Three-layer GFRP cover with end brace
14	$C\_L_{1\_}EM$	Single-layer CFRP cover – hollow column
15	$C\_L_{2\_}EM$	Two-layer CFRP cover – hollow column
16	$C\_L_{3\_}EM$	Three-layer CFRP cover – hollow column
17	$G\_L_{1\_}EM$	Single-layer GFRP cover – hollow column
18	$G\_L_{2\_}EM$	Two-layer GFRP cover – hollow column
19	$G\_L_{3\_}EM$	Three-layer GFRP cover – hollow column
20	$C\_L_{1\_}FF$	Single-layer CFRP cover – filled column
21	$C\_L_{2\_}FF$	Two-layer CFRP cover – filled column
22	$C\_L_{3\_}FF$	Three-layer CFRP cover – filled column
23	$G\_L_{1\_}FF$	Single-layer GFRP cover – filled column
24	$G\_L_{2\_}FF$	Two-layer GFRP cover – filled column
25	$G\_L_{3\_}FF$	Three-layer GFRP cover – filled column

3. Results

We used two strain gauges at the middle of the beam and force point to investigate the flexural behavior of the beam. The displacement at each of these points was measured using strain gauges with accuracy of 0.001in and the behavior of other beams was evaluated in comparison with the reference beam. Figure 1-3 illustrates the flexural strength, Percentage of increased flexural strength and Ultimate creep of reinforced samples compared to the reference beam.

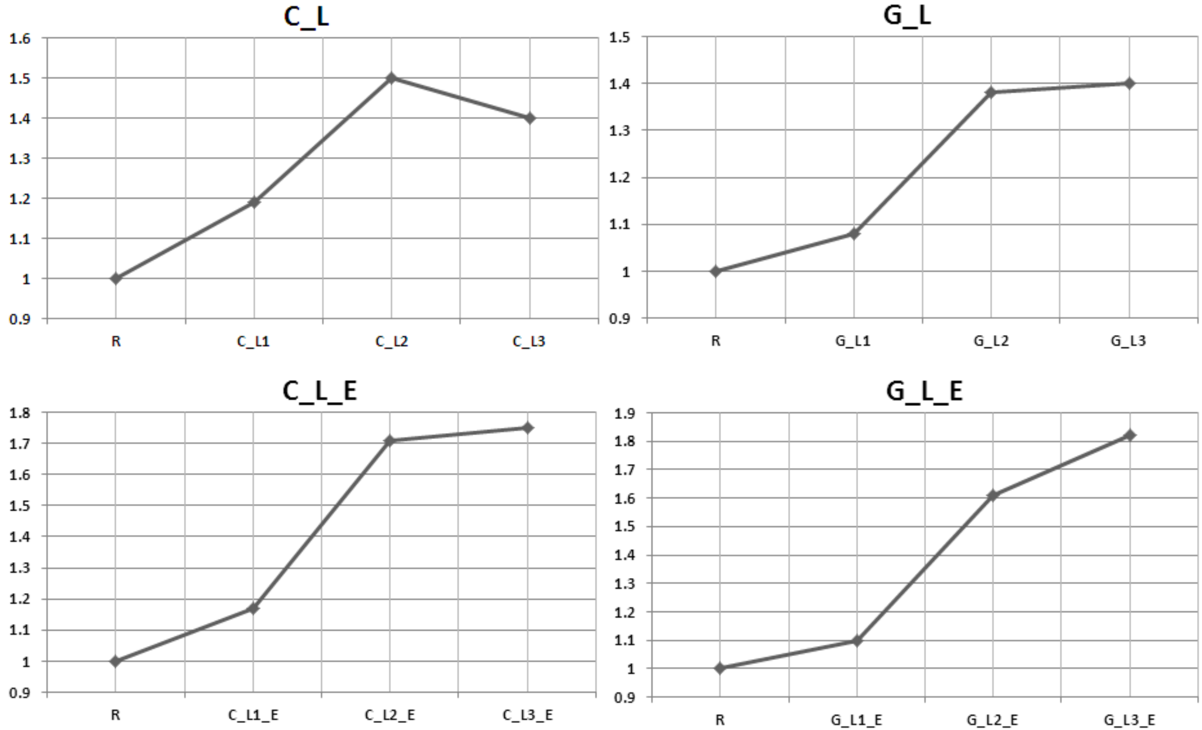

Figure 1. Flexural Strength

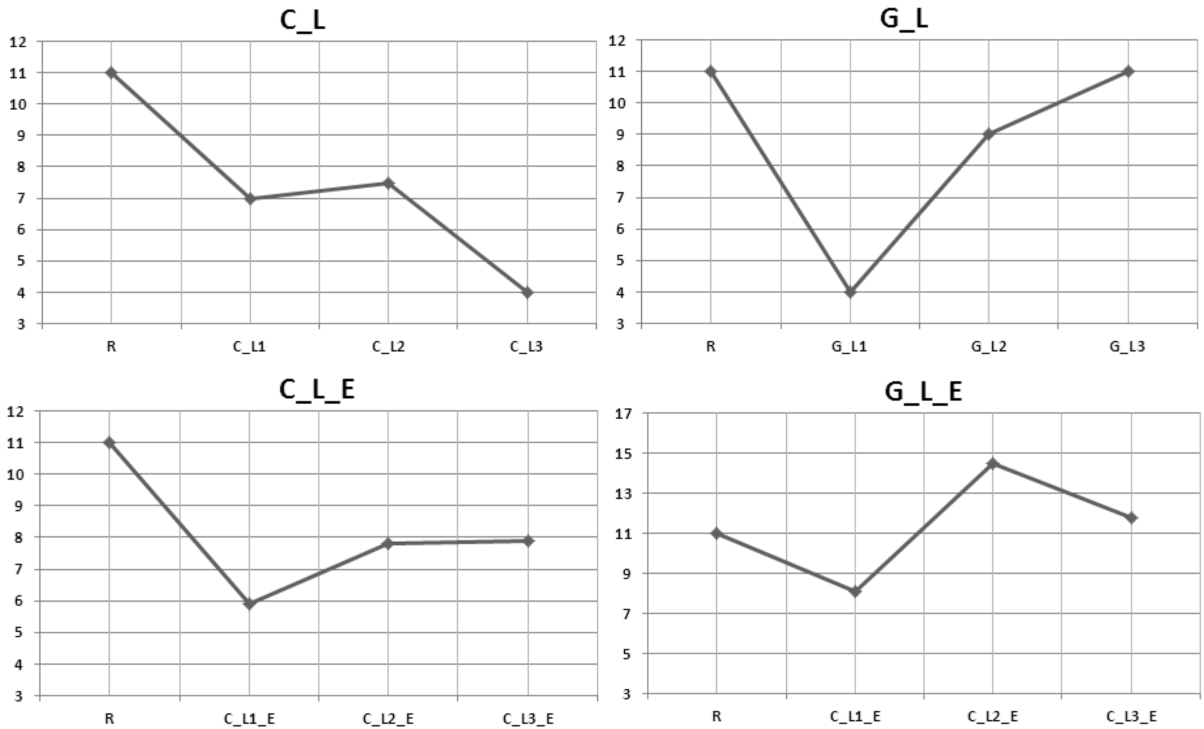

Figure 2. Ultimate creep

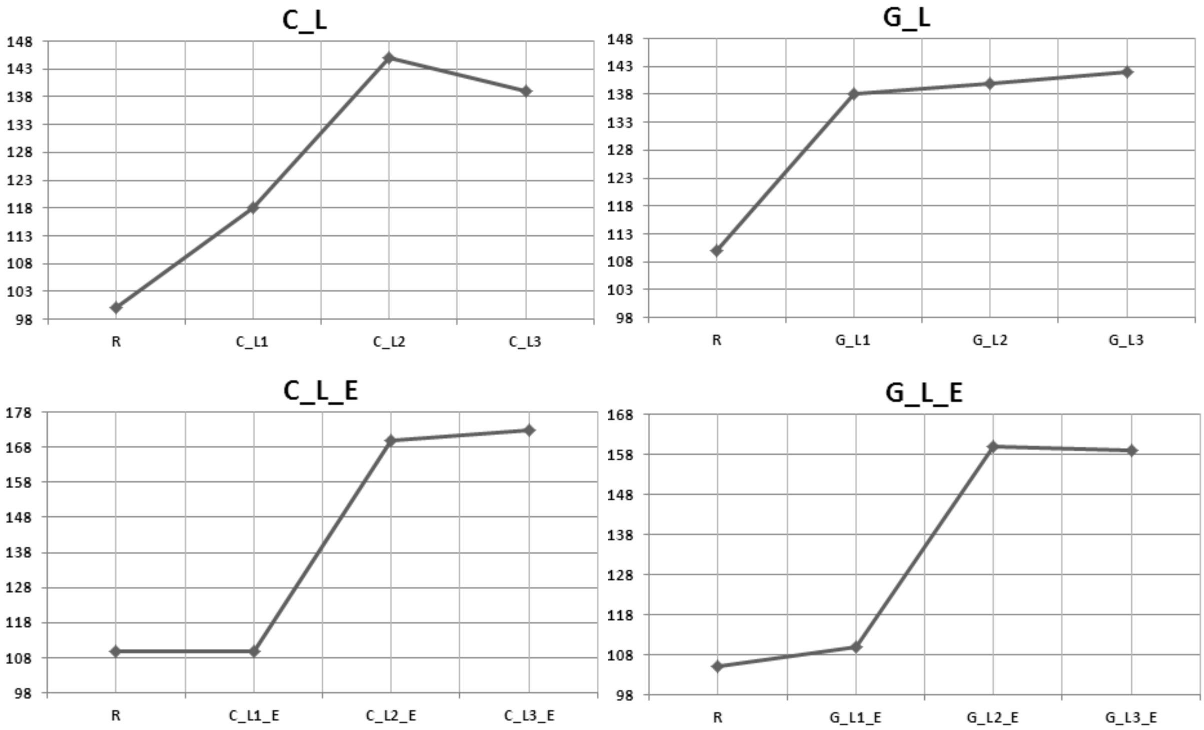

Figure 3. Percentage of increased flexural strength

We compared the computational results mentioned in the directive with laboratorial results. The results indicated a difference in some of the samples, particularly those reinforced by glass fiber. This difference may be explained by the fact that the directive uses carbon fiber rather than glass fiber in flexural strengthening.

As you can see in Figures 1-3, the highest load bearing capacity belongs to three-layer GFRP sample (83KN.m), which means 72% increase compared to the reference beam. The ultimate creep of this sample is 7.495 mm. The lowest load bearing capacity belongs to single-layer GFRP sample (49.5 KN.m). The highest ductility belongs to three-layer GFRP sample (11.684mm) and the lowest ductility belongs to three-layer CFRP sample (4.14mm).

The use of CFRP sheets increased the flexural capacity of the beams. The increased number of FRP layers led to the increased flexural capacity (15.5% for one layer, 46.6% for two layers, and 38.86% for three layers). As you can see, the increased thickness of layers positively affects the flexural capacity up to a certain point. After a specific limit, the increased thickness does not affect the flexural capacity. The increased flexural capacity depends on the increased number of layers and there is not an optimal value for the number of layers. Also, the increased flexural capacity is accompanied with the reduced ductility of the beams.

No one of the samples underwent FRP failure. In all cases, detachment of concrete cover at the end of FRP system was the main cause of failure, which indicated that the entire capacity of fiber had not been used and that the system had a high tensile capacity. Therefore, if properly used, this system may be a good restorative material. Also, there is not any sign of warning crack in the system, so sufficient care must be exercised when using this system. Moreover, shear failure of the beam under the increased load should be taken into consideration (Figure 4).

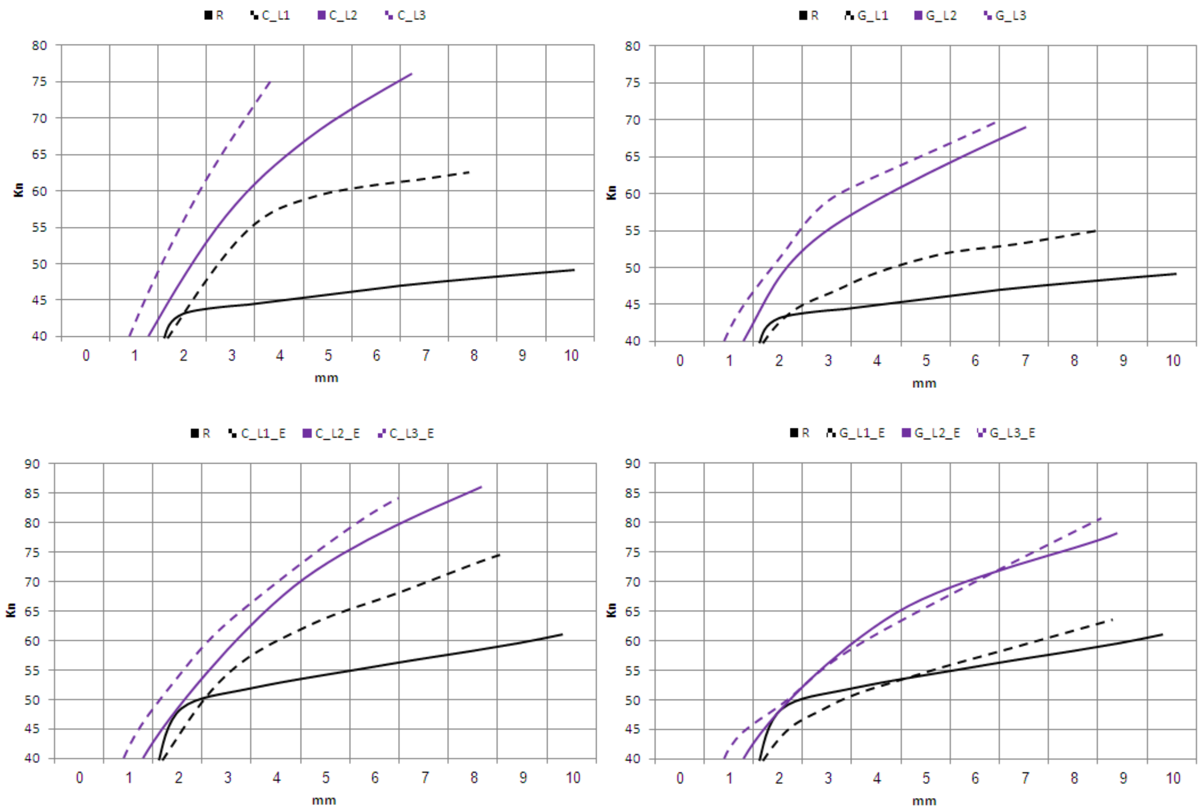

Figure 4. Force-displacement diagram

As you can see in Figure 4, the increased thickness of layers has led to the increased stiffness of the samples. The failure in all four samples was due to lamination at the end of FRP, which is explained by the concentrated stress at the end of fiber.

In CFRP samples, the concurrent existence of FRP sheets in the tensile area of the beam and U-shaped wrap of FRP sheet at the end of tensile area positively affected the flexural behavior and ductility of the beams. FRP wraps prevented the deepening of cracks in shear stress area (Figure 1), as the result of which no lamination occurred at the end of fibers. Therefore, load bearing capacity of the beams increased and the capacity of FRP sheet was optimally used.

In GFRP samples, likewise, the end of FRP sheet was braced by glass fiber, with the only difference that carbon was used instead of glass fiber for the purpose of flexural strengthening. Since glass fiber had higher strain than carbon fiber, GFRP samples had more ductility than CFRP samples. In many cases, the ultimate ductility of GFRP samples even surpassed that of control beam (Figure 1-3).

Since the end of fiber had been braced, load bearing capacity of the samples increased considerably, with three-layer sample having the highest displacement (which even exceeded the reference beam). There was FRP failure in one-layer GFRP samples. In other two samples, detachment of glass fiber and concrete cover was the main cause of failure. In the final steps of loading, the force in tensile part of the beam was borne only by the fiber, with concrete playing no role in practice. Finally, beam failure was due to U brace failure.

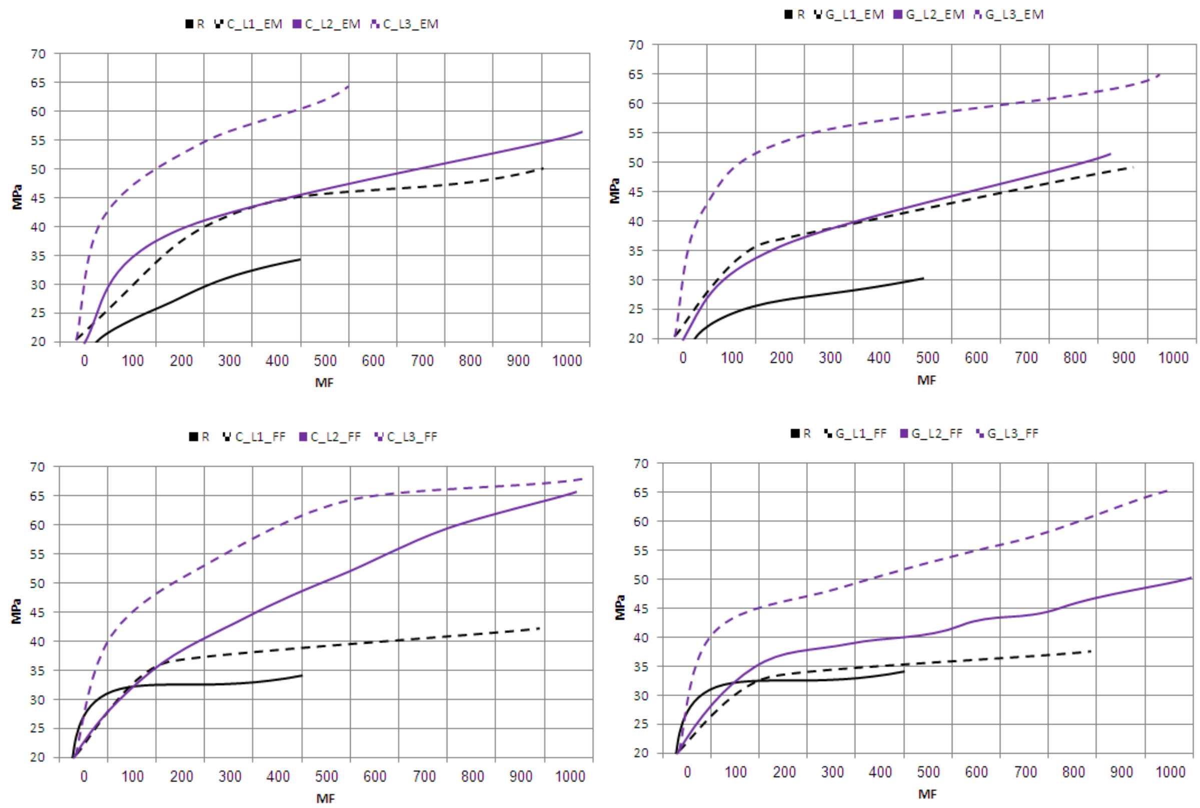

Figure 5. Lateral stress-strain diagram for cylindrical columns

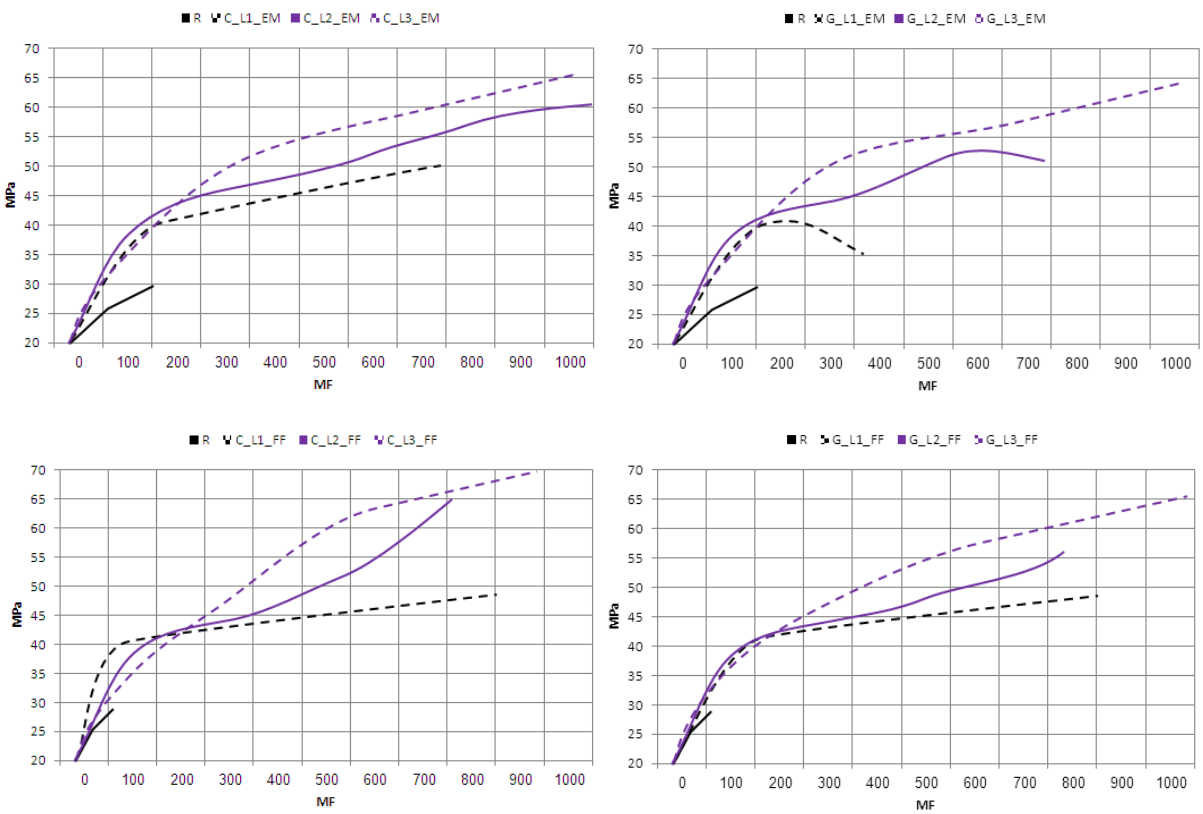

Figure 6. Axial stress-strain diagram for hollow cylindrical columns

As you can see in Figures 5 and 6, FRP has increased the strength and ductility of all samples. The columns wrapped in CFRP have higher compressive strength, ductility and axial and lateral stiffness compared to GFRP samples. The compressive strength increased by 66% in one-layer CFRP hollow column, 96% in two-layer CFRP hollow column, and 123% in three-layer CFRP hollow column, 36% in one-layer GFRP hollow column, 63% in two-layer GFRP hollow column, 105% in three-layer CFRP hollow column, 71% in one-layer CFRP filled column, 138% in two-layer CFRP filled column, 154% in three-layer CFRP filled columns, 45% in one-layer GFRP filled column, 79% in two-layer GFRP filled column, and 144% in three-layer GFRP filled column.

Generally, fiber wrap had a higher impact on hollow columns than on filled columns. Yet this impact was considerable in hollow columns as well. Moreover, CFRP was more effective than GFRP. The results of flexural-shear strength tests indicated the increased ultimate strength and stiffness of the reinforced beams compared to the reference beam and the reduced ductility of the reinforced beams.

The failure in all of the reinforced beams was of shear type. CFRP beams showed higher ultimate strength but lower ductility compared to other beams. The ultimate strength of the beams with flexural-shear strengthening was higher than other beams. Index 1 means flexural strength and index 2 means flexural-shear strength (Figure 7).

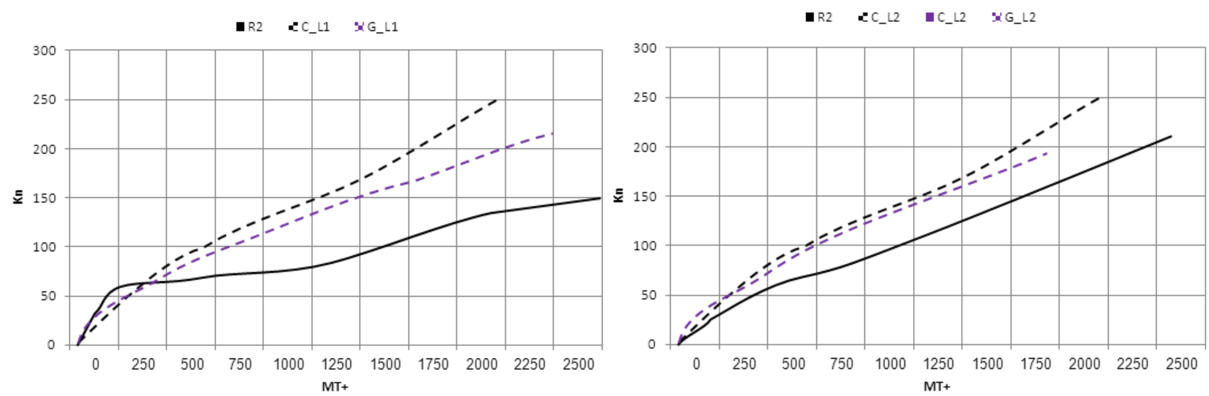

Figure 7. Tensile load-strain diagram

Figure 8 illustrates the results obtained from ultrasonic test after conversion to pulse speed unit (m/s). As you can see, ultrasonic wave speed has increased in all samples as the result of the increased age. In all ages, the increased fiber has led to the increased speed of the waves passing the concrete. The major part of speed growth occurred in the ages of 3-14 days, followed by a gradual decline in speed growth.

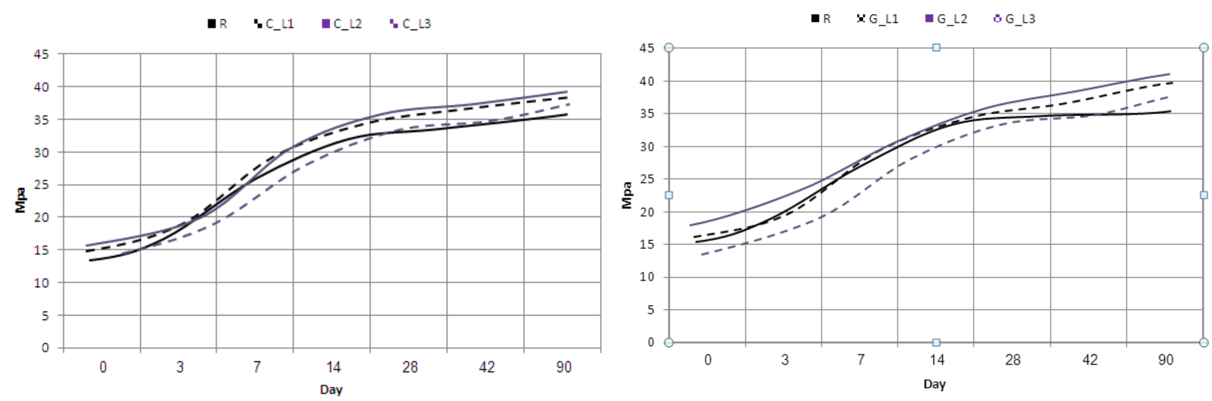

Figure 8. Ultrasonic waves passing the concrete

4. Conclusion

FRP method increased the flexural strength of the beams. The samples with FRP sheets and end brace showed a higher load bearing capacity compared to those without a brace. A disadvantage of this system is lamination of layers, which can be prevented by various methods such as fiber brace and electronic brace. The increased thickness of the layers resulted in the increased load bearing capacity of the beams up to a specific limit, so there is an optimal point for the thickness of layers. The use of glass fiber increased load bearing capacity and the creep of the beams. In some cases, the creep of the reinforced beams even exceeded the control beam.

In this laboratorial study, we tested 14 hollow and filled columns using concrete mixture with the strength of 20mpa. The results indicated that FRP sheet increased the compressive strength and ductility of the column. Generally, fiber wrap had a higher impact on filled columns than on hollow columns. Yet this impact was considerable in hollow columns as well. Moreover, CFRP was more effective than GFRP.

When the concentrated stress at the end of fiber reached the maximum point, the fiber detached from concrete at the area of tensile reinforcement. To prevent this, the end part of the fiber had to be far enough from the area of tensile reinforcement. This was done by sticking a U-shaped brace at the end of fiber.

In all samples, the increased age resulted in the increased speed of ultrasonic waves. Also, the increased percentage of fiber resulted in the increased speed of ultrasonic waves in all ages compared to control sample. The highest speed growth occurred in the ages of 3-28 days, followed by a gradual decline in speed growth. The highest speed growth in the ages of 3-90 days belonged to G1sample (14% growth in ultrasonic wave speed). In all samples, the increased compressive strength resulted in the increased speed of ultrasonic waves. The relationship between these two variables was linear.

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