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An Economic Approach to the Confinement of Different Concrete Classes with Carbon and Glass Fibers Reinforced Polymers

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ABSTRACT

One of the current approaches for concrete retrofitting is called fiber reinforced polymer (FRP) wrapping. In this study, concrete retrofitting means compressive strength and seismic parameters improvement (such as failure strain, energy absorption, and ductility). Cost analysis may raise issues of concern regarding the economic value of this kind of retrofitting and for this reason, economic analysis was conducted based on experimental works. In this regard, 21 samples were prepared for three compressive strengths of concrete (20, 35, and 50MPa) and warped with different layers of carbon and glass fiber reinforced polymers (0, 1, 3, and 5 layers). Samples were subjected to stress-strain tests and concrete properties were estimated. The results showed that carbon and glass fibers, respectively, are more effective in improving the compressive strength and seismic parameters of concrete. But, the economic analysis indicated that glass fiber is more cost-benefit than carbon fiber in improving the concrete properties, especially for one layer of FRP. The economic analysis was not able to specify the application of FRP for which concrete samples are more economical, and for this reason, statistical analysis was used to respond to this vague and achieve a comprehensive assessment. The analysis indicated that the use of FRP is more cost-benefit for lower concrete strength.

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1. INTRODUCTION

Study shows rehabilitation of structure is often a more practical and cost-effective choice in comparison to reconstruction for reducing seismic vulnerability. There are several techniques for retrofitting of older or damaged buildings such as the addition of a shear wall, steel bracing, steel jacketing, and fiber reinforced polymer (FRP). These techniques can reduce lateral deflections due to stiffen or strengthen of the structure, in addition, they prevent the brittle failure modes of structure through the increase of ductility.

1. 1. Fiber Reinforced Polymer (FRP) This research overviews the FRP application in structural retrofitting. FRP is composed of polymer matrix and fiber. The most common fiber reinforced polymers are carbon and glass, which they called CFRP and GFRP, respectively [1, 2]. FRP advantages include fatigue resistance, low chemical reactivity, ease of application, and formation in various shapes. Besides, FRP has higher tensile strength and is lighter in weight in comparison to steel plate but, high expenditure and inadequate fire-protection are expressed as the most disadvantages of FRP [3, 4].

1. 2. Concrete Confined by FRP This section discusses the advantages of wrapping FRP in the strengthening concrete samples. As a solution to the seismic retrofitting issue, concrete is confined by FRP in the non-linear section of the structural element to increase compressive strength and ductility also, prevent bond slip and buckling of longitudinal reinforcement [3]. Regarding this issue, numerous experimental studies were carried out which confirm the validity of the solution. Youssf et al. [5] studied the capability of FRP

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confinement on improving concrete behavior. The results were based on the stress-strain test. They demonstrated that the effect of confinement can be strongly improved if a corner of the rectangular column section is circularized. Zeng et al. [6] conducted semilar research and confirmed the results obtained by Youssf et al. [5]. Taghia et al. [7] investigated the performance of FRP wraps in improving the mechanical and seismic properties of concrete classes. They figure out that FRP is more effective in developing the performance of low-strength concrete and also the growth rate of improvement declined by increasing the FRP layers. Sirach et al. [8] surveyed the effect of high-strain FRP wrapping on the behavior of high- and ultrahigh-strength concrete. They included three parameters in the study such as fiber type, concrete strength, and fiber thickness, and specified the role of these parameters on stress-strain behavior.

Studies illustrated that confinement provides noticeable increases in the final stress and strain of concrete [9-11].

Many researchers underlined the importance of the establishment of appropriate constitutive laws for confined concrete by FRP [4, 12].

Although, FRP contributes to the strength of the structure, but it can be costly for the structural retrofitting in comparison to other solutions (see section “1.1. Fiber Reinforced Polymer (FRP)”), therefore from a practical point of view, an economic analysis should be considered too.

1. 3. Cost-benefit Assessment Cost-benefit analysis is conducted to assess the efficiency of FRP application as a solution for structural retrofitting regarding financial considerations [13]. In this way, several researchers performed different types of assessments. Shapira et al. [14] achieved economic and constructability analyses of FRP cages used for strengthening of concrete beams. Although FRP is more expensive than steel reinforcement, in total, analyses revealed that FRP cages are more economical. Sahirman et al. [15] compared the application of FRP with steel reinforced concrete (SRC) for retrofitting of bridges. They improved a curve theory to estimate future costs of bridges. Based on the analysis of two data sets, their study proved that FRP application is more cost-beneficial than SRC for a period of 10 years. Berg et al. [16] conducted a cost-benefit analysis of concrete bridges in which FRP was applied for rehabilitation. The investigation demonstrated that FRP application reduces construction time and maintenance costs and increases concrete durability. Brayack [17] studied the technical and economic adequacy of FRP for retrofitting of concrete bridges. A cost-benefit analysis was performed to weight retrofitting with FRP and traditional methods. Based on some examples, it has been concluded that FRP is a cost-effective strategy and can be replaced by the traditional methods. Yan et al. [18] implemented technical and economic analyses regarding the strengthening of the substation framework. They analyzed the economic aspects of two-span FRP and steel gantries and concluded that FRP application can reduce the total cost by 10%. As an economic solution for pipeline retrofitting with FRPs (carbon and glass fabrics), Sever and Ehsani [19] proposed an optimal design procedure. Chen et al. [20] studied the interply hybridization’s effects of carbon, glass, and basalt fibers to enhance their flexural behavior and economic efficiency. They simultaneously applied the experiments and numerical simulation in their study. Investigations indicated higher efficiency for glass/carbon fibers regarding strength/cost and modulus/cost ratios. The results indicated that glass fiber demonstrates better behavior with reference to basalt fiber. Rodsin et al. [21] used accessible and inexpensive GFRP for concrete confinement and concluded that GFRP is very economical in order to improve compressive strength and ductility. It can be attributed to the improvement of stress and strain of wrapping concrete. Taghia et al. [22] compared the application of carbon and glass fiber wrappings on enhancing the mechanical properties and seismic parameters. They found that the carbon and glass fibers are more effective in improving compressive strength and seismic behavior respectively. seismic parameters consisted of failure strain, energy absorption, and ductility in their study. Shubhalakshmi et al. [23] conducted an economic analysis in the application of FRP wrapping used in strengthening of concrete slabs. The analysis was estimated according to the price of the material, wrapped area, and strength gained. They found that this technique can increase the bearing capacity of slabs by 6%. El Youbi et al. [24] performed a numerical simulation to estimate the effect of the CFRP warping on the compressive strength and the final strain of reinforced concrete. They developed a FE model associated with the parametric study to assess the impact of different layers of FRP. They indicated that CFRP has a noticeable impact on the ultimate load of eccentrically loaded columns relative to concentrically loaded ones. Salahaldin et al. [25] experimentally studied the capabilities of retrofitting of the damaged hybrid reinforced concrete beams having openings in the shear region. The research considered the difference in rehabilitation strategies of hybrid beams relative to conventional beams. They indicated that the traditional concrete beam reaches to the whole capacity for all kinds of openings. However, the hybrid beams just obtain 84% of ultimate strength.

In practical engineering, there are many structures that have low concrete strength for various reasons, and it is possible that they will not have proper seismic behavior in an earthquake and will suffer significant damage. As mentioned before, to improve the performance of concrete, one of the best solutions is concrete confinement. Today, using fibers has expanded significantly due to their excellent features. But the high price of fibers is always a deterrent factor along with all the positive features. Therefore, it is necessary to academically optimize using fibers in order to achieve the greatest improvement in the behavior of concrete at the lowest cost. This forms the main idea of current research. The study aims to evaluate the impact of glass and carbon fiber wrapping (more available in the Iranian market) on improving the compressive strength and seismic characteristics of different concrete classes from an economic point of view.

1. 4. Research Significance Simultaneous attention to the economic approach in the application of fibers along with considering their mechanical and seismic properties forms the importance of the current research. The study tries to fill the gap in previous research which mainly focused on the positive characteristics of fibers in improving the behavior of concrete and paid less attention to economic aspects in practical engineering. Another issue that highlights the importance of the current research is the use of glass and carbon fibers in a comparative manner, which in past research has often individually handled their characteristics in improving the performance of concrete. Meanwhile, there is a question about whether the concrete class is effective in the optimal selection of fibers or not. These are important issues that the current research tries to give a proper answer.

2. EXPERIMENTAL PROCEDURE

In this section, the material types, mix design, preparation, and curing are described, respectively.

2. 1. Material Types Ordinary Portland cement is used in the specimens. The samples are made according to ASTM C150 [26] standard. The gravel and sand aggregates are of river type in accordance with ASTM C33 [27] standard. The sand sizes range from 0 to 4.75 mm with an apparent weight of 2650 kg/m^3 in the Saturated Surface Dry (SSD) state with 24-hour water absorption of 1.5%, and additionally, the super-plasticizer of P10-3R type is used based on ASTM C494 [28]. CFRP and GFRP are of type YC-N160 and EVR-200, respectively. The specifications of two types of polymers, and the epoxy DUR 300 resin, are presented in Tables 1 and 2, respectively.

2. 2. Sample Preparation With a practical approach to the subject, three classes of concrete are selected which are common in construction projects in Iran (20, 35, and 50MPa). First, concrete is constructed and then inserted into pre-prepared cylindrical molds (with dimensions of 15 cm × 30 cm). They are kept in constant temperature and humidity to harden. After 24 hours, the specimens are removed from the molds and placed into a water pond at temperature of 20±2°C for curing. The curing time of the samples is equal to 28 days. Then, the samples are taken out from the pond and placed in the laboratory for drying the surface of the samples. Two days later, the concrete samples are wrapped with different numbers of layers (1, 3, and 5). Meanwhile, in order to compare the results and reach a comprehensive conclusion, a control sample without wrapping is also prepared. By taking into account different concrete classes and the number of different layers used, a total of 21 samples were prepared and, after 7 days, subjected to stress-strain tests. Tests are done in compliance with ASTM C469 [29] (see Figure 1).

In this study, Cs followed by the value mean the concrete class, and Ls followed by the value represent the number of the polymer sheet.

TABLE 1. The specifications of two types of polymers: (a) Carbon and (b) Glass

(a)

Property	Specification
Type	YC-N160
Tensile strength	4900 MPa
Elastic modulus	230 GPa
Fracture strain	2.13%
Weight per unit area	160 g/m^2
Thickness	0.09 mm

(b)

Property	Specification
Type	EWR200
Tensile strength	2200 MPa
Fracture strain	2.8 %
Weight per unit area	200 g/m^2
Moisture Content	<0.2 %

TABLE 2. Technical properties of Resin

Property	Specification
Mixing ratio	A: B = 100:34.5 by weight.
Tensile strength	Curing 7 days, +23°C: 45 N/mm^2
Flexural modulus	Curing 7 days , +23°C: 3000 N/mm^2
Tensile modulus	Curing 7 days, +23°C: 3500 N/mm^2

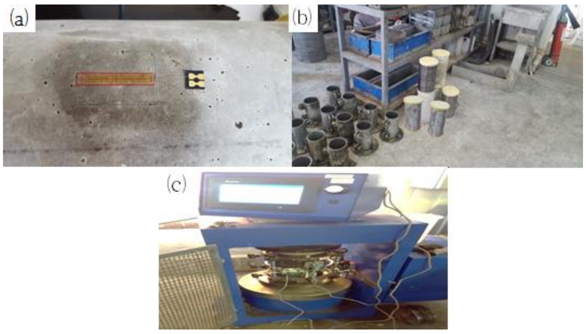


Figure 1. Preparing samples for experiments: (a) strain gauge installation; (b) FRP wrapping; (c) stress-strain device

3. EXPERIMENTAL DATA AND INTERPRETATION

To analyze the data, firstly, the effect of fiber reinforcement on characteristics of different concrete classes is investigated. Concrete characteristics include compressive strength and seismic properties of concrete (i.e. failure strain, energy absorption, and ductility). Then the cost-benefit analysis of fiber application is performed. The index in economic analyses is used to figure out the effect of FRP type, CFRP vs. GFRP, numbers of FRP layers, and compressive strength categories on the economic aspects for improving the strength and seismic properties of the concrete samples. The economic index is defined as an increase in compressive strength or seismic parameters of concrete samples strengthened with FRP wrapping divided by the expenses of strengthening these samples in Euros. The larger this index means, the greater performance improvement is achieved for a given cost of concrete wraps.

Table 3 shows the cost of CFRP and GFRP layers that are used for the wrapping of concrete samples. As it can be seen, the costs of strengthening are noticeable, therefore the number of FRP layers must be chosen, carefully.

Finally, a statistical approach is illustrated to reach a practical and comprehensive conclusion.

3. 1. The Stress-strain Experiments

Figures 2-4 illustrate stress-strain plots for three classes of concrete (i.e. C20, C35, and C50) with different numbers of FRP layers. According to ACI 440.2R reference [30], concrete loses its integrity in a longitudinal strain greater than 1% and rebar reaches the failure strain and cohesion between concrete and rebar decreases, intensively. For this reason, in the current research, the failure strain values are limited to 1% in the entire Figures 2-4.

In the following sections, economic analysis is presented with respect to sample properties.

TABLE 3. The cost of CFRP and GFRP layers used for concrete samples

CFRP cost (€)			GFRP cost (€)		
One layer	**Three layers**	**Five layers**	**One layer**	**Three layers**	**Five layers**
2.25	6.83	11.08	0.89	2.56	4.23

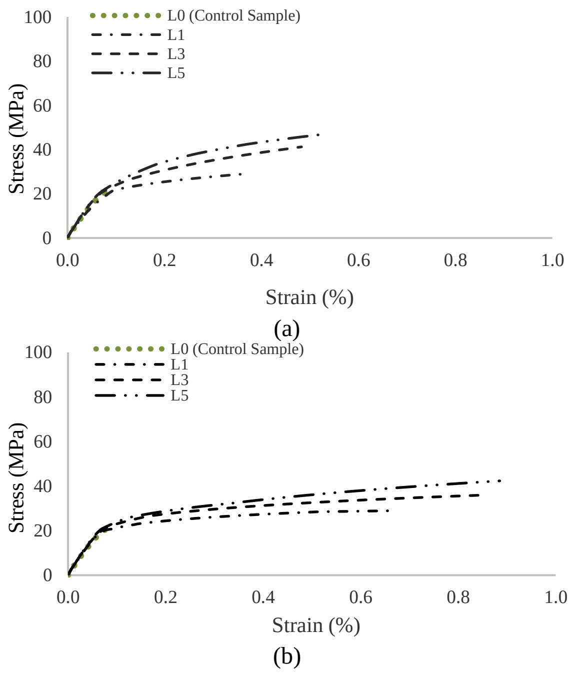


Figure 2. Stress-strain diagrams of samples for C20 class wrapped by: (a) CFRP; (b) GFRP

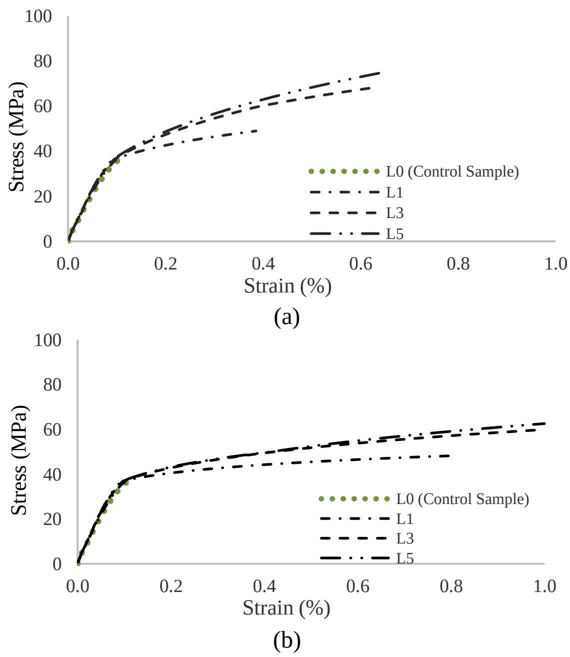
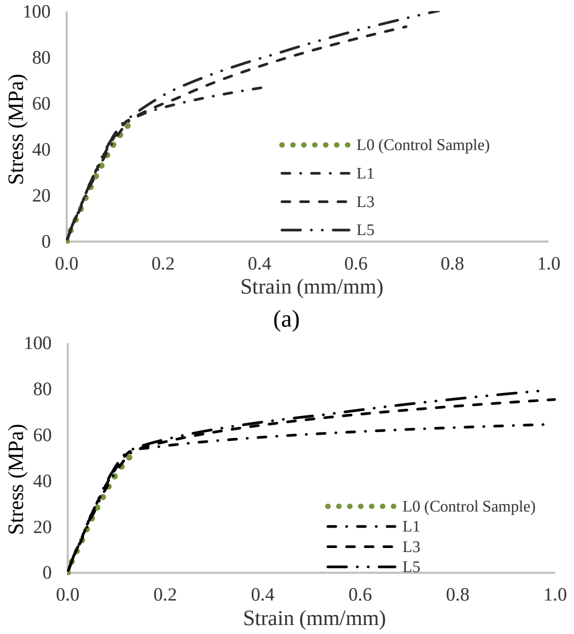


Figure 3. Stress-strain diagrams of samples for C35 class wrapped by: (a) CFRP; (b) GFRP



(b)

Figure 4. Stress-strain diagrams of samples for C50 class wrapped by: (a) CFRP; (b) GFRP

3. 1. 1. Compressive Strength In this study, the maximum values of stress in Figures 2-4 are determined and considered as compressive strength for designed samples. Figure 5 demonstrates the effects of FRP types and the number of polymer sheets on concrete strength for different concrete classes.

This figure indicates that the compressive strength of concrete samples raises with the increase of the number of FRP layers due to the development of the confinement effect, especially for higher strength concrete. Moreover, the compressive strength of samples wrapped by carbon fibers is higher than glass fibers. The reason can be attributed to the higher tensile strength of carbon fibers with respect to glass fibers (see Table 1) which provides higher lateral pressure on concrete samples wrapped by CFRP.

The economic indices are estimated for the compressive strength of samples. The results are presented in Figure 6.

The plot in Figure 6, shows that the sample with one FRP layer is more economical. The analysis shows that additional FRP layers for improving the compressive strength are unworthy in order to strengthen the samples since this will increase the cost. The plot also indicates that FRP is more economical for higher concrete strength because FRP increases the compressive strength of higher concrete classes in comparison to the lower ones. (see Figure 5). Finally, the figure demonstrates that GFRP is more economical with respect to CFRP (Almost double). This means that the application of CFRP instead of GFRP, leads to more expenses for preparing the samples and not much gain in the compressive strength of concrete.

3. 1. 2. Failure Strain In Figures 2 through 4, final strains of samples with different concrete classes and FRP layers are specified and referred to as failure strains which are reported in Figure 7.

Figure 7 also, demonstrates that the longitudinal failure strains of samples wrapped by glass fiber are higher than the corresponding samples wrapped by carbon fiber, especially for higher concrete classes. This can be attributed to the more effective role of FRP to confine higher concrete strength and also higher failure strain of GFRP with respect to CFRP. However, GFRP has lower tensile strength relative to CFRP (see Table 1), but concrete withstands higher lateral strain prior to the breaking point without losing its integrity.

The economic indices are estimated regarding failure strains for entire samples. The results are presented in Figure 8.

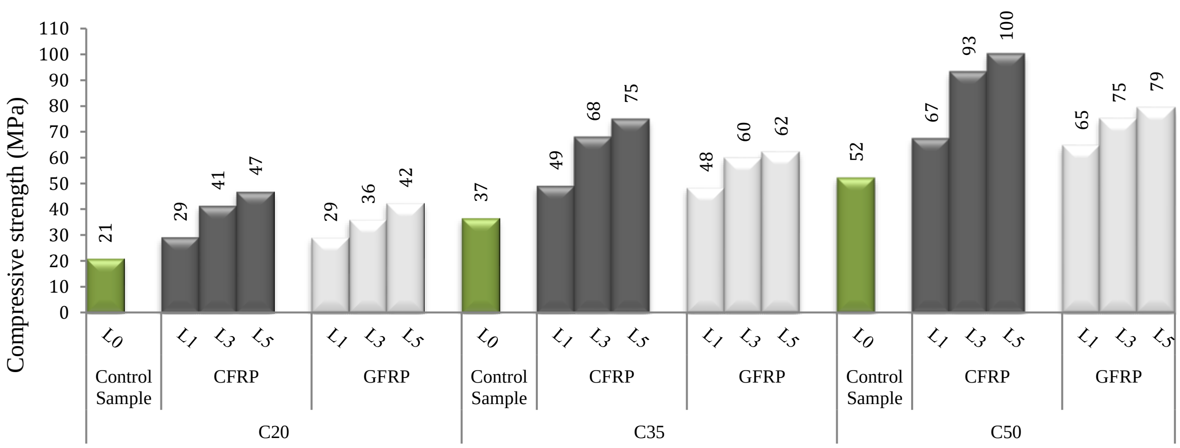


Figure 5. The values of compressive strength in the experiment

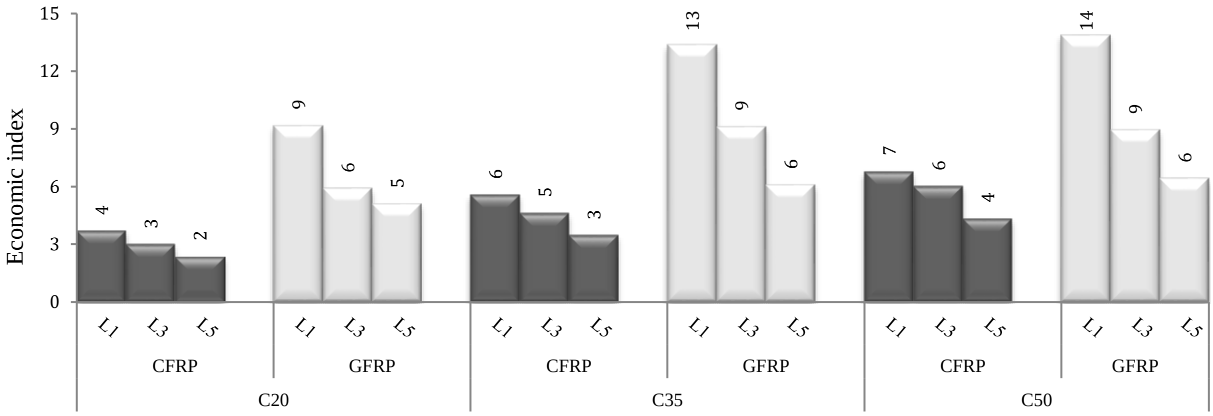


Figure 6. Economic analysis regarding compressive strength for entire samples

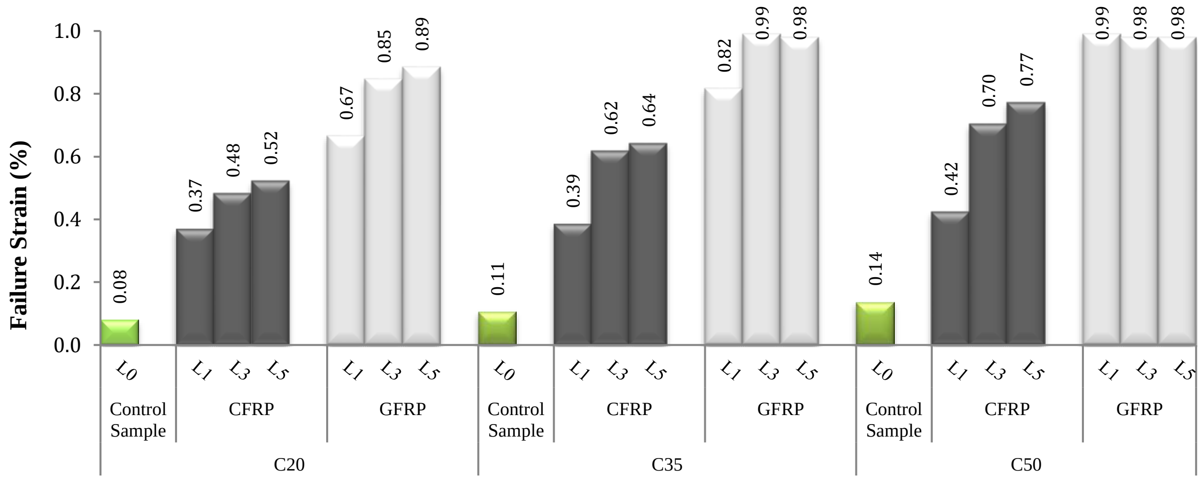


Figure 7. The values of failure strain in the experiment

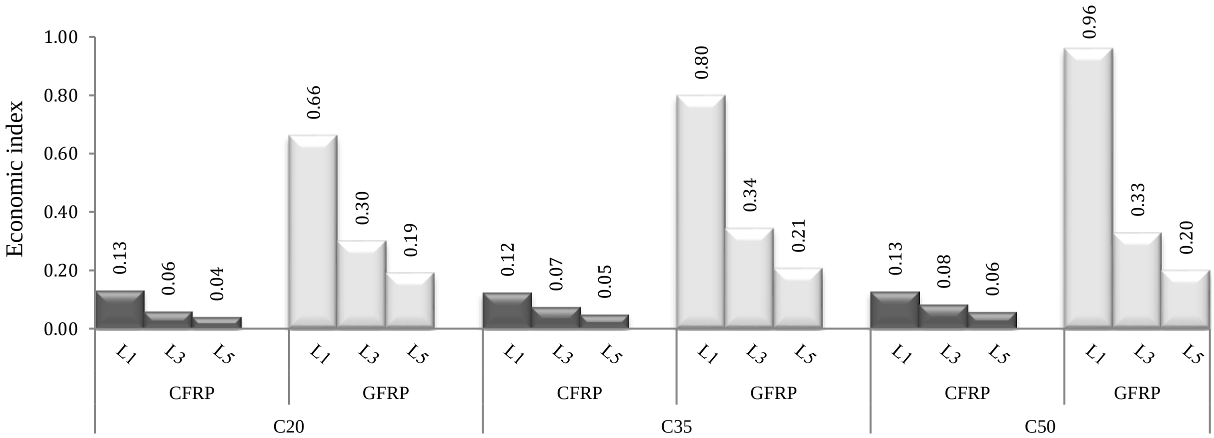


Figure 8. Economic analysis regarding failure strain for entire samples

With a similar argument stated in section "3.1.1." regarding economic analysis of compressive strength, there is more cost-benefit for one layer of GFRP, especially for higher concrete strength. This clearly reveals in Figure 8.

3. 1. 3. Energy Absorption Energy absorption can be estimated from the areas under the curves of Figures 2 through 4 up to failure strain for the entire samples. The large scale of the area indicates that more energy is absorbed. The area is calculated by applying the MATLAB program. In this process, the area of each curve is computed, individually and normalized to the area under the curve of the corresponding control sample. The normalized energy absorption of the samples is illustrated in Figure 9.

Figure 9 demonstrates that samples wrapped by GFRP have higher energy absorption than those wrapped by CFRP. The reason behind this is due to higher failure strain in glass fiber compared to carbon fiber.

The economic indices are estimated for entire samples corresponding the energy absorption, the results are shown in Figure 10.

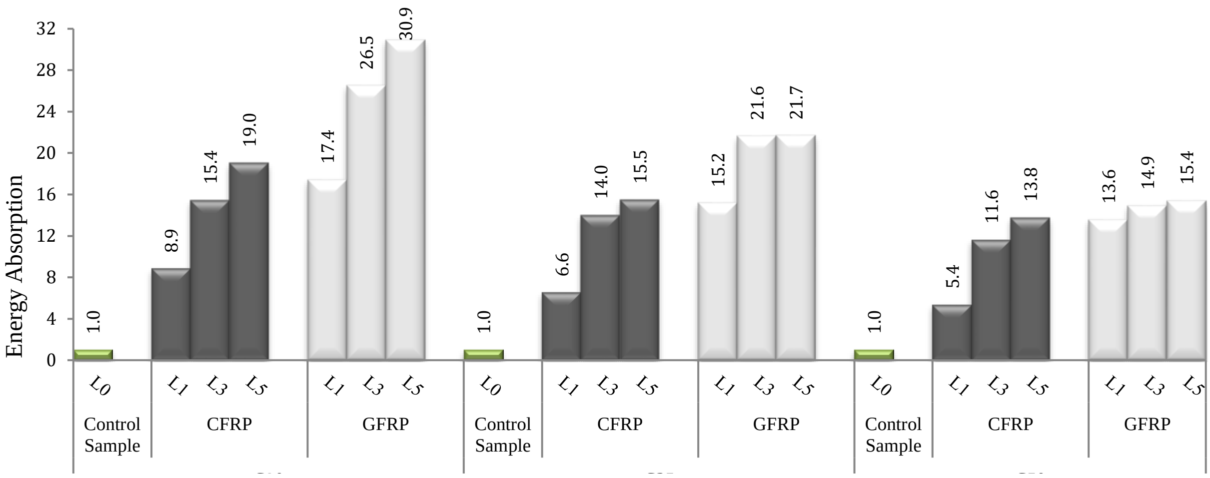


Figure 9. The values of energy absorption in the experiment

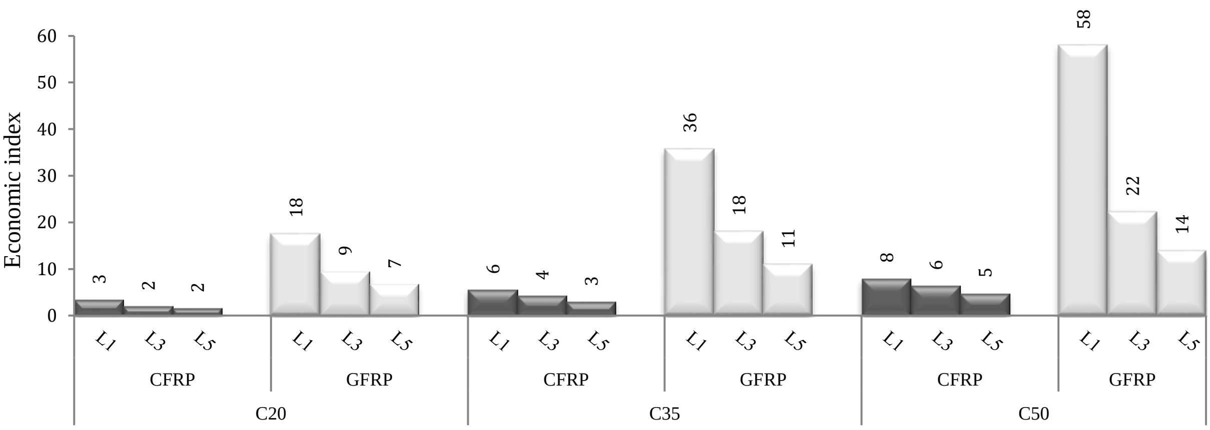


Figure 10. Economic analysis regarding energy absorption for entire samples

3. 1. 4. Ductility According to ASCE41 [31], the ductility of the samples (μ) is defined by dividing the failure strain (ε_f) over the yielding strain (ε_y). The yield strain is estimated by the following procedure: at first, the stress-strain curve of each sample is replaced by an equivalent bilinear form using MATLAB software, then the intersection of these two straight lines is introduced as the yield strain, ε_y. For instance, in Figure 11, the procedure is presented for the C20 class wrapped by three layers of GFRP (i.e. C20, GFRP-L3).

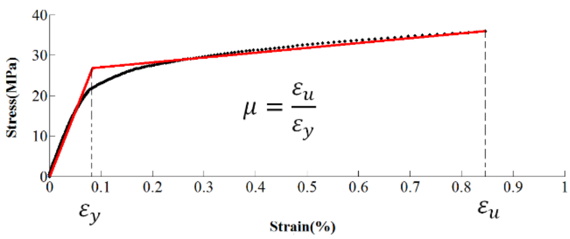


Figure 11. Ductility calculation for sample C20, GFRP-L3 using MATLAB software (2019)

The results of ductility calculation are reported in Figure 12 for the entire samples (corresponding to Figures 2 through 4).

In a similar fashion as explained in the previous section, Figure 12 reveals that the ductility in samples wrapped by GFRP is higher than those wrapped by CFRP due to the higher failure strain of glass fiber compared to carbon fiber.

The economic indices are estimated regarding ductility for entire samples. The results are illustrated in Figure 13. This figure is shown that more cost-benefit is obtained for one layer of GFRP and lower concrete classes.

Evaluation of plots in the economic analysis shown in Figures 6, 8, 10, and 13, indicates that FRP strengthening is more economical in regard to the improvement of compressive strength, failure strain, and energy absorption for higher concrete classes. In contradiction, the use of FRP is more cost-benefit regarding the improvement of ductility for lower concrete classes.

3. 2. Statistical Approach The statistical approach is needed to achieve a full-scale cost analysis of entire research.

Paired t-test in statistical approach, provides the possibility of comparing two samples in different cases in which two-sample jams are essentially reduced to a one-sample case by using the computed differences d_1, $d_2, \ldots, d_n$. Thus, the hypothesis reduces to:

$$H_0: \mu_1 - \mu_2 = d_0 \quad (1)$$

where μ_1 and μ_2 represent the population means.

H0 is rejected at significance level α when the computed t-statistic:

$$t = \frac{\bar{d} - d_0}{s_d/\sqrt{n}} \quad (2)$$

exceeds $t_{\alpha/2,n-1}$ or is less than $-t_{\alpha/2,n-1}$ (critical regions). Parameter "n" is the sample size.

$\bar{d}$ and s_d are parameters in relations (1) and (2). They represent the sample mean and standard deviation of the differences in the observations, respectively [32].

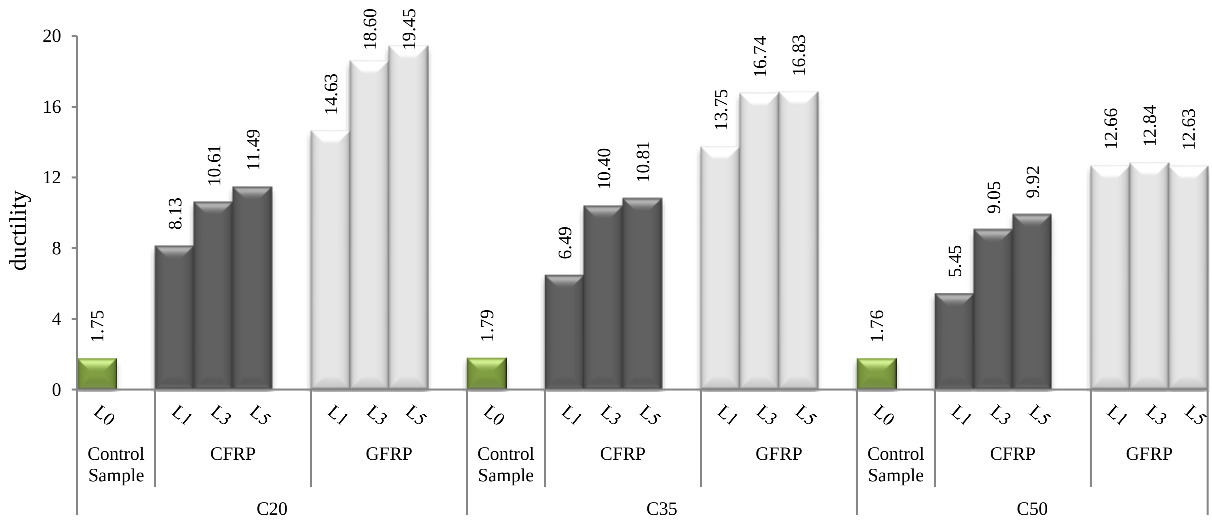


Figure 12. The values of ductility in the experiment

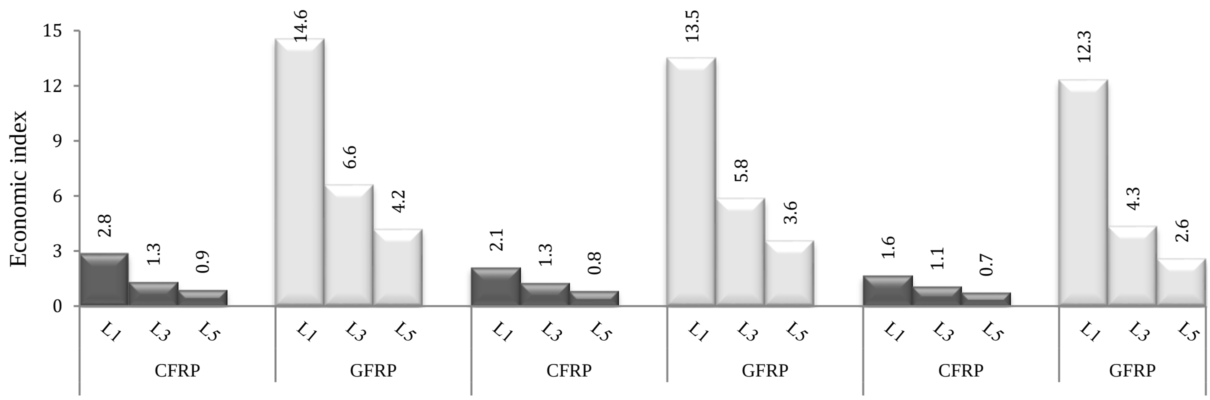


Figure 13. Economic analysis regarding ductility for entire samples

In the current study, the samples are economic indices related to concrete properties (reported in Figures 6, 8, 10, and 13), and d_0 variable, represents the improvement or decline of the index in comparison to the two samples.

Multiple comparisons of cases are conducted in the following:

Case 1: using glass fibers in comparison to carbon fibers for strengthening of concrete samples

Case 2: using different layers of FRP in comparison to one layer for wrapping of concrete samples

Case 3: strengthening of higher concrete classes in comparison to lowest concrete class by FRP wrapping

Cost-benefit analysis of the above cases is examined in the following three sections, respectively:

3. 2. 1. Case 1: Using Glass Fibers in Comparison to Carbon Fibers The purpose of this section is to estimate the values of improvement or reduction in the economic index, do in application of glass fibers (sample 1) in comparison to carbon fibers (sample 2) in concrete strengthening. This estimation is calculated for mechanical and seismic properties, individually. The results of Paired t-test are tabulated in Table 4.

Estimation showed that the values of do are always positive which means that glass fibers are more cost-benefit than carbon fibers regarding the improvement of concrete properties. For more clarification, the values of do are plotted in Figure 14.

Figure 14 reveals, the maximum and minimum improvement in the economic index is obtained for energy absorption and failure strain, respectively (6.05 vs. 0.17).

TABLE 4. amounts of $\bar{d}$, s_d and d_0 variables related to case 1

Concrete properties	$\bar{d}$	s_d	d_0
Concrete strength	4.25	2.11	2.63
Failure strain	0.36	0.26	0.17
Energy absorption	17.11	14.43	6.05
Ductility	6.09	4.01	3.00

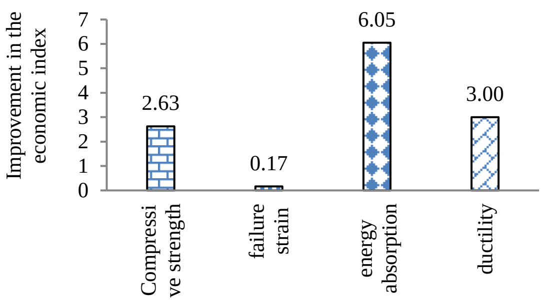


Figure 14. Values of d_o in case 1 for different concrete properties and FRP types

From now on, evaluation of glass fibers will be the focus of the discussion, since the prior section has shown that the use of glass fibers is more economical than carbon fibers.

3. 2. 2. Case 2: Using Multiple Layers of FRP in Comparison to a Single Layer The aim of the current section is to estimate the values of improvement or reduction in economic index d_0 when one layer of glass fibers, as in sample 1, is utilized in comparison to three and five layers of glass fibers, as in sample 2, for concrete strengthening. This estimation is performed for the entire concrete properties. The values of the Paired t-test are represented in Table 5.

Estimation reveals that the values of d_0 are always negative, which means that a single layer is more economical than three and five layers of glass fibers regarding the improvement of concrete properties. For more clarification, the values of do are plotted in Figure 15.

Figure 15 shows that the maximum and minimum changes in the economic index belong to energy absorption and failure strain, respectively. Moreover, the graph reveals that the effect of an increase in GFRP layers from three to five layers is not noticeable in the economic index.

TABLE 5. Amounts of $\bar{d}$, s_d and d_0 variables related to case 2

Concrete properties	L3			L5		
	$\bar{d}$	s_d	d_0	$\bar{d}$	s_d	d_0
Concrete strength	-4.15	0.83	-6.23	-6.28	1.90	-11.00
Failure strain	-0.48	0.14	-0.83	-0.61	0.15	-0.97
Energy absorption	-20.58	14.07	-55.61	-26.63	16.71	-68.31
Ductility	-7.87	0.18	-8.32	-10.03	0.32	-10.81

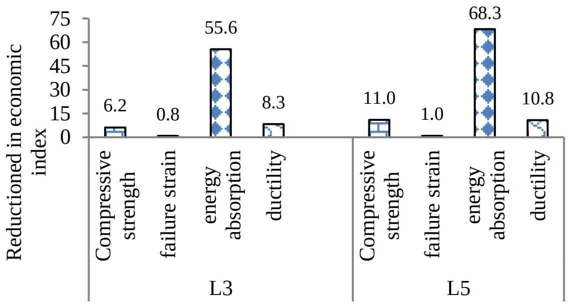


Figure 15. Values of d_0 in case 2 for different concrete properties and GFRP layers

3. 2. 3. Case 3: Strengthening of Higher Concrete Classes in Comparison to Lowest Concrete Class

The goal of the current section is to assess the values of improvement or reduction in economic index d_0 when lowest concrete class, as in sample 1, is compared to higher concrete classes, as in sample 2 for concrete strengthening with GFRP wrapping. Assessment is estimated for the entire concrete properties. The conclusions of the Paired t-test are tabulated in Table 6.

Table 6 shows that the values of d_0 are always negative, which implies that GFRP is more cost-benefit for the lowest concrete class regarding the improvement of concrete properties. For a better understanding, the values of d_0 are plotted in Figure 16.

Figure 16 demonstrates that the maximum and minimum changes in the economic index are related to energy absorption and failure strain, respectively.

TABLE 6. Amounts of $\overline{d}$, s_d and d_0 variables related to case 3.

Concrete properties	C35			C50		
	$\overline{d}$	s_d	d_0	$\overline{d}$	s_d	d_0
Concrete strength	2.81	1.64	-1.30	3.03	1.69	-1.16
Failure strain	0.07	0.06	-0.09	0.11	0.16	-0.29
Energy absorption	10.36	7.15	-7.45	20.19	17.83	-24.23
Ductility	-0.80	0.21	-1.33	-2.03	0.36	-2.94

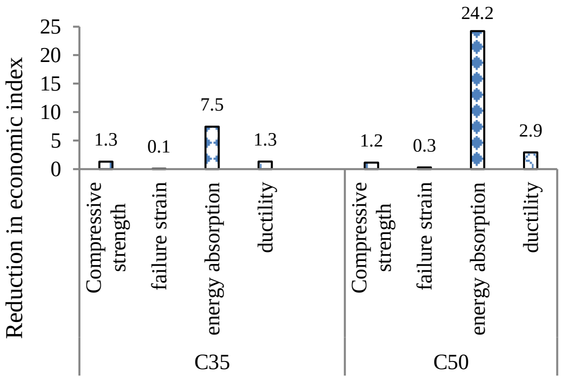


Figure 16. Values of d_0 in case 3 for different concrete properties and classes

4. CONCLUSIONS

Using fibers as an excellent solution in the improvement of non-resistant or earthquake-damaged structures is well known. Past research shows that carbon and glass fibers have proper performance in increasing the compressive strength and improving the seismic behavior of concrete, respectively. Despite all the excellent FRP features, the considerable cost of fibers has always been an inhibiting factor in the development of the application of this method. Paying attention simultaneously to the economic approach in practical engineering in the application of FRPs (choosing the type and number of layers and concrete class) and considering their mechanical and seismic characteristics indicates the importance of the current research. The economic theoretical analysis performed in this study has been less discussed in past studies and is important in three ways (question form) and contributes to the new knowledge:

- Comparatively, which type of fiber (glass or carbon) is more economical in terms of improving the mechanical and seismic properties of concrete? Economic analysis revealed that the answer to this question is glass fibers.
- Choosing how many layers of fibers is more economical in concrete retrofitting? The economic analysis indicated that the lowest number of layers (one layer) is the answer to the problem and economic efficiency decreases with an increase in the number of FRP layers.
- Fibers are more economically effective on which concrete class in terms of improving performance? Statistical analysis clarified that fibers are more cost-effective in improving the behavior of low-strength concrete.

Regarding the limitations of the current research, it should be noted that the study was designed in response to the needs of the engineering society, and therefore its results are valid within the same scope. It is obvious that by choosing a wider range of concrete classes and the type and number of selected wraps, the research can be more comprehensive. Also, the effect of fibers from an economic aspect was focused on the compressive behavior of concrete. While the flexural behavior of concrete in the moment frame caused by an earthquake could be the subject of future research.

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6. REFERENCES

1. Correia, J., "Pultruded glass fiber (gfrp). Application in gfrp composite beams gfrp-concrete in construction", Master thesis, Instituto Superior Técnico (in Portuguese), (2004),
2. Cabral-Fonseca, S., "Polymeric composite material reinforced with fibers used in civil engineering—features and application",

LNEC, Lisbon, Portuguese: Scientific and Technical Information, (2005).

3. GangaRao, H.V., Taly, N. and Vijay, P., "Reinforced concrete design with frp composites, CRC press, (2006).

4. Gevin McDaniel, P.E., "Fiber reinforced polymer (FRP) composites", in America: American Composites Manufacturers Association. Vol., No. Issue, (2014 of Conference).

5. Youssf, O., Hassanli, R. and Mills, J.E., "Retrofitting square columns using frp-confined crumb rubber concrete to improve confinement efficiency", ***Construction and Building Materials***, Vol. 153, (2017), 146-156. https://doi.org/10.1016/j.conbuildmat.2017.07.108

6. Zeng, J., Teng, J., Lin, G. and Li, L., "Large-scale frp-confined rectangular rc columns with section curvilinearization under axial compression", ***Journal of Composites for Construction***, Vol. 25, No. 3, (2021), 04021020. https://doi.org/10.1061/(ASCE)CC.1943-5614.0001129

7. Taghia, S., Darvishvand, H.R., Ebrahimi, M. and Razavi, H.S.N., "Evaluating the performance and effect of the number of frp composite wrapping on strength and ductility for low strength concrete", in 16th European Conference on Earthquake Engineering (16ECEE), Thessaloniki, Greece., (2018), 18-21.

8. Sirach, N., Smith, S.T., Yu, T. and Mostafa, A., "Experimental study on the confinement of concrete cylinders with large rupture-strain frp composites", ***Journal of Composites for Construction***, Vol. 25, No. 4, (2021), 04021026. https://doi.org/10.1061/(ASCE)CC.1943-5614.0001137

9. Picher, F., "Confinement of concrete cylinders with cfrp, fiber composites in infrastructure", in Proceedings of the first International Conference on Composites in Infrastructure., (1996), 829-841.

10. Matthys, S., Taerwe, L. and Audenaert, K., "Tests on axially loaded concrete columns confined by fiber reinforced polymer sheet wrapping", ***Special Publication***, Vol. 188, (1999), 217-228. doi.

11. Bisby, L.A. and Williams, B.K., "An introduction to frp strengthening of concrete structures", in ISIS Educational Module. Canada., (2004).

12. Monti, G., Nisticò, N. and Santini, S., "Design of frp jackets for upgrade of circular bridge piers", ***Journal of Composites for Construction***, Vol. 5, No. 2, (2001), 94-101. https://doi.org/10.1061/(ASCE)1090-0268(2001)5:2(94)

13. Abdelrahman, K. and El-Hacha, R., "Cost and ductility effectiveness of concrete columns strengthened with cfrp and sfrp sheets", ***Polymers***, Vol. 6, No. 5, (2014), 1381-1402. doi: 10.3390/polym6051381.

14. Shapira, A. and Bank, L.C., "Constructability and economics of frp reinforcement cages for concrete beams", ***Journal of Composites for Construction***, Vol. 1, No. 3, (1997), 82-89. https://doi.org/10.1061/(ASCE)1090-0268(1997)1:3(82)

15. Sahirman, S., Creese, R.C., GangaRao, H.V. and Brown, C., "Economic analysis of fiber reinforced polymer (FRP) bridge decks", in IIE Annual Conference. Proceedings, Institute of Industrial and Systems Engineers (IISE)., (2003), 1.

16. Berg, A.C., Bank, L.C., Oliva, M.G. and Russell, J.S., "Construction and cost analysis of an frp reinforced concrete bridge deck", ***Construction and Building Materials***, Vol. 20, No. 8, (2006), 515-526. https://doi.org/10.1016/j.conbuildmat.2005.02.007

17. Brayack, D.A., "Technical and economic effectiveness for repair with frp of concrete t-beam bridges: Case study for penndot-district 3", (2006). https://doi.org/10.33915/etd.3243

18. Wang, Y., Li, L., Zhang, Y.F., Xu, M.X. and Sun, Q., "Techno-economic analysis of fiber reinforced polymer substation", in Applied Mechanics and Materials, Trans Tech Publ. Vol. 357, No. Issue, (2013), 1194-1199.

19. Sever, V.F. and Ehsani, M., Designing an economical frp system for pipeline rehabilitation, in Pipelines 2019: Planning and design. 2019, American Society of Civil Engineers Reston, VA.117-124.

20. Chen, D., Sun, G., Meng, M., Jin, X. and Li, Q., "Flexural performance and cost efficiency of carbon/basalt/glass hybrid FRP composite laminates", ***Thin-Walled Structures***, Vol. 142, (2019), 516-531. https://doi.org/10.1016/j.tws.2019.03.056

21. Rodsin, K., Hussain, Q., Suparp, S. and Nawaz, A., "Compressive behavior of extremely low strength concrete confined with low-cost glass frp composites", ***Case Studies in Construction Materials***, Vol. 13, (2020), e00452. https://doi.org/10.1016/j.cscm.2020.e00452

22. Haj Seiyed Taghia, S.A., Darvishvand, H.R., Asadi, S. and Pourhasan, M., "A comparative study on the implementation of carbon and glass fibers wrappings to improve the compressive strength and seismic behavior of concrete", ***Asian Journal of Civil Engineering***, Vol. 21, (2020), 1389-1398. https://doi.org/10.1007/s42107-020-00285-5

23. Shubhalakshmi, B., Jagannatha Reddy, H., Prabhakara, R. and Kasi, A., "Performance-based economic evaluation of retrofitted slabs with different frp's and different configurations", Trends in Civil Engineering and Challenges for Sustainability: Select Proceedings of CTCS 2019, (2021), 323-331. https://doi.org/10.1007/978-981-15-6828-2_25

24. El Youbi, M., Tbatou, T., Kadiri, I. and Fertahi, S.E.-D., "Numerical investigation of hsc columns retrofitted by cfrp materials under combined load", ***Civil Engineering Journal***, Vol. 8, No. 4, (2022), 765-779.

25. Salahaldin, A.I., Jomaa'h, M.M., Oukaili, N.A. and Ghaidan, D.J., "Rehabilitation of hybrid rc-i beams with openings using cfrp sheets", ***Civil Engineering Journal***, Vol. 8, No. 01, (2022).

26. Standard, A., "Astm c150: Standard specification for portland cement", Annual Book of ASTM Standards, American Society for Testing and Materials, West Conshohocken, PA, (2001).

27. ASTM, A., "C33/c33m-18 standard specification for concrete aggregates", ASTM International: West Conshohocken, PA, USA, (2018).

28. "ASTM C494, standard specification for chemical admixtures for concrete, " ***A***STM International: West Conshohocken, PA, USA, (2017).

29. ASTM, A., "C469/c469 m-14 (2014) standard test method for static modulus of elasticity and poisson's ratio of concrete in compression", ***A***STM International, West Conshohocken.

30. Committee, A., "Guide for the design and construction of externally bonded frp systems for strengthening concrete structures (ACI 440.2 r-17)", American Concrete Institute, Farmington Hills, MI, (2017).

31. Engineers, A.S.o.C., "Seismic evaluation and retrofit of existing buildings, American Society of Civil Engineers. (2017).

32. Walpole, R.E., Myers, R.H., Myers, S.L. and Ye, K., "Probability and statistics for engineers and scientists, Macmillan New York, Vol. 5, (1993).

Persian Abstract

چکیده

یکی از رویکردهای حاضر برای مقاوم سازی بتن، دورپیچ FRP نام دارد. در این مطالعه، مقاوم‌سازی بتن به معنای بهبود مقاومت فشاری و پارامترهای لرزه‌ای (مانند کرنش شکست، جذب انرژی و شکل‌پذیری) است. تحلیل هزینه ممکن است مسائل نگران کننده ای را در رابطه با ارزش اقتصادی این نوع مقاوم سازی ایجاد کند و به همین دلیل، تحلیل اقتصادی بر اساس کارهای آزمایشگاهی انجام شد. در این راستا، ۲۱ نمونه برای سه رده مقاومت فشاری بتن (۲۰، ۳۵ و ۵۰ مگاپاسکال) آماده و با لایه‌های مختلف پلیمرهای تقویت‌شده با الیاف کربن و شیشه (۰، ۱، ۳ و ۵ لایه) دورپیچ شد. نمونه ها تحت آزمایش تنش-کرنش قرار گرفتند و خواص بتن برآورد شد. نتایج نشان داد که الیاف کربن و شیشه به ترتیب در بهبود مقاومت فشاری و پارامترهای لرزه ای بتن موثرتر هستند. اما، تحلیل اقتصادی نشان داد که الیاف شیشه نسبت به الیاف کربن در بهبود خواص بتن، به ویژه برای یک لایه FRP، از نظر هزینه- فایده مناسب تر است. تحلیل اقتصادی نتوانست مشخص کند که کاربرد FRP برای کدام نمونه های بتنی مقرون به صرفه تر است و به همین دلیل برای پاسخ به این ابهام و دستیابی به یک ارزیابی جامع از تحلیل آماری استفاده شد. تحلیل نشان داد که استفاده از FRP برای بتن کم مقاوم از نظر هزینه- فایده مناسب تر است.