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Comparative Experimental Study of Different Types of Fiber Reinforced Polymer Wrapping in Repairing of Reinforced Concrete Deep Beams with Circular Openings

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ABSTRACT

Openings of reinforced concrete (RC) deep beams can be used to pass electrical, mechanical, and architectural equipment. A comparative experimental study of fiber reinforced polymer (FRP) type on the performance of deep RC beams with the circular opening was the most important purpose of this study. The variables were FRP type (carbon, glass, and aramid) and the number of layers (1, 2, and 3). The geometric and rebar characteristics of the beams were considered constant in all cases. Deep RC beams were constructed, and their response to four-point loading was evaluated. Depending on the layers (1, 2 and, 3), aramid, carbon and glass fiber reinforced polymers (AFRP, CFRP, and GFRP) sheets increased the maximum load by about 65 to 94%, 87 to 130%, and 133 to 196%, respectively. In RC deep beams retrofitted with GFRP sheets, the sheet separation from the beam surface decreased with expanding the number of layers. The CFRP sheets debonded from the beam surface at the supports along the center of the circular opening. CFRP showed much better performance in energy absorption capacity and load capacity than AFRP and GFRP. The CFRP were debonded from the beam surface at the moment of rupture. However, no significant separation was observed in RC deep beams retrofitted with AFRP and GFRP sheets. SEM images of the cores specimens showed that the fracture surface of the specimens extracted from the beam retrofitted with GFRP and CFRP sheets was much rougher than the control specimen, which indicates a stronger bond between the concrete components.

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1. INTRODUCTION

One of the topics that construction industry experts have considered in recent years is repairing existing structures that are still in operation after their lifetime. Errors in construction and execution, the weakness of old regulations, increasing the number of storys, and the impact of destructive environmental factors are among the reasons for the need for retrofitting computational errors [1-3].

On the other hand, many RC structures are damaged by cracking or excessive rising, caused by various factors such as earthquakes, excessive vibrations, corrosion of rebars, etc. One of the materials used in Europe since 1960 to strengthen or repair RC structures is fiber reinforced polymer (FRP) installed on the concrete from the outside [4-6].

Extensive research has been conducted on retrofitting RC beams using FRP in the past decades [7-10]; most of which have been to achieve the maximum capacity of FRP and thus maximize the bearing capacity of existing beams.

In RC structures, deep beams are used as load-bearing beams and coupling shear walls of tall buildings. Openings must be designed in deep RC beams for electrical and computer network cables, mechanical installations, or commuting from room to room [11-14]. These openings interrupt the transfer of compressive forces from the place of application of the load to the abutment and cause it to collapse, and many cases requiring retrofitting [15-21]. Zhang et al. [22] investigated RC deep beams. Half of the beams were tested with an effective shear-depth ratio of 1.875 and

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the other half with 1.25. The beams were retrofitted with FRP sheets with different arrangements by the EBR method. Retrofitting with the FRP sheet increases the bearing capacity of the deep beam. The shear contribution of FRP sheets increases horizontally at a 45-degree angle [22]. Di Ludovico et al. [23] examined the effect of retrofitting prestressed beams by CFRP sheets. Retrofitting using CFRP sheets is structurally adequate and can play a significant role in recovering the capacity of damaged specimens [23]. Hussain and Pimanmas [24] investigated RC deep beams retrofitted using GFRP. With increasing the thickness of the GFRP, the shear strength would increase [24]. Chin et al. [25] studied various methods and issues related to retrofitting RC beams with the opening. It was stated that studies on retrofitting of beams around the opening are necessary [25]. Rahim et al. [26] examined the behavior of RC deep beams with CFRP. Their behavior was assessed using load-displacement curves. CFRP increases the capacity of the beams by about 10 to 40% [26]. Al-Bdari et al. [27] examined the performance of deep beams retrofitted with CFRP sheets. The CFRP sheets with vertical arrangement could increase the ultimate strength of the beam by about 20 to 32.6% [27]. Kumari and Nayak [28] evaluated the crack and maximum loads of the retrofitted deep beams using GFRP. The relationships were presented and compared with the relationships introduced in the regulations [28].

In our literature review, it has been pointed out that the openings diminish RC deep beams' bearing capacity [29-31]. Openings of RC deep beams can be used to pass electrical, mechanical, and architectural equipment. These openings can reduce the bearing capacity. Previous studies showed that carbon fiber reinforced polymer (CFRP) sheets could influence RC deep beams' ductility and bearing capacity. In this laboratory research, the impact of aramid and glass fiber reinforced polymer (AFRP and GFRP) sheets on the retrofitting of RC deep beams with the circular opening was investigated. Their response was compared with CFRP sheets. Another distinguishing feature of this study compared to other studies is that a comparative study of three different types of polymer sheets in retrofitting of RC deep beams with circular openings was conducted in this study. The results of this study can be used as validation of numerical analysis.

2. LABORATORY PROGRAM

2. 1. Variables

The RC deep beams with circular openings retrofitted with three types of FRP sheets were investigated. Aramid, glass, and carbon fiber reinforced polymers (AFRP, GFRP, and CFRP) sheets were used. The number of layers was considered 1, 2, and 3, respectively. Two beams with and without openings were constructed as control beams to evaluate the variables' parameters. Table 1 summarized the investigated beams. An abbreviation was given to each of the beams. According to the variables, eleven RC deep beams were built.

2. 2. Geometric Characteristics of Beams

Iranian national building code (part 9) [32] and the American concrete institute (ACI) [33] introduced deep beams as high-bending members. According to these regulations, the rules of flexural members with high height can be applied for beams that have the following conditions:

- Span to length ratio is less than four ($l \leq 4h$).
- It is possible to create pressure handles from the load side to the support. Deep beams are used as load-bearing beams that load from the top columns and transfer them to the supporting columns. These beams are placed in areas where removing several columns is necessary, such as parking entrances.
- In RC deep beams, openings are sometimes made to perform essential services such as air ducts, access to electrical and computer network cables, mechanical installations, or commuting from room to room. These openings interrupt the transfer of compressive forces from the place of application of the load to the abutment and cause it to become distorted, causing a severe reduction in the resistance of the beams.

The effective length was considered 320 mm. The beams' ratio of effective length to width is 2.13, and this value is less than 4. Therefore, beams are considered a deep type. The cover on the rebars was considered 40 mm. Steel plates were utilized to avoid the concentrating stress on top of the beams. The geometric characteristics of the beams and the arrangement of the steel reinforcement are shown in Figure 1.

TABLE 1. Introduction of variables

No.	Beam name	FRP type	Number of FRP layers
1	CB	Control beam without opening	-
2	CB-O	Control beam with opening	-
3	1AFRP	Aramid	1
4	2AFRP	Aramid	2
5	3AFRP	Aramid	3
6	1GFRP	Glass	1
7	2GFRP	Glass	2
8	3GFRP	Glass	3
9	1CFRP	Carbon	1
10	2CFRP	Carbon	2
11	3CFRP	Carbon	3

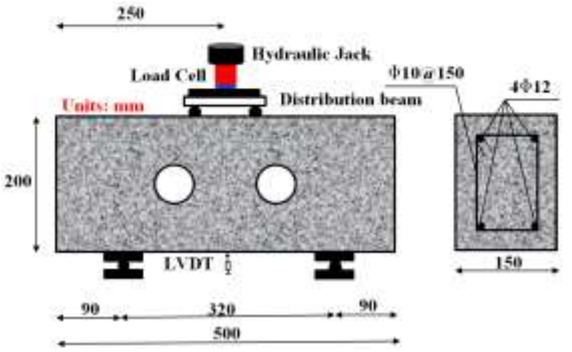


Figure 1. Geometric characteristics

The design of deep beams was done according to the ninth topic of the national building regulations of Iran. For this purpose, a six-story concrete building was first modeled and designed in Etabs software, and the details of the rebar and its geometric dimensions were extracted. Due to laboratory limitations, the beam was made on a 1:6 scale and subjected to four-point loading. The geometric properties of the beam and the characteristics of the rebars used in all cases were considered constant. The effect of FRP sheet type and number of layers on the response of deep beams with opening was considered as the most important objective of the research.

Four rebars with a diameter of 12 mm were used. Also, stirrups with a diameter of 10 mm were used with intervals of about 105 mm. There are two circular openings in the center of the beams. The distances between the two openings and their diameter were 150 mm and 60 mm, respectively.

2. 3. Materials

The materials used to make the main RC deep beams (without reinforcement) were sand, gravel, cement, water, and superplasticizer. Cement specifications are presented in Table 2. The aggregates used were fine river sand as filler and crushed gravel. The grading curve according to ASTM C33-87 [34]. The saturation density with the dry surface of the gravel and sand is 2.62 and 2.54 g/cm^3, respectively. The superplasticizer was obtained in each mixing design based on achieving acceptable performance and preventing the phenomenon of aggregate separation. A carboxylate-based superplasticizer (brand name WRM-TPP) was used. The slump, compressive and tensile strength were determined [35-37].

TABLE 2. Cement Specifications

Components	Cement type II
SiO_2 %	21.27
Al_2O_3 %	4.95
Fe_2O_3 %	4.03
CaO %	62.95
MgO%	1.55
SO_3 %	2.26
K_2O %	0.65
Na_2O %	0.49

The amount of materials used to make the beams and the test results are presented in Table 2. RC deep beams and cylindrical and cubic specimens were poured together. Three samples were made for compressive and tensile strength tests, and their mean at 28 days of age was obtained. The beams vibrated adequately. Samples were cured in a water tank for 28 days.

Two rebars with diameters of 12 and 10 mm were used to make the RC beams (Table 4).

FRP sheets, with high resistance to corrosion (It can be easily used as a layer to protect reinforced concrete structures), have attracted many researchers' attention in recent years. Acceptable modulus of elasticity, high tensile strength, and corrosion resistance are among the characteristics of the FRP [38-40]. FRP is made using

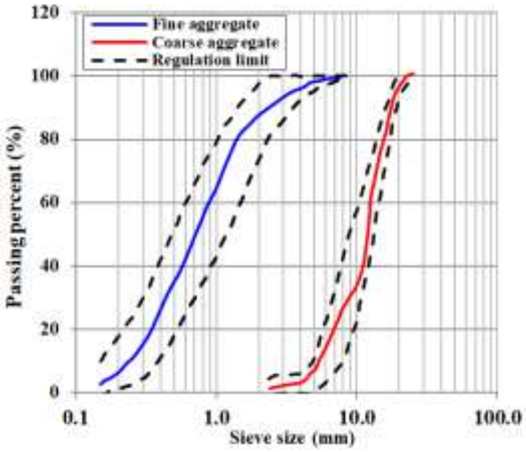


Figure 2. Coarse and fine aggregates grading curves

TABLE 3. Mixture design and the test results

Cement (kg/m^3)	Water-Cement ratio	Sand (kg/m^3)	Gravel (kg/m^3)	Slump (mm)	Compressive strength (MPa)	Splitting tensile strength (MPa)
400	0.50	900	900	47	27.1	2.41

TABLE 4. Specifications of steel rebars

Rebar diameter (mm)	Yield stress (MPa)	Ultimate stress (MPa)
10	381	340
12	577	524

various fibers, the most famous of which are carbon, glass, and aramid fibers, together with a special epoxy resin adhesive. In this study, three types of sheets, AFRP, GFRP, and CFRP, were used to strengthen the beams (Table 5). The thicknesses of AFRP, GFRP, and CFRP sheets were considered 0.193, 1.3, and 11 mm, respectively.

The adhesive utilized to bond the FRP sheets was a two-part adhesive consisting of hardener and resin. According to the manufacturer's catalog, this adhesive's density and tensile strength are equal to 1.11 g/cm^3 and 76.1 MPa, respectively.

2. 4. Construction of the Beams Wooden molds were used to make the beam. The lower part of the molds was connected to the ground to prevent the molds from moving during vibration. The thickness of the wooden molds was considered 70 mm, and in addition to glue, special screws were used to connect the woods to each other. PVC pipes were used to create the circular opening of the beams. Figure 2 shows the steps for formatting and processing specimens. A mixing machine was used to mix the materials. The specimens were moisture treated at 20°C from molding to the moment of testing and kept in a water tank and a non-vibration environment. Figure 3 shows the steps of fabrication and curing of samples.

TABLE 5. Specifications of FRP sheets

FRP type	Ultimate strain (MPa)	Tensile strength (MPa)	Density (kg/m^3)
AFRP	0.026	1800	1250
GFRP	0.020	1800	2000
CFRP	0.015	2250	1900

Figure 3. Construction and curing of the beams a: Formwork and reinforcement b: Concreting c: Curing

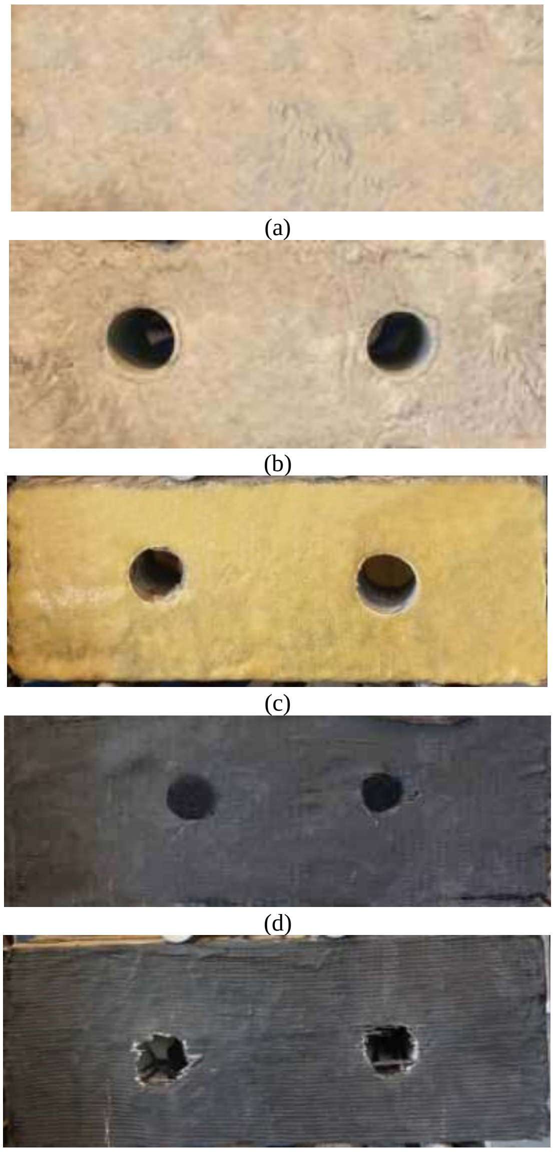
2. 5. Installation of FRP Sheets First, the concrete surface of the RC deep beams was sanded to remove the weak surface with a Grinding Stone, and then a wire brush was pulled to clean the surfaces. Before applying the adhesive on the concrete surface, the concrete surface at the installation site and the surface of the FRP sheet were cleaned with a special solution. Then the two-component adhesive was mixed and spread by the spatula in the desired places, and then FRP sheets were placed on the adhesive and installed under a certain pressure. FRP sheets were cut to the desired size with scissors with fine teeth. FRPs were impregnated with an adhesive to install and execute the next layers, and the layering operation was started. FRP contains coatings that are removed after bonding to the surfaces, and the fibers attached to the surface are again impregnated with epoxy resin by a roller. The installation operation should be started from the middle part and continue to both ends to prevent bubbles. After smoothing the fiber surface by hand, a small hand roller should be pressed firmly onto the FRP surface. In all cases, the surfaces of the beams were painted, and the crack distribution could be observed. Figure 4 shows images of RC deep beams with circular openings before painting.

2. 6. Loading The beams were tested with simple two-end support conditions. The forces were applied to the specimens in four points by the hydraulic jack in specific locations (Figure 1). This method is one of the most common methods used in many studies [41-43] related to the study of bending and shear behavior of beams. In the studies that have used this method, no specific standard has been announced. It has been stated that this method is similar to the three-point load test (according to ASTM-C293) in some references. The only difference is the number of supports and the type of placement. Applying a load to more points causes the wider points of the beam to be stressed, and this method is usually used for more brittle materials such as concrete. The load-displacement values are extracted in this method. The loading continued at a constant speed with specific steps until the failure stage.

3. LABORATORY RESULTS

In this section, the results obtained from the experiments are presented, and the behavior of the beams is discussed.

3. 1. Laboratory Observations and Load-displacement Curves The load-deflection values of the control beams and the beams retrofitted with AFRP sheets are presented in Figure 6. The first crack of the control beam with openings (CB-O) was recorded



(e)

Figure 4. The investigated RC deep beams with circular openings a:CB b:CB-O c:AFRP d:GFRP e:CFRP

Figure 5. Loading device used

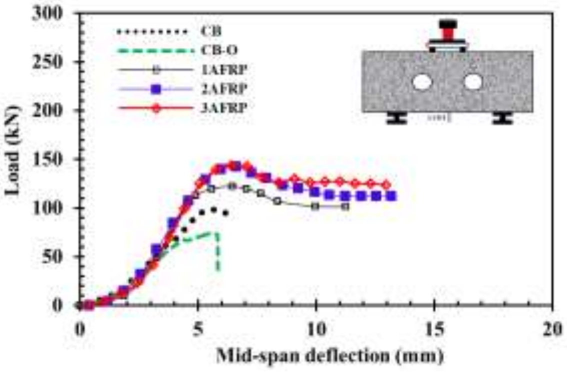


Figure 6. The results of four-point loading for the control beams and the beams retrofitted with AFRP

at 48 kN. These cracks were primarily observed in the loading area. With increasing load, shear-flexure cracks were watched within the lower regions of the beam. The yield load and yield deflection of the CB-O were 67 kN and 4.6 mm, respectively. As the load expanded, the cracks on the beam expanded and inevitably failed at a load equivalent to 74 kN. Figure 9 shows the deformable shape of the control beam after loading.

Adding a layer of AFRP sheet increases the maximum bearing capacity of the RC deep beam. The maximum load corresponding to 1AFRP, 2AFRP, and 3AFRP beams is 122, 143.1, and 143.2 kN, respectively. In retrofitted beams with AFRP sheets, many diagonal shear cracks occurred before flexural cracks. After hardening, the cracking patterns were similar, but the number and width of cracks by visual inspection were smaller. At the boundary of the AFRP material, no signs of debonding were observed at the boundary of the adhesive reinforced material in the attached AFRP sheet. For 1AFRP, 2AFRP, and 3AFRP beams, initial cracks of about 84, 124, and 126 kN were observed. Figure 9 shows the failure of beams retrofitted with AFRP sheets.

The load-deflection values of the controls and the beams retrofitted with GFRP sheets are presented in Figure 7. In beams using one, two, and three layers of GFRP, the primary flexural cracks were recorded at loads of about 98.3, 98.4, and 99.1 kN. In a beam using a layer of GFRP sheet, the cracks developed in shear. As the layers of GFRP increased, the width of the cracks decreased.

The maximum bearing capacity of RC deep beam with one, two, and three layers of GFRP sheets was 138, 164, and 170.5 kN, respectively. Images of 1GFRP, 2GFRP, and 3GFRP beams after failure are shown in Figure 9. Most of the cracks are flexural and were associated with rupture of GFRP sheets that adhered to deep beams in a U-shape. GFRP sheets as a reinforcing element in RC deep beams delayed the compression crushing, which increased the beam capacity and increased the beams' ductility.

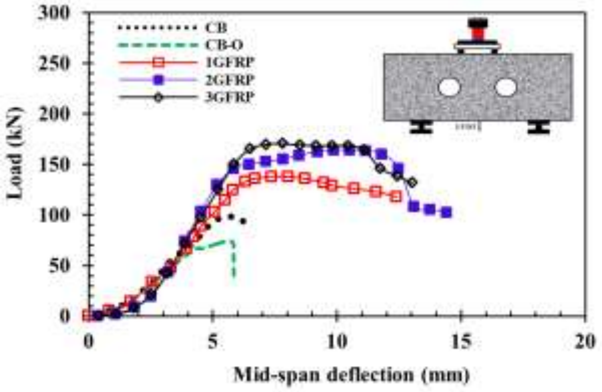


Figure 7. The results of four-point loading for the control beams and the beams retrofitted with GFRP

The load-deflection values of the control beam and the beams retrofitted with CFRP sheets are presented in Figure 8. In the 1CFRP beam, the first flexural crack occurred under a load of 98.3 kN, then the number of flexural cracks increased with continued loading. With increasing load, the number of cracks and the height of flexural and shear cracks increased until 172.5 kN load. The beam failed by separating the CFRP sheet from the concrete and crushing the concrete in the compressive zone between the two loads. After the formation of diagonal shear cracks, these cracks were restrained by CFRP sheets that are perpendicular to the crack and prevent the expansion of diagonal cracks and their increase in width. This prevented the premature shear failure of the beam and increased the bearing capacity of the RC deep with the opening.

After the start of the nonlinear part of the load-deflection curve, the RC deep Beams retrofitted with CFRP sheets showed more stiffness than beams retrofitted with GFRP and AFRP sheets. But with the sudden rupture of CFRP sheets, the ductility of these beams has been significantly reduced compared to the other two groups.

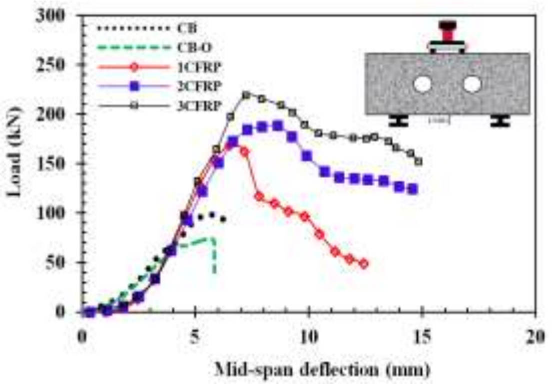
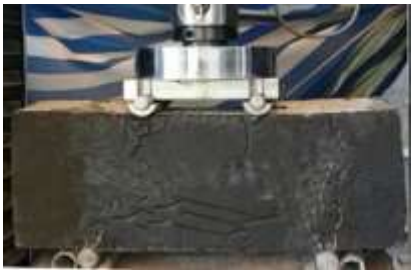


Figure 8. The results of four-point loading for the control beams and the beams retrofitted with CFRP



CB

CB-O

1AFRP

2AFRP

3AFRP

1GFRP

2GFRP

3GFRP

1CFRP

2CFRP

3CFRP

Figure 9. Crack distribution and deformable shapes

The load-deflection curves of the beams retrofitted with CFRP sheets have a relatively sharp drop compared to the beams retrofitted with AFRP and GFRP sheets. The reason is the separation of the FRP sheet; before the maximum bearing capacity of FRP is used, the sheet is separated from the beam surface. The glue used was the same in all cases; AFRP and GFRP sheets have much better adhesion to the concrete surface.

Figure 9 shows the images of RC deep beams retrofitted after loading. In 2CFRP and 3CFRP RC deep beams, in which 2 and 3 layers of CFRP sheet were used for retrofitting, respectively, the first flexural cracks occurred under loads of 98.4 and 99.1 kN, then the number of flexural cracks increased with continued loading. As the load increased, the number of cracks and the height of the flexural and shear cracks increased until 188.2 and 219 kN loads, 2CFRP and 3CFRP beams failed when the concrete was crushed in the compressive zone between the two loads. The cracking loads of RC deep beams with 2 and 3 layers were significantly increased than the reference beam. As the number of layers increases, separation does not occur due to the greater involvement of the CFRP sheet with the concrete.

According to the load-deflection curves, CFRP sheets showed much better energy absorption capacity and flexural capacity than AFRP and GFRP sheets. But the important point here is that the CFRP sheets were detached from the beam surface at the moment of rupture. However, no significant separation was observed in deep beams reinforced with AFRP sheets.

In RC deep beams retrofitted with GFRP sheets, the sheet separation from the beam surface decreased with increasing layers. CFRP sheets detached from the beam surface at the lateral abutment and along the circular openings. The crack path expanded from the lateral abutment to the points of concentrated load application.

Table 5 summarizes the results of the four-point loading test. This table presents crack load, yield load, maximum load, crack displacement, yield displacement, ultimate displacement, ductility, and energy absorption capacity. In the following, each of these parameters is examined using various comparative diagrams.

3. 2. The Bearing Capacity of RC Deep Beams with Openings

The maximum load that each RC deep beam can withstand is called the bearing capacity of the beams. The comparative diagram of Figure 10 compares the bearing capacity of RC deep beams with openings. In this figure, the increased percentage in bearing capacity compared to the control beam is also presented. As can be seen in all cases, the addition of FRP sheets has increased the bearing capacity of RC deep beam beams compared to the control sample. The circular cavities created on the reinforced concrete deep beams have reduced the bearing capacity of the beam by about 24%.

TABLE 5. The test results

Name	Crack point		Yield point		P_{max} (kN)	Δ_U (mm)	Ductility	Energy absorption (N.mm)
	Δ_{cr} (mm)	P_{cr} (kN)	Δ_y (mm)	P_y (kN)				
CB	3.97	67	4.93	85	98	6.5	1.32	333
CB-O	3.3	48	4.60	67	74	5.52	1.2	234
1AFRP	3.95	84	4.61	107	122	11.3	2.45	894
2AFRP	5.1	124	5.76	139	143.1	13.20	2.31	1223
3AFRP	5.3	126	5.81	139	143.2	12.97	2.23	1836
1GFRP	4.49	97.1	5.82	125	138	12.4	2.13	1141
2GFRP	5.20	124	5.84	150	164	14.43	2.47	1887
3GFRP	5.22	125	5.86	151	170.5	13.03	2.22	1769
1CFRP	4.5	98.3	5.93	165	172.5	12.43	2.10	971
2CFRP	4.51	98.4	6.67	172	188.2	14.59	2.18	1609
3CFRP	4.58	99.1	6.56	198	219	14.90	2.27	1989

Δ_{cr}: Crack deflection, Δ_y:Yield deflection, Δ_u: Ultimate deflection
P_{cr}: Crack load, P_y: Yield load, P_{max}: Maximum load

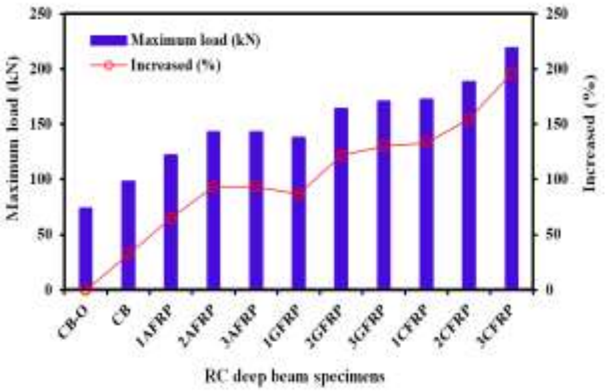


Figure 10. Comparison of bearing capacity and percentage increase

However, addition of AFRP, GFRP, and CFRP sheets to the deep beam with openings has increased the bearing capacity in most cases by 94, 130, and 196 percent, respectively, compared to the control beam with openings.

The addition of one, two, and three layers of AFRP sheet has improved the bearing capacity by 65%, 93%, and 94%, respectively. One, two, and three layers of the GFRP sheet have increased the bearing capacity by 87, 121, and 130%, respectively. One, two, and three layers of the CFRP sheet have increased the bearing capacity by 133, 154, and 196%, respectively. According to the changes, CFRP sheets in deep reinforced concrete beams in load-bearing capacity have a much better performance than AFRP and GFRP sheets.

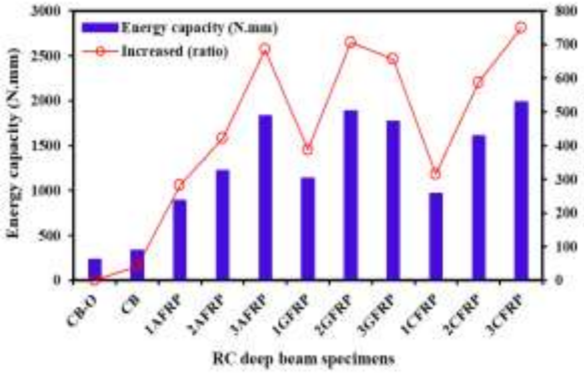


Figure 11. Comparison of energy absorption

3. 3. The Energy Absorption

Energy absorption capacity is one of the parameters that can be used to evaluate the efficiency of the desired retrofitting method. This parameter is obtained using the area under the load-deflection curve [1-3, 44, 45]. Figure 11 compares the energy absorption of RC deep beams made in eleven different modes. As expected, FRP in RC deep beams with openings played an influential role. They increased the energy absorption capacity depending on the type and number of layers by 3.8 to 8.5 times. The highest energy absorption capacity was obtained in RC deep beams in which three layers of CFRP sheet were used. Although the beams retrofitted with one and two layers of GFRP sheets had less load-bearing capacity, their energy absorption capacity has increased compared to beams retrofitted with one and two layers of CFRP sheets. This is because GFRP sheets had more adhesion than CFRP sheets and increased their energy absorption capacity. However, by increasing the number of sheets to three layers, the retrofitted beams with CFRP sheets performed better and showed more energy absorption capacity. The use of more layers in all cases has led to an increase in the energy absorption of RC deep beams with the opening.

For example, the energy absorption of three-layer retrofitted beams with CFRP, GFRP and AFRP is 17, 24, and 27% higher than single-layer retrofitted beams with CFRP, GFRP, and AFRP, respectively.

3. 4. Comparison of Deflection Ductility

One of the most important considerations in addition to strength and serviceability in concrete beams is the issue of ductility. The important point is that the structure exhibits malleable behavior in a sudden damage close to the failure load. This means that the structure will not be damaged by a sudden brittle failure but will withstand large deformations near its maximum bearing capacity. Making large displacements near the maximum load will cause the residents to be informed before it breaks down, and as a result, the necessary safety will be achieved. The members' ductile behavior also provides the basis for the redistribution of bending moment and the design. In cases where design is required to load an earthquake, ductility is one of the most important parameters. The structure has sufficient ductility to absorb and dissipate seismic energy because the structure's performance against earthquake load is beneficial [46]. The ductility coefficient is obtained by dividing the ultimate deflection by the yield deflection of the beams. The ductility of the made beams is presented in Figure 12. This diagram also shows the bearing capacity (Maximum load).

The ductility of the retrofitted RC beams is about 1.75 to 2 times higher than the control sample, depending on the FRP type and layer numbers. AFRP sheets are much more ductile than CFRP and GFRP sheets. The ductilities of retrofitted beams with one, two, and three layers of AFRP sheet are 2.45, 2.31, and 2.23, respectively. Meanwhile, the ductilities of RC deep beams retrofitted with one, two, and three layers of CFRP sheet are 2.1, 2.10, and 2.18, respectively. In the RC deep beams retrofitted with AFRP sheets, increasing the number of layers has reduced the ductility. However, in the RC deep beams retrofitted with CFRP sheets, increasing the number of layers has increased ductility. Also, in RC deep beams retrofitted with GFRP sheets, increasing the number of sheets first reduced the ductility and then increased it. Therefore, according to the changes made, it can be concluded that the type of FRP sheet has an impact on the ductility of RC deep beams with openings.

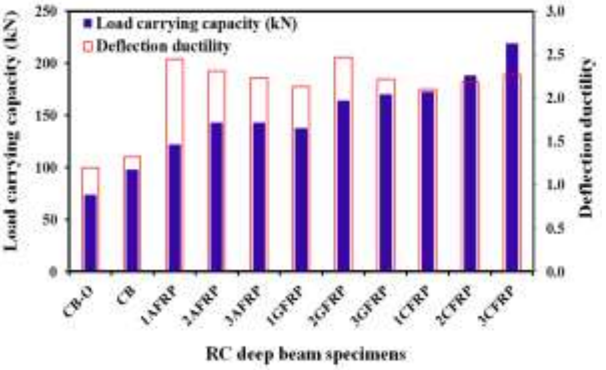
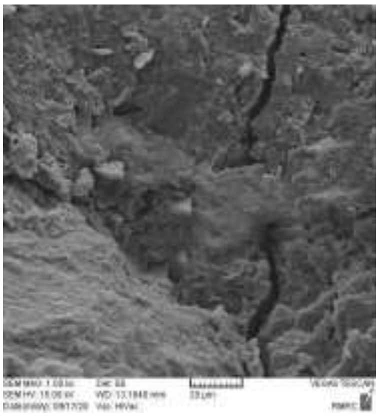


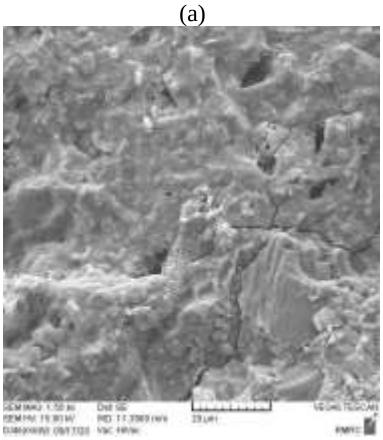
Figure 12. Comparison of deflection ductility

3. 5. Investigation of the Scanning Electron Microscope (SEM)

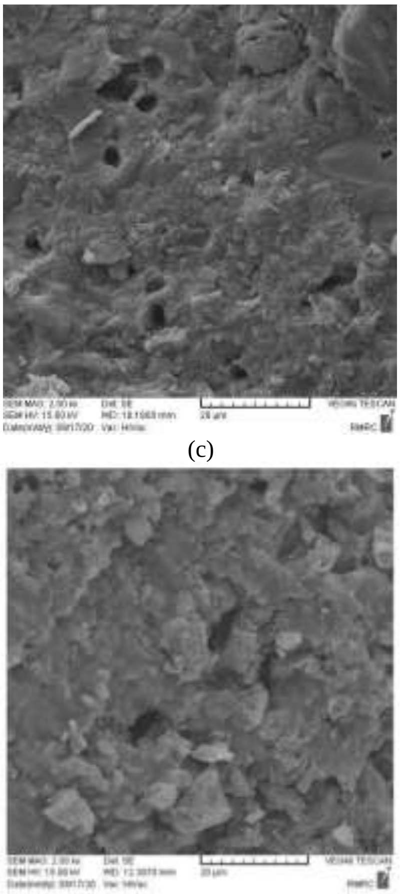
The microstructure of several specimens was evaluated using SEM images. This was done to investigate the specimens' general failure after four points loading and compare them with the state without retrofitting. For this purpose, cores were taken from the lower part of the loading area and within the openings of the control beam and retrofitted beams with three layers of AFRP, GFRP, and CFRP, and their SEM images were prepared. Figure 13 shows the SEM images of the mentioned specimens. After cracking, there was no factor to control and prevent crack growth



(a)



(b)



(c)

(d)

Figure 13. SEM images of core specimens of a number of investigated RC deep beams

in the control beam specimen. The crack in this specimen grew easily, and its width increased rapidly. Figure 13a shows that the concrete specimen has cracked and broken after withstanding the stress. The crack created in the sample is fully developed, and the width of the crack is considerable.

The core specimen of the 3AFRP beam cracked after withstanding its ultimate stress. The cracks due to stress in this specimen have a very small width and have not grown much. This sample has cracked after enduring its maximum stress. However, the crack created in this specimen has a much smaller width even than the control specimen, and its growth and development have been very low. More closely in these images, it can be seen that the fracture surface of the specimens extracted from the beam retrofitted with GFRP sheets is much rougher than the control sample, which indicates a stronger bond between the concrete components in the retrofitted beams with GFRP sheets. In the core specimen of the 3GFRP beam, after crack formation, the cracks did not grow much, and their width is much less than the control specimens. The use of CFRP sheets in concrete beams significantly increases flexural strength and energy absorption. The CFRP sheets lead to the enclosure of the perimeter surfaces of the beam, which makes the internal structure of the concrete more compact and can have a higher load-bearing capacity.

4. CONCLUSION

In the present experimental study, retrofitting of deep beams with the opening was investigated using three types of sheets: AFRP, GFRP, and CFRP. For this purpose, the behavior of ten RC deep beams with openings against four-point loading was evaluated. A summary of the most important results is provided in this section.

- In retrofitted beams with AFRP sheets, many diagonal shear cracks occurred before flexural cracks. After hardening, the cracking patterns were similar, but the number and width of cracks by eye inspection were smaller.
- In retrofitted beams with CFRP sheets, diagonal shear cracks were restrained by CFRP sheets that are perpendicular to the crack, and the expansion of diagonal cracks and their increase in width was prevented.
- Beams retrofitted with CFRP sheets after the start of the nonlinear part of the load-deflection curve showed more stiffness than beams retrofitted with GFRP and AFRP sheets. But with the sudden rupture of CFRP sheets, the ductility of these beams has been significantly reduced compared to the other two groups.
- The crack loads of RC deep beams with 2 and 3 layers were significantly increased compared to the reference beam. As the number of layers increased, separation did not occur due to the greater involvement of the CFRP sheet with the concrete.
- According to the load-deflection curves, CFRP sheets showed much better load capacity than AFRP and GFRP sheets. But the important point here is that the CFRP sheets were detached from the beam surface at the moment of rupture. However, no significant separation was observed in deep retrofitted beams with AFRP sheets.
- The corresponding curves with four-point loading of CFRP retrofitted beams have a relatively sharp drop compared to beams retrofitted with AFRP and GFRP sheets. The reason is the separation of the FRP sheet; Before the maximum bearing capacity of FRP is used, the sheet is separated from the beam surface. The glue used was the same in all cases; AFRP and GFRP have much better efficiency in adhesion to the concrete surface.
- FRP sheets in RC deep beams with opening had an influential role and increased the bearing capacity by

3.8 to 8.5 times depending on the type and number of layers. The highest energy absorption capacity was obtained in deep reinforced concrete beams in which three layers of CFRP sheet were used. Beams retrofitted with one and two layers of GFRP sheet. Although they had more load-bearing capacity, their energy absorption capacity has increased compared to beams retrofitted with one and two layers of CFRP sheet. This is because GFRP sheets had more adhesion than CFRP sheets and increased their energy absorption.

- In RC deep beams retrofitted with GFRP sheets, the separation from the beam surface decreased with increasing the layers number. The CFRP sheets debonded from the beam surface at the lateral support and along with the circular opening. The crack path expanded from the lateral supports to the concentrated load points.
- By increasing the layers number, the retrofitted beams with CFRP sheets performed better and showed more energy absorption capacity. The bearing capacity of three-layer retrofitted beams with CFRP, GFRP and AFRP are 17, 24, and 27% higher than single-layer retrofitted beams with CFRP, GFRP, and AFRP, respectively.
- Adding all three types of FRP sheets used has increased the ductility of the beams. This increase is about 1.75 to 2 times higher than the control sample, depending on the FRP type and layer number.
- In the beams retrofitted with AFRP sheets, increasing the number of layers has reduced the ductility. However, in RC deep beams retrofitted with CFRP sheets, increasing the number of layers has increased ductility. Also, in RC deep beams retrofitted with GFRP sheets, increasing the number of sheets first reduced the ductility and then increased it. Therefore, according to the changes made, it can be concluded that the type of FRP sheet has an impact on the ductility of deep beams.

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Persian Abstract

چکیده

حفرات ایجاد شده در تیرهای عمیق می‌تواند برای عبور تجهیزات برقی، مکانیکی و نیازهای معماری مورد استفاده قرار گیرد. این حفرات می‌توانند ظرفیت باربری تیرها را کاهش دهند. یکی از راه‌های تقویت چنین تیرهایی استفاده از ورق‌های FRP می‌باشد. در مطالعات گذشته گزارش شده است که ورق‌های پلیمری کربنی (CFRP) می‌تواند نقش تاثیرگذاری بر شکل پذیری و ظرفیت باربری تیرهای عمیق بتن مسلح داشته باشد. در مطالعه آزمایشگاهی حاضر تاثیر ورق‌های پلیمری آرامیدی (AFRP) و ورق‌های پلمیری شیشه‌ای (GFRP) در مقاوم سازی تیرهای عمیق بتن مسلح با بازشو مورد بررسی قرار گرفته و پاسخ آنها با کارایی ورق‌های CFRP مقایسه شده است. تعداد لایه‌های FRP ۱، ۲ و ۳ لایه در نظر گرفته شد. ابعاد هندسی، مشخصات فولادگذاری و مقاومت فشاری بتن در تمامی حالت ها ثابت فرض شد. افزودن ورق‌های AFRP، CFRP و GFRP بسته به تعداد ورق‌ها، ظرفیت باربری تیرها را به ترتیب ۶۵ تا ۹۴ درصد، ۸۷ تا ۱۳۰ درصد و ۹۶ تا ۱۳۳ درصد افزایش داد. منحنی‌های بار – جابجایی تیرهای مقاوم سازی شده با ورق‌های CFRP به دلیل جداشدگی زودتر، دارای افت بیشتری در مقایسه با تیرهای مقاوم سازی شده با ورق‌های AFRP و GFRP بودند. بطوریکه قبل از آن که از حداکثر ظرفیت باربری FRP استفاده شود، ورق از سطح تیر بتن مسلح عمیق جدا شد. بنابراین می‌توان نتیجه گرفت که ورق‌های AFRP و GFRP از جنبه چسبندگی با سطح بتن عملکرد بمراتب بهتری دارند. همچنین تصاویر SEM از مغزه‌های تهیه شده از تیرها نشان داد که که سطح شکست حاصل از نمونه‌های استخراج شده از تیر مقاوم سازی شده با ورق‌های GFRP و CFRP نسبت به نمونه شاهد بسیار زبرتر و خشنتر است که این امر نشان از پیوند قوی تر میان اجزای بتن در تیرهای مقاوم سازی شده با ورق‌های GFRP می‌باشد. در بتن تهیه شده از تیرهای مقاوم سازی شده با ورق‌های GFRP پس از تشکیل ترک، ترکها زیاد رشد نکرده و عرض آنها نسبت به نمونه شاهد بسیار کمتر است. افزودن ورق‌های CFRP به تیرهای عمیق بتن مسلح دارای بازشو منجر به محصور شدگی سطوح پیرامونی تیر می‌شود و این موضوع سبب می‌شود که ساختار داخلی بتن متراکم‌تر شود و بتواند ظرفیت باربری بیشتری داشته باشد.