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Retrofitting of Reinforced Concrete Beams with Steel Fiber Reinforced Composite Jackets

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ABSTRACT

In the present study, a new method for retrofitting reinforced concrete beam is introduced in which steel-concrete composite jackets containing steel fiber is used. For this purpose, 75% of the peripheral surface of reinforced concrete beams was initially reinforced using steel plates and bolts, and steel fiber reinforced concrete was used between the steel plates and the peripheral surfaces of the beam. Thus, due to the relatively high tensile strength of concrete reinforced with steel fibers, not only the cross-section and moment of inertia of the beam will increase, but the tensile strength of the beam will also increase. The variables studied were steel fiber value (0, 1 and 2% by volume of concrete) and type of retrofitting (concrete jacket, steel-concrete composite jacket, and carbon fiber reinforced polymer (CFRP) sheet). Thus, 8 reinforced concrete beams were constructed and their response to four-point loading was compared by examining the parameters such as crack load, yield load, ultimate load, ductility, stiffness, and energy absorption capacity. The results showed that steel fiber-reinforced composite jackets delay the formation of the first crack in concrete and the yield of steel rebars with confinement and they result in an increase in energy absorption capacity of the beams by 89 to 129% depending on the amount of steel fiber. On the other hand, the use of steel-concrete composite jackets, due to their higher flexural stiffness, exhibits higher flexural capacity compared to steel-reinforced concrete jackets and CFRP sheets. They have a much better performance in terms of ductility.

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1. INTRODUCTION

Reasons for retrofitting of buildings include factors such as extra floor construction, performance weakness, design deficiencies, change of use and change of regulations [1-3]. In this regard, presenting a comprehensively scientific, economical and practical plan for retrofitting of buildings requires high knowledge with sufficient experience in this field. Given that many buildings need to be retrofitted, it is, therefore, necessary to provide proper and practical strategies to safeguard each country's national capital as well as to prevent human casualties. Therefore, the present study is an attempt to provide a method for retrofitting concrete beams by the use of steel fiber reinforced concrete. The devastating and catastrophic earthquakes of recent decades have shown that Iran is an earthquake-prone country. Unfortunately, some cities in Iran have been formed on the margins of the faults; hence, there is a need to retrofit buildings with scientific criteria.

The retrofitting of buildings is aimed at increasing strength and ductility of structure. In the first case, the strength of the structure is increased by installing and executing shear walls and braces or by increasing the cross-section of the elements. In the second case, the rapid failure of main elements of building under earthquake loading was prevented by anticipating new techniques such as the use of dampers [4-6]. Various studies have been carried out on the use of different types of concrete and steel jackets by different researchers [7-12]. Raval and Dave [13] investigated the effectiveness of different methods of using concrete jackets in

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retrofitting reinforced concrete beams. For this purpose, 10 reinforced concrete beams with dimensions of 2100×300×150 mm were made. Eight beams were retrofitted with 60 mm thick reinforced concrete jackets and two beams were tested as control specimens. The results showed that the performance of concrete jackets on beams with chipped surfaces is better than beams with smooth surfaces [13]. Chalioris et al. [14] studied retrofitting of reinforced concrete beams using self-compacting concrete jackets. Twenty reinforced concrete beams were retrofitted with different arrangements of longitudinal and transverse reinforcement mesh and their performance was evaluated. The results showed that the use of self-compacting concrete jackets can significantly increase the load-carrying capacity of reinforced concrete beams [14]. Pandian and Karthick [15] investigated retrofitting of reinforced concrete beams using concrete jacket methods and GFRP sheets. A reinforced concrete beam was constructed and the flexural capacity and crack propagation pattern were investigated. The beams were then made with the same dimensions and retrofitted with two methods of concrete jacket and GFRP sheets (single and double-layered) and their load carrying capacity was compared. Load-deflection curves and crack propagation patterns were studied in detail. The results showed that beams retrofitted with reinforced concrete jackets had better flexural strength than the reference beams. On the other hand, beams retrofitted with GFRP sheets failed due to FRP separation in relatively small deformations [15]. Chalioris et al. [16] investigated retrofitting of damaged reinforced concrete beams using U-shaped mortar jackets. The results showed that shear strength and deformability of retrofitted beams were significantly increased compared to reference beam beams [16]. Katakalos et al. [17] investigated retrofitting of T reinforced concrete beams using (SFRP) under cyclic loading. The distance between the SFRP strips and the use of anchoring system were among the parameters studied. The results showed that the anchoring system had a significant effect on the beam performance. Moreover, SFRP strips appear to have good potential for use in shear retrofitting [17]. The variables studied were retrofitting arrangement (U-shaped and fully wrapped), fabric density (1.57 and 4.72 Cordscm) and the number of reinforcing layers (one and two), respectively. The results showed that steel reinforced grout can increase beam strength and deformation capacity of the beams by 160 and 450%, respectively [17]. Zhou et al. [18] investigated retrofitting of reinforced concrete beams using U-shaped steel plates. The results showed that U-shaped steel plates can improve the load-carrying capacity of reinforced concrete beams.

In most studies, retrofitting of reinforced concrete beams were examined using concrete jackets containing conventional concrete, steel plates, and FRP plates. In this study, the retrofitting of beams was conducted by the use of steel-concrete composite jackets containing steel fibers. Using concrete jackets surrounded by steel plates can be effective in improving the performance of concrete beams. This is due to the efficiency of internal concrete, which significantly increases the local buckling capacity of jackets. In general, the combined use of concrete and steel plates has many advantages over concrete jackets or steel plates because the concrete in the plates with inhibitory effect and high compressive strength results in delay in local buckling of the plates and provides greater strength and ductility for concrete due to the limitation of concrete by the steel plate. On the other hand, the use of steel-concrete composite jackets reinforced with steel fibers is practically more effective in retrofitting of the beams that have an irregular outer surface and lack proper concrete cover compared to the use of FRP plates. In other words, for providing a proper bonding between the jacket and the beam surface, the use of steel-concrete composite jackets containing steel fibers will be more appropriate if the peripheral surface of damaged beams is uneven.

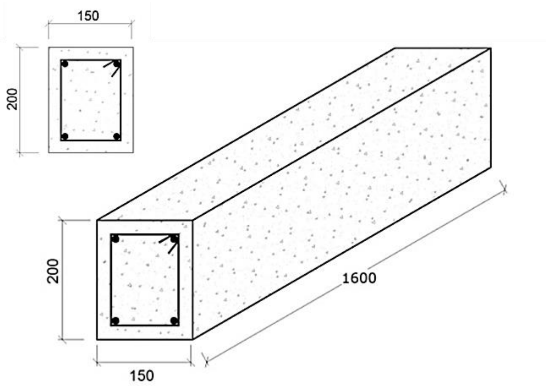
On the other hand, according to previous studies, steel fibers can significantly increase the tensile, compressive and flexural strengths of concrete [19-23]. Because the tensile strength of conventional concrete is low in concrete jackets, the use of steel fibers can compensate for this weakness and significantly increase the load-carrying capacity and energy absorption rate of the beam. In the proposed method, 75% of peripheral surface of concrete beams was initially reinforced using steel and bolt sheets, and concrete reinforced with steel fibers was used between the steel sheets and the peripheral surfaces of the beam. Thus, due to relatively high tensile strength of concrete reinforced with steel fibers, not only the cross-section and moment of inertia of the beam will increase but the tensile strength of the beam will also increase.

2. STUDY PROCEDURE

In studies on retrofitting of reinforced concrete beams, the entire peripheral surfaces of the beams are retrofitted with retrofitting elements [24-26]. However, it is not possible to access all surfaces of the beam in reality. Therefore, in the present study, retrofitting of the beams is not accomplished by the use of composite jackets reinforced with steel fibers throughout the beam surface and only part of it is reinforced in the tensile zone (75 percent of the height of the beam). In other words, this study will focus on retrofitting of reinforced concrete beams that cannot be fully reinforced. This is while in related studies, only the behavior of the beams entirely made of jacket (concrete or steel) and FRP (sheet or rebar) have already been evaluated. The variables studied are steel fiber value (0, 1 and 2% by volume of concrete) and the type of retrofitting method, respectively (concrete jacket, steel-concrete composite jacket, CFRP sheet). The types of cases examined in this study are presented in Figure 1 and Table 1.

3. EXPERIMENTAL PROGRAM

3. 1. Used Material Materials used for constructing the main beams are coarse aggregates, fine aggregates, cement, water, and superplasticizer, respectively.



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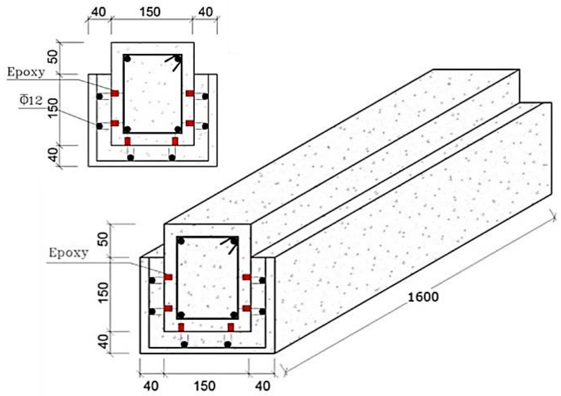

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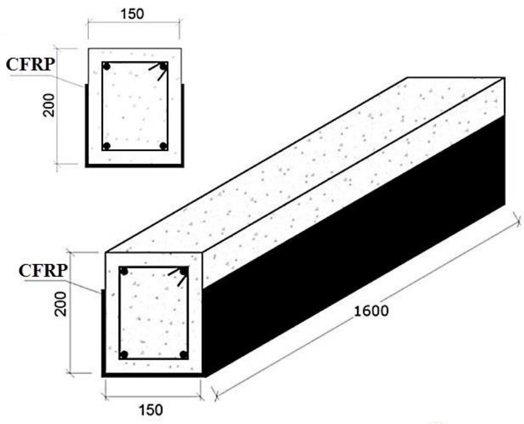

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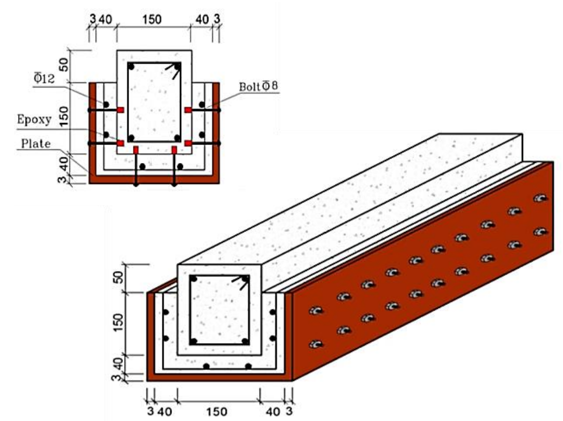

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Figure 1. Types of modes investigated in the present study a: Non-retrofitted beam b: Retrofitting with concrete jacket (containing 0, 1 and 2% steel fibers) c: Retrofitting with steel-concrete composite jacket (containing 0, 1 and 2% steel fibers) d: Retrofitting with two layers of CFRP sheet

TABLE 1. The investigated parameters

Beam	**Type of retrofitting method**	**Volume percentage of steel fiber in jacket**
NR	Non-retrofitted beam	-
J-F0	Retrofitting with concrete jacket	0
J-F1		1
J-F2		2
CJ-F0	Retrofitting with steel-concrete composite jacket	0
CJ-F1		1
CJ-F2		2
CFRP	Retrofitting with two layers of CFRP sheet	-

Moreover, the materials used in constructing concrete jackets are coarse aggregates, fine aggregates, cement, water, superplasticizer, and steel fibers, respectively. Gravel and sand are of crushed type. Coarse and fine aggregates grading test is conducted according to ASTM-C33 [27]. The apparent density of the sand in saturated state with dry surface is 2.6 ton/m^3 and its water absorption rate is 3.2%. The apparent density of gravel in saturated state with dry surface is 2.65 t/m^3 and its water absorption rate is 1.98%. Coarse and fine aggregates grading curve is presented in Figure 2. Portland cement type II was used for constructing original beams and RC jackets. This cement is a product of Hamedan's Hegmatan plant and it has been produced in accordance with ISIRI- 389 (National Standard of Iran) and ASTM C 150. The chemical properties of this cement are presented in Table 2. The density and specific surface area of cement were 3.16 g/cm^3 and 3350 cm^2/g, respectively. The tab drinking water in accordance with ASTM C190 was used. The brand of superplasticizer is Jika Plast. This superplasticizer is liquid and its color is brown. Its density is 1.1 g/cm^2. The steel fibers are simple with hooked ends (Figure 3). The use of such forms of steel fibers greatly enhances tensile strength. The properties of the used steel fibers are presented in Table 3.

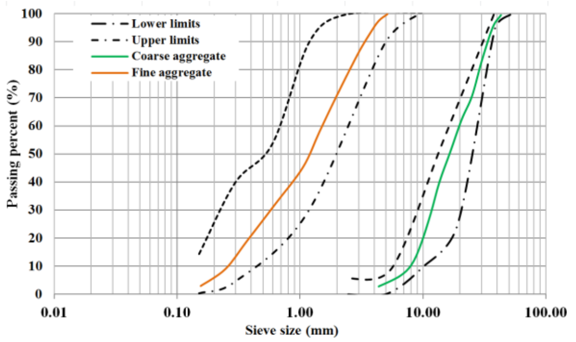


Figure 2. Coarse-grained and fine-grained curves used in construction of the beams

Figure 3. Steel fibers used

TABLE 2. Chemical properties of Portland cement type II

Components (%)	Cement type II
SiO_2	21.27
Al_2O_3	4.95
Fe_2O_3	4.03
CaO	62.95
MgO	1.55
SiO_3	2.26
K_2O	0.65
Na_2O	0.49

TABLE 3. Properties of steel fiber used

Density (kg/m^3)	Length to diameter ratio	Diameter (mm)	Length (mm)
6740	45	0.8	36

3. 2. Geometric Properties and Preparation of Original Beams Length, width, and height of all original beams were 1600, 125 and 200 mm, respectively. The section of all original beams is rectangular. Two longitudinal rebars with a diameter of 14 mm in the tensile section of the beam and two longitudinal rebars with a diameter of 10 mm in the compressive section of the beam were used. For stirrups, plain rebars with a diameter of 8 mm were used. The intervals between the stirrups near the support and in the middle of the beam were 80 and 150 cm, respectively. The geometric properties and the steel reinforcement arrangement of original beams are shown in Figure 4.

Wooden molds were constructed according to dimensions of the beams and prior to concrete pouring, they were smeared with release material to remove them easily. 24 hours after concrete pouring, specimens were removed from molds and stored in a water tank for 28 days. After curing, the beams were prepared for retrofitting. For each turn of concrete pouring, three concrete cubic specimens of 15×15×15 cm and three cylindrical specimens of 30×15 were made to determine the compressive and tensile strength of concrete. The steps of formwork, steel reinforcement, concrete pouring and curing of the original beams are shown in Figure 5.

3. 3. Preparation of Concrete Jackets The beams were retrofitted at the bottom and lateral sides up to 75% of the beam height. Steel reinforcement mesh was prepared at 5 cm intervals and installed 2 cm from the beam surfaces. The diameter of the steel reinforcement mesh was 10 mm. In the method of retrofitting with concrete jackets, a number of rebars with intervals of 30 cm were planted for installing the rebar mesh jacket on the beams and the rebar mesh was connected to them. For this purpose, peripheral beam surfaces were initially made with 30 cm intervals in the peripheral surfaces. Then the steel rebar mesh was placed around the beam. The holes created were filled by the epoxy paste and L-shaped rebars were placed inside it.
After placement of the rebar mesh on the beam surfaces, the concrete used was made with the properties presented in the mixed design section and sprinkled into a 4 cm thick jacket mold. In order to improve the adhesion of the jacket concrete coverage to the main beam, the beam was moistened with water and then concrete operations were

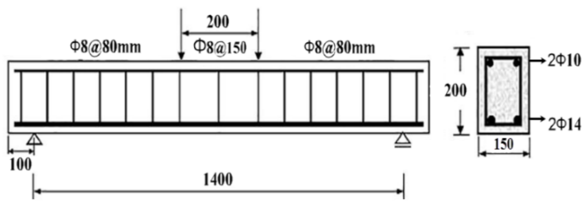


Figure 4. Geometric properties and steel reinforcement arrangement of original beams

performed. To do this, the concrete layers were poured heavily into the mold. Also, the jacket reinforcement mesh was first installed on the surfaces of the beam for the implementation of steel-concrete composite jackets. In the next step, cavities with diameters of 6 mm and intervals of 15 cm were made on steel sheets with thickness of 3 mm and then bonded to the surface of the beams using rebars with diameters of 6 mm and it was done between the sheet and beam surface. In fact, steel strips have been used to create concrete confinement and thereby increase the load-carrying capacity. For the force to be transferred between the concrete member and the steel plate, a proper connection must be made between them. For this purpose, before installing the plates, some holes were made in the concrete member and steel plates, then the plates were placed on the member and the bolts were installed inside the hole. Then the remaining space inside the hole was filled with epoxy. Figure 6 shows preparation of the jackets

3. 4. Mixed Design Mixed design details of the original beams and the concrete jackets are presented in Table 4.

3. 5. Experimental Tests Compressive and tensile behavior of concrete specimens were investigated by performing compressive strength and splitting tensile strength tests. These two tests were performed in accordance with ASTM-C39 and ASTM-C496, respectively. Table 5 presents the average compressive and splitting tensile strengths of concrete specimens after 28 days. Flexural loading of beams is a four-point concentrated type. A fully automatic flexural beam jack with load-carrying capacity of 2000 kN is used for loading of the beams in the laboratory. The supports of the beams under study are considered simple according to many related research studies. The distance of the center to the center of the supports is 140 cm and the distance of the center to the center of the loading pins is 20 cm. Location of supports, loading and strain gauge were marked for precise loading, and the beams were placed precisely under the device. The arrangements of the beam placement and how the load iapplied are shown in Figure 7.

4. RESULTS AND DISCUSSION

Details and properties of the beams and the retrofitting methods were fully presented in the previous sections.

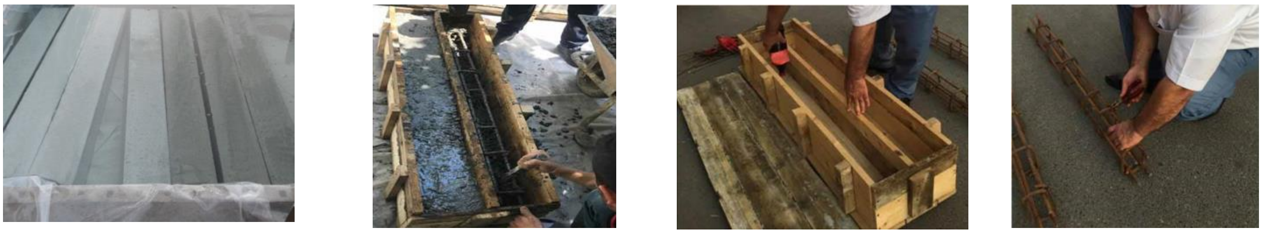


Figure 5. Preparation steps of beams

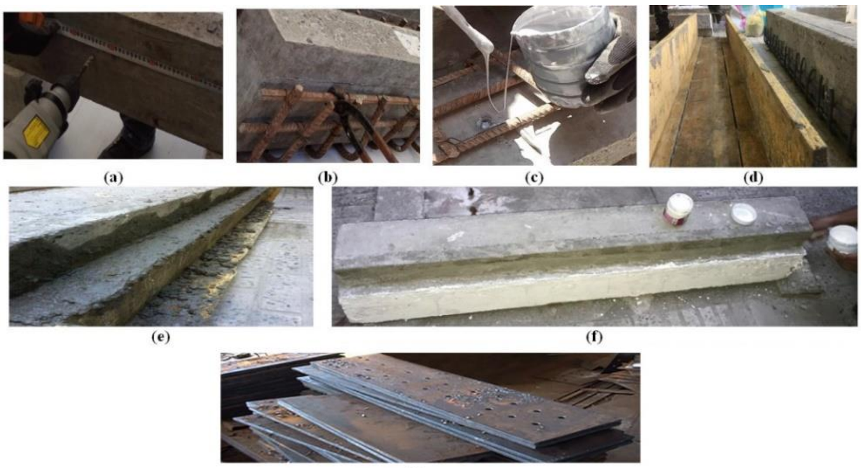


Figure 6. Preparation of concrete jackets a: Creating a hole on the main beam to install a concrete jacket b: Making and installing a steel jacket on the main beam c: Pouring epoxy paste into the hole d: Making mold for installing concrete jacket e: Concrete pouring of concrete jacket f: Preparing concrete beam retrofitted with concrete jacket g: Steel sheet with holes

TABLE 4. Mixed design

No	Member	Mix code	$\frac{W}{C}$	C (kg/m^3)	W (kg/m^3)	G (kg/m^3)	S (kg/m^3)	F (%)	SP (%)
1	Original Beam	NR	0.45	350	157.5	955	885	-	-
2	RC Jacket	J-F0	0.45	500	225	785	710	0	1
3		J-F1	0.45	500	225	785	710	1	1
4		J-F2	0.45	500	225	785	710	2	1
5		CJ-F0	0.45	500	225	785	710	0	1
6		CJ-F1	0.45	500	225	785	710	1	1
7		CJ-F2	0.45	500	225	785	710	2	1

W: Water C: Cement G: Gravel S: Sand F: Steel fiber SP: Superplasticizer

TABLE 5. Compressive and splitting tensile strengths

No	Member	Steel fiber (%)	Compressive strength (MPa)	Splitting tensile strength (MPa)
1	Original Beam	0	27.3	2.61
2	RC Jacket	0	36.9	3.12
3		1	37.1	3.89
4		2	37.6	3.98

Figure 7. Loading details of the beams

After the beams were made in different cases, they were examined using a loading device. This section presents the results of the experiments and their interpretations. The behavior of the beams was compared using load-displacement curves and parameters such as ultimate load, crack load, yield load, crack displacement, yield displacement, ultimate displacement, ductility, energy absorption capacity, and stiffness.

4. 1. Observations and Primary Results Evaluating the overall behavior of the tested beams and recording of their qualitative observations is one of the most important experimental studies in the field of reinforced concrete beams. Although the functions of the beams can be easily judged by quantitative results, using qualitative observations can provide a better understanding of the behavior and the results. Generally, recording of the observations related to the mechanism and the crack propagation pattern and failure as well as the loading steps of the specimens from the beginning to the final failure in experimental studies can be helpful for better understanding the behavior of the specimens as well as better inferring of the results. For this purpose, this study has attempted to express as much as possible the qualitative observations, which will be discussed in detail below.

4. 1. 1. The NR Beam The NR beam with a rectangular section was considered as the reference specimen, which its shape and its longitudinal and shear reinforcement are similar to other specimens. The first crack in the specimen was occurred under a load of about 4.1 kN in the middle of the span. The yield of tensile rebars occurred at a force of about 34.2 kN. The crackings also started with the tensile cracks in the middle of the span, gradually expanded and moved to the supports and their widths were increased. Most cracks appeared in the middle part of the beam. They expanded with increasing force and moved to the compressive part of the beam. At the end, the test was completed due to the decrease in the load-carrying of the beam and an increase in the displacements of the center of the span. The ultimate load and the maximum displacement of the NR beam were 52 kN and 11.7 mm, respectively. The concrete was crushed at the place of applying centralized forces. Figure 8 illustrates the NR beam failure mode.

4. 1. 2. The J-F0 Beam In the second stage, the J-F0 beam in which reinforced concrete jacket without steel fibers used was tested. The details of reinforcement and mixed design of this beam are similar to the reference beam. The first crack in the beam occurred at a force of

Figure 8. NR beam failure mode

7.2 kN in the middle of the span. The yield of tensile rebars occurred at a force of about 66.3 kN. The cracks also began with the tensile cracks in the middle of the span, gradually expanded and their widths were increased. The shear cracks also appeared near the supports at an angle of 45 degrees, but these cracks were limited and their widths did not increase much. These cracks did not expand with increasing force and they entered the compression section. The ultimate load and maximum displacement of the J-F0 beam were 85 kN and 14.7 mm, respectively. Figure 9 presents the J-F0 beam failure mode.

4. 1. 3. The J-F1 Beam After loading the J-F1 beam, the first flexural crack was observed in the range of one-third of the middle of beam with applying a load equal to 9.3 kN. The cracks were increased and were deepened by increasing load. The load corresponding with tensile yielding strength of steel rebar was 68.9 kN. Next, a large amount of displacement was created by increasing the load to the point where the concrete beam compression zone was on the verge of spaling. In the ultimate mode, abnormal sounds like concrete bursting were heard inside the beam during concrete spalling of the compression zone and the concrete jacket surface was slowly spalled and the load changes were slowed and finally stopped. Spalling of the concrete jacket can be a good warning for the coming of the concrete spalling stage of compression zone beam

The ultimate load and displacement of the J-F1 beam are 93 kN and 17.9 mm, respectively. By comparing the behavior of the J-F1 beam with the J-F0, it can be stated that fibers also act as a crack inhibitor. That is to say, by the start of cracking, the fibers play a role in sewing the crack and limiting the size of the crack and preventing the cracking from continuing even as the loading continues. However, cracking continued on the top of the beams without steel fiber. The crack in beam with concrete jacket containing steel fibers does not move halfway up the beam height, and by opening the crack, the fibers connect the gap to the sides of the failure area and delay the beam collapse. Figure 10 illustrates the failure mode in the J-F1 beam.

Figure 9. J-F0 beam failure mode

4. 1. 4. The J-F2 Beam The crack load and the yield load of the J-F2 beam were 9 and 68.7 kN, respectively. The maximum bearing load of this beam was recorded 91 kN. The increase in spalling load on the concrete jacket continued as the cracks widened. The expansion of these cracks was evident in the lower part of the concrete jacket. The failure of the beam was caused by crippling of the concrete jacket over the compression section. At all loading stages, no apparent deboning was observed between steel fiber reinforced concrete jacket and beam concrete. Again, it can be pointed out that the development of cracks in the beams that have no steel fibers is far more than the fibers used in the jackets. After the first crack, the fibers connect the two sides of the crack and prevent the crack from widening. Figure 11 illustrates the J-F2 beam failure mode.

4. 1. 5. The CJ-F0 Beam The first crack in the CJ-F0 beam was observed at a load of about 11.1 kN. Crippling occurred with the spalling and buckling of the concrete-steel composite jacket in the compression zone. The yielding of tensile steels was observed with a significant increase in displacement at 87.2 kN. The maximum bearing load and the ultimate displacement were recorded 96.1 kN and 22.7 mm, respectively. Figure 12 illustrates the CJ-F0 beam failure mode.

4. 1. 6. The CJ-F1 Beam Among the studied beams, the CJ-F1 beam had a much better performance

Figure 10. J-F1 beam failure mode

Figure 11. J-F2 beam failure mode

Figure 12. CJ-F0 beam failure mode

compared to other beams. The combined use of concrete and steel sheet has made the concrete beam more capable of withstanding loads . The first CJ-F1 beam crack was observed at the load of 13.6 kN. As the loading of the composite jacket spalling was observed at the compression area, this crippling increased with increasing load. The yielding of tensile steels was recorded by increasing the displacement at a load of 101 kN and then the crippling of the upper part of the reinforcement zone was observed. This crippling was due to the presence of large amounts of fibers, along with the failure of the compression zone, and with increasing load and expansion of the crippling zone, one of the cracks under the load widened and beam failure occurred with tearing of the steel plates. The ultimate load and maximum displacement of the CJ-F1 beam were 119 kN and 31.8 mm, respectively. Figure 13 illustrates the CJ-F1 beam failure mode.

4. 1. 7. The CJ-F1 Beam The first crack was observed in the CJ-F2 beam between the jacket and the concrete beam at 12.9 kN. These cracks were distributed in the middle range of the beam and spread to the jacket by increasing the load of cracks. Increasing load increased the depth and the width of cracks. With yielding of tensile steels at a load of about 89.3 kN, load increasing was limited and an increase in the amount of displacement in the middle of the span was observed. The spelling of the beam compression zone began at about 91.2 kN, indicating the beginning of plastic deformations in the beam compression zone. Crushing of the compression zone after flowing the tensile steels resulted in the beam failure. At all loading stages, no significant separation was observed between the jacket and the concrete beam. Figure 14 illustrates the CJ-F2 beam failure mode.

4. 1. 7. The CFRP Beam The last beam tested is a beam which is retrofitted with two layers of CFRP sheet. The first crack created under the force of 5.1 kN in the middle of the span. Also, tensile rebars flowed at 62.3 kN. The cracks also began with the tensile cracks in the middle of the span, gradually expanded and widened. Shear cracks appeared at an angle of 45 degrees but these cracks were limited and their width did not increase much. These cracks expanded with increasing force and entered the compression zone. The ultimate load and the maximum displacement of CFRP beams were 90.8 kN and 17.5 mm, respectively. Figure 15 illustrates the CJ-F2 beam failure mode.

Figure 13. CJ-F1 beam failure mode

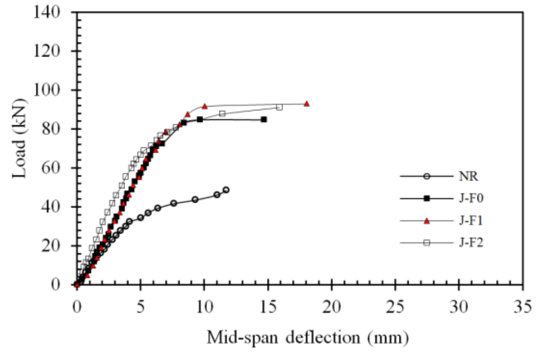
Figure 14. CJ-F2 beam failure mode

4. 2. Load-displacement Curves The load-displacement curves of the reference beam, beams retrofitted with concrete jacket, beams retrofitted with steel-concrete composite jacket, and the beam retrofitted with CFRP sheet are presented in Figure 16.

The values of crack load, yield load, ultimate load, crack displacement, yield displacement and ultimate displacement, ductility, stiffness, and energy absorption capacity of the beams are presented in Table 6. Figure 17 shows an increasing percentage of crack, yield and ultimate loads of retrofitted beams compared to the reference beam. As can be seen, the addition of concrete jackets containing 0, 1 and 2% of steel fibers increased the beam crack load by 75, 127 and 120%, respectively, compared to the reference beam. By improving the mechanical properties of the concrete used in concrete jackets, steel fibers can be a suitable option leading to confinement of the concrete and increasing the strength of the beam against cracking. On the other hand, the use of steel-concrete composite jackets containing 0, 1 and 2% increased the beam crack load by 171, 232 and 215%, respectively, compared to the reference beam. In fact, steel plates delay the crushing of concrete in beams by creating confinement and increasing their load-carrying capacity. The use of CFRP plates also increased the beam crack load by 24%.

In all of the beams, the use of all three proposed methods increased the yield load so that the yield load corresponding to the beams retrofitted with concrete jackets containing 0, 1 and 2% steel fibers increased by 94, 101 and 101%, respectively. Adding steel fibers reduces the slip of the used rebars in the jacket and the width of the cracks. Also, the yield load corresponding to the beams retrofitted with steel-concrete composite jackets containing 0, 1 and 2% steel fibers increased by 155, 161 and 195%, respectively. On the other hand, the yield load corresponding to the beams retrofitted with using CFRP sheets increased by 82%. According to Figure 17, the addition of steel fiber reinforced

Figure 15. CJ-F2 beam failure mode



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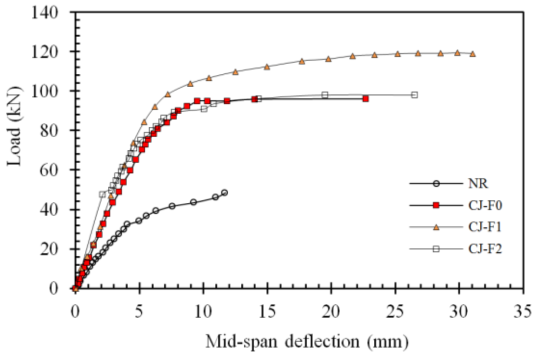

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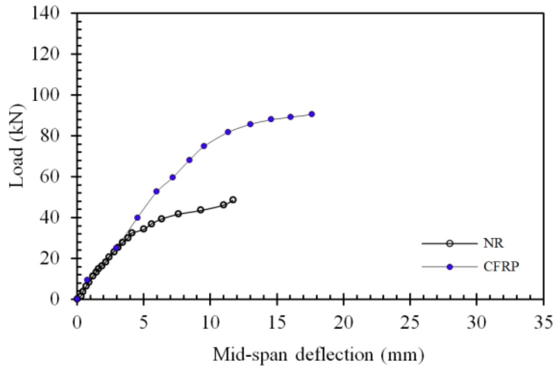

(c)

Figure 16. Load – displacement curves of retrofitted beams in different modes (a) The use of concrete jackets (b) The use of steel and concrete composite jackets (c) The use of CFRP

concrete jackets containing 0, 1 and 2% increased the ultimate load of the beams by 63, 79 and 75%, respectively. Adding steel fibers to concrete jackets increased the ultimate capacity of the beams. In fact, the fibers significantly increased the tensile toughness of the concrete. Regarding the strength drop of the retrofitted beam with 2% steel fibers, it can be stated that due to high volume of fibers, the compression and mixed operation was not performed properly. Also, the use of steel-concrete composite jackets containing 0, 1 and 2% steel fibers increased the amount of ultimate load of the beams compared to the reference beam by 85, 89 and 129%, respectively. On the other hand, the use of CFRP sheet increased the ultimate load-carrying capacity of the beam by 75%. Table 5 presents the crack, yield and ultimate displacement of the beams under study. An increase in percentage of crack, yield, and ultimate displacement of retrofitting beams compared to the reference beam are shown in Figure 18. Adding concrete jackets containing 0, 1 and 2% steel fiber increased the displacement of the cracks by 100, 140 and 160%, respectively. Addition of steel-concrete composite jackets containing 0, 1 and 2%

TABLE 6. Summary of the results of the four-point flexural test

No.	Name	Load (kN)			Mid-Span deflection (mm)			Ductility	Stiffness (N/mm)	Energy absorption (J)
		Crack	Yield	Ultimate	Crack	Yield	Ultimate			
1	NR	4.1	34.2	52.0	0.50	5.00	11.7	2.34	8228.6	382
2	J-F0	7.2	66.3	85.0	1.00	5.70	14.7	2.58	8605.7	916
3	J-F1	9.3	68.9	93.0	1.30	6.16	17.9	2.69	9222.9	1097
4	J-F2	9.0	68.7	91.0	1.20	5.90	15.9	2.91	8948.6	1266
5	CJ-F0	11.1	87.2	96.1	1.80	7.70	22.7	2.95	15085.7	1822
6	CJ-F1	12.9	101.0	119.0	2.40	8.95	31.8	3.55	16457.1	3119
7	CJ-F2	13.6	89.3	98.1	2.10	7.73	26.6	3.44	16525.7	2259
8	CFRP	5.1	62.3	90.8	0.89	7.30	17.5	2.40	8537.1	1074

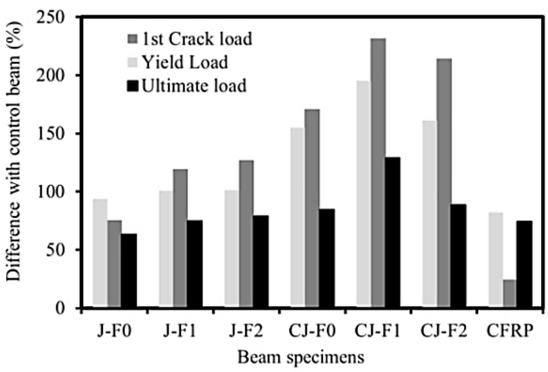

Figure 17. Increasing percentage in crack, yield and ultimate loads of retrofitted beams compared to the reference beam

of steel fibers increased the crack displacement by 260, 380 and 320%, respectively. The use of the CFRP sheet also increased crack displacement by 78%. According to Figure 18, the ultimate displacement of J-F0, J-F1, J-F2, CJ-F0, CJ-F1, CJ-F1 and CFRP specimens compared to the reference specimen increased by 100, 140, 160, 260, 380, 320 and 78 %, respectively. Also, the yield displacement of J-F0, J-F1, J-F2, CJ-F0, CJ-F1, CJ-F1 and CFRP specimens compared to the reference specimen increased by 14%, 18, 23, 54, 79, 55 and 46%, respectively.

According to the results, it can be seen that the use of concrete jackets containing steel fibers can have an important role in improving the load-carrying capacity of reinforced concrete beams. So that adding fibers can improve the flexural strength, flexural capacity and maximum displacement of the member by improving the bonding strength. The mechanism of increasing flexural capacity due to the use of steel fibers can be described as follows:

The fibers prevent from creating very fine cracks in concrete texture by creating a proper bonding in concrete jacket and they reduce the amount of stress at the tip of the cracks by transferring stress between the edges of the cracks, and by this way, they prevent from increasing the width of cracks and turning small cracks into large cracks.

4. 3. Ductility Ductility is one of the most important features of structural elements, which is usually considered in studies about retrofitting of beams. Ductility is the ability of a member to withstand inelastic deformation prior to failure without losing a lot of strength. The reason for choosing this index is its high importance in flexural loading structures. Equation (1) calculates deflection ductility.

$$\mu = \frac{\Delta_u}{\Delta_y} \quad (1)$$

In this equation, Δ_u is the ultimate deflection and Δ_y is the yield deflection in load-deflection curves [33-36]. Figure 19 compares the flexural capacity and ductility index of the beams under study . As it can be seen, the presence of fibers increases the ductility and flexural load carrying capacity of the specimens so that the concrete jackets containing fibers cause the beams to withstand more forces with greater ductility . On the other hand, using steel-concrete composite jackets, due to greater flexural stiffness, shows greater flexural capacity compared to steel fiber reinforced concrete jackets and GFRP sheets and they also have a much better performance in terms of ductility. So the ductility of the beams retrofitted with steel-concrete composite jackets containing steel fiber increased from 26 to 52% depending on the control specimen. The use of steel-concrete composite jackets in the investigated beams not only increases the ultimate load-carrying capacity but also increases the energy absorption capacity and ductility by creating confinement. Also, the ductility of the beams retrofitted with using 2 layers of CFRP sheets compared to the control beam increased by 2%, respectively. However, the ductility of the beams retrofitted with concrete jackets containing steel fiber compared to the control specimen increased from 10 to 24% depending on fiber content. In fact, the use of steel fibers in concrete jackets improves the ductility of the beams by preventing abrupt cracks.

Therefore, concrete jackets retrofitted with reinforced steel-concrete composite jackets containing steel fiber have more ideal flexural strength than the reference beam. The beams retrofitted with CFRP sheets failed due to FRP deboning in relatively small deformations. Although reinforced concrete jackets can increase the ductility of reinforced concrete beams, the CFRP method cannot provide enough ductility. Therefore, the concrete jacket and the steel-concrete composite jacket method can perform better in seismic zones than the concrete jacket method.

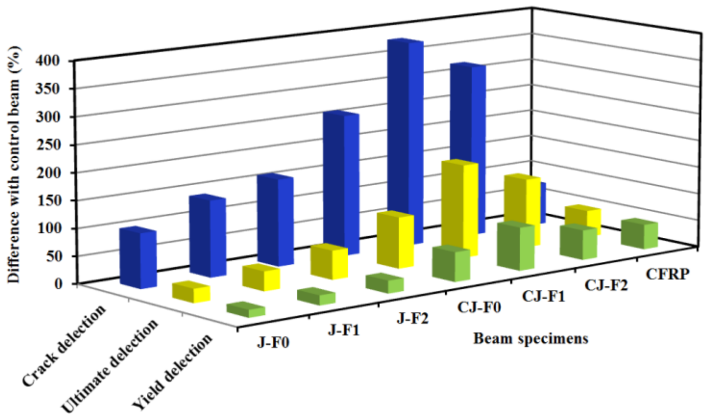

Figure 18. The increasing percentage in crack, yield and ultimate displacement of reinforced concrete beams compared to the reference beam

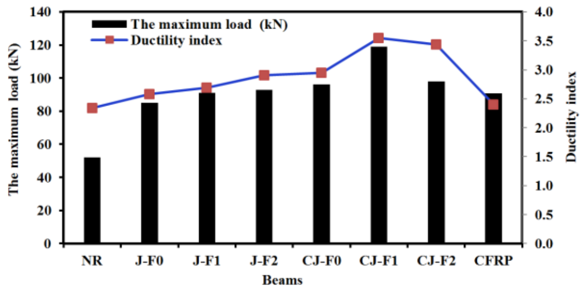

Figure 19. Comparison of flexural capacity (maximum load) and ductility index of the investigated beams

4. 4. Stiffness Stiffness means the strength of a body against deformation and is one of the most important parameters in examining the behavior of concrete structures. Stiffness is one of the parameters that can be used to predict the strength of structural members against crack propagation and deflection. In RC buildings, stiffness depends on factors such as applied load, cracks in beams, reinforcement bars, etc. [37]. In this study, the stiffness amount was obtained from dividing service load by service deflection. According to ACI318, the service load on the load-displacement curve is achieved at a point corresponding to L/480. Figure 20 compares the stiffness of the examined beams. Using steel fiber reinforced concrete jackets, steel-concrete composite jackets and CFRP sheets in all cases improved the stiffness of the beam. The highest stiffness value was obtained for the CJ-F1 specimen, where the beam stiffness increased by 92%. The combined use of steel and concrete as a jacket prevented the crushing of the concrete jacket and increased the flexural stiffness in addition to the joint participation of steel sheet and concrete in load carrying. The performance of composite concrete and steel sections is such that the steel sheet buckling is delayed due to the presence of concrete core. On the other hand, confinement of the concrete jacket by steel sheet reduced the expansion of cracks, crushed concrete in the compression zone, and increased the stiffness of the beam. The use of 2-layers of CFRP sheets also increased the stiffness of the beams by 71% compared to the reference beam.

In the case of improvement in elastic stiffness, specimens reinforced with steel-concrete composite jacket containing steel fibers performed better than those reinforced with FRP sheets and concrete jackets.

4. 5. Energy Absorption Capacity Since the most important effect of fibers on concrete is the increase of ductility, the measurement of flexural toughness (energy absorption capacity) has been considered by most researchers. The greater the energy absorption capacity is, the better its member performs [38, 39]. In this study, the energy absorption capacity of the beam was calculated by determining the area under the load-displacement curve. The energy absorption capacity and its increasing amount compared to the reference beam for different beams are presented in Figure 21. The results show that the addition of concrete-steel composite jackets containing steel fibers has a significant effect on increasing the energy absorption capacity of the beams; So, depending on the amount of steel fiber, the energy absorption capacity of the beams increased by about 377 to 716 %.

Adding fibers to the concrete jacket significantly increased the toughness and energy absorption, which plays an important role in the type of concrete failure. When the fibers are present in the concrete, the cracks cannot expand without increasing the length or release of the fibers, so considerable energy is required for the fibers to be broken or released before the concrete is fully broken. Also, the energy absorption capacity of retrofitted beams with concrete jackets containing steel fibers increased from 139 to 231% depending on the amount of steel fibers. Fiber concrete increases depreciation energy and load-carrying capacity and delays damage in the concrete. Increasing the energy absorption capacity of reinforced beams with steel fiber jackets can be due to friction between the cement paste and steel fibers. Since the fibers are scattered in the concrete body in three-dimensional form, if a crack is formed in different directions, it creates bonding fibers and prevents crack propagation. Therefore, the fiber strands are actively involved in limiting the width of the

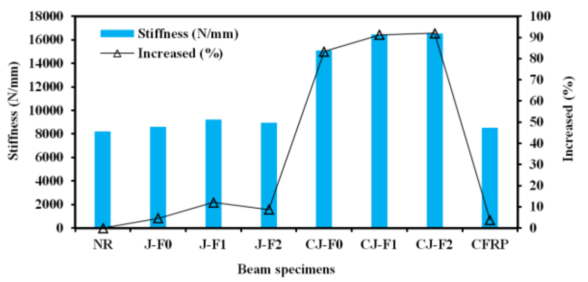

Figure 20. Comparison of the stiffness of the beams under study

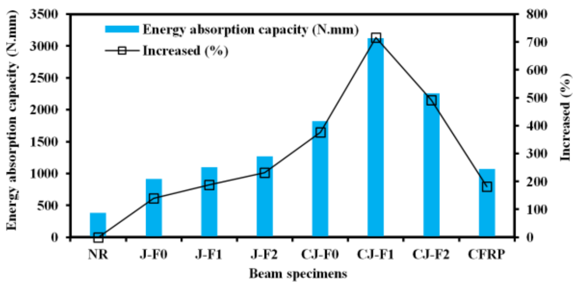

Figure 21. Comparison of energy absorption capacity of the beams under study

cracks and contribute to the formation of microcracks. As a result, they increase the usability of concrete. On the other hand, the energy absorption capacity of retrofitted beams with CFRP sheets increased by 181%. CFRP sheets have less energy absorption capacity than other methods because of the deboning of FRP from the beam surface and deboning phenomena. In general, reinforced steel-concrete composite specimens have both achieved the highest energy absorption capacity and exhibited greater plasticity. Retrofitted specimen with FRP sheets also improved ductility, and reinforcement with concrete jackets considerably increased load carrying capacity and improved ductility.

In specimens reinforced with steel-concrete composite jacket, a specimen in which 1% of steel fibers was used treated better than the other specimens in terms of ultimate strength, ductility, and energy absorption. In fact, it can be said that due to the relatively limited jacket space, using 1% of fibers has a greater effect on the beam behavior. Although specimens reinforced with concrete jacket had a significant improvement in bearing loads, they showed less energy absorption capacity due to less confinement.

5. CONCLUSION

In the present study, retrofitting of reinforced concrete beams using steel fiber reinforced concrete jacket, steel-reinforced concrete composite jacket, and CFRP sheets were investigated. The use of steel composite jackets containing steel fibers and its comparison with concrete jackets and CFRP sheets are the most important innovations of the present study. According to the mentioned methods, eight beams were made and placed under four-point flexural loading. The most important results are presented in this section:

- The addition of concrete jackets containing 0, 1 and 2% of steel fibers increased the beam crack load by 75, 127 and 120%, respectively, compared to the reference beam. By improving the mechanical properties of the concrete used in concrete jackets, steel fibers can be a suitable option leading to confinement of the concrete and increasing the strength of the beam against cracking.
- The use of steel-concrete composite jackets containing 0, 1 and 2% increased the beam crack load by 171, 232 and 215%, respectively, compared to the reference beam. In fact, steel plates delay the crushing of concrete in beams by creating confinement and increasing their load-carrying capacity.
- Adding steel fiber to concrete jackets increased the ultimate capacity of the beams by 63 to 79%. In fact, the fibers significantly increased the tensile toughness of the concrete. The use of steel-concrete composite jackets containing 0, 1 and 2% steel fibers increased the amount of ultimate load of the beams compared to the reference beam by 85, 89 and 129%, respectively. In addition, the use of CFRP sheet increased the ultimate load-carrying capacity of the beam by 75%.
- The addition of concrete-steel composite jackets containing steel fiber had a significant effect on increasing the energy absorption capacity of the beams; So, depending on the amount of steel fiber, the energy absorption capacity of the beams increased from 377 to 716 %.
- The highest stiffness value was obtained for the CJ-F1 specimen, where the beam stiffness increased by 92%. The combined use of steel and concrete as a jacket prevented the crushing of the concrete jacket and increased the flexural stiffness in addition to the joint participation of steel sheet and concrete in load carrying. The performance of composite concrete and steel sections is such that the steel sheet buckling is delayed due to the presence of concrete core.
- The performance of composite concrete and steel sections is such that the steel plate buckling is delayed due to the presence of concrete core. On the other hand, the confinement of concrete jacket by steel plate reduced the expansion of cracks and crushing of the concrete in the compression area and increased the stiffness of the beam.

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Persian Abstract

چکیده

در مطالعه حاضر یک روش پیشنهادی به منظور مقاوم سازی تیرهای بتن مسلح معرفی شده است که در آن از روکش‌های کامپوزیتی فولادی – بتنی حاوی الیاف فولادی استفاده شده است. برای این منظور ۷۵ درصد سطح پیرامونی تیرهای بتن مسلح در ناحیه کششی، در ابتدا با استفاده از ورق‌های فولادی و بولت مسلح شدند و در حد فاصل بین ورق های فولادی و سطوح پیرامونی تیر از بتن مسلح به الیاف فولادی استفاده شد. بدین ترتیب ضمن افزایش سطح مقطع و ممان اینرسی تیر، با توجه به مقاومت کششی نسبتاً بالای بتن‌های مسلح به الیاف فولادی مقاومت کششی تیر نیز افزایش خواهد یافت. متغیرهای مورد بررسی به ترتیب شامل مقدار الیاف فولادی (۰، ۱ و ۲ درصد حجم بتن) و نوع روش مقاوم سازی (روکش بتنی، روکش کامپوزیتی فولادی – بتنی و ورق CFRP) می‌باشند. بدین ترتیب ۸ تیر بتن مسلح ساخته شد و پاسخ آنها در برابر بارگذاری چهار نقطه‌ای با بررسی پارامترهایی نظیر بار ترک، بار تسلیم، بارنهایی، شکل پذیری، سختی و ظرفیت جذب انرژی با یکدیگر مورد مقایسه قرار گرفت. نتایج حاصل نشان داد روکش‌های کامپوزیتی مسلح به الیاف فولادی با ایجاد محصور شدگی تشکیل اولین ترک در بتن و تسلیم میلگردهای فولادی را به تاخیر می اندازد و سبب می‌شود بسته به مقدار الیاف فولادی ظرفیت جذب انرژی تیرها را در حدود ۸۹ تا ۱۲۹ درصد افزایش یابد. از سوی دیگر استفاده از روکش‌های کامپوزیتی فولادی - بتنی به دلیل سختی خمشی بیشتر، ظرفیت خمشی بیشتری در مقایسه با روکش‌های بتنی مسلح به الیاف فولادی و ورق‌های CFRP از خود نشان می‌دهند و از جنبه شکل پذیری نیز دارای عملکرد بمراتب بهتری هستند.