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STRENGTHENING OF REINFORCED CONCRETE BEAMS IN A DAMAGED BUILDING USING CARBON FIBER MATERIALS

Abstract. This article discusses modern methods for calculating various methods for checking the bearing capacity of a beam after its strengthening in a multi-story commercial building (on the example of the Al-Salam Commercial complex), located at the address: Iraq, Ramadi, St. Alcinama. The building was damaged by the war, necessitating a study to determine the best and most cost-effective way to strengthen concrete beams using carbon fiber composite materials as the external strengthening. Based on the data obtained as a result of the strength assessment, recommendations were given on the method of strengthening reinforced concrete beams.

Keywords: strengthening, beam, reinforced concrete, shear, carbon fiber, strength, bending, polymer composite, rod

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УСИЛЕНИЕ ЖЕЛЕЗОБЕТОННЫХ БАЛОК В ПОВРЕЖДЕННОМ ЗДАНИИ С ИСПОЛЬЗОВАНИЕМ УГЛЕРОДНЫХ МАТЕРИАЛОВ

Аннотация. В данной статье рассмотрены современные методы расчетов различных способов проверки несущей способности балки после ее усиления в многоэтажном коммерческом здании (на примере торгового комплекса Аль-Салам), расположенном по адресу: Ирак, город Рамади, ул. Альсинама. Здание было повреждено в результате военных действий, что потребовало проведения исследования по определению наилучшего и наиболее экономичного способа усиления железобетонных балок с использованием композитных материалов на основе углеродного волокна в качестве системы внешнего армирования. На основании полученных данных в результате оценки на прочность были даны рекомендации по способу усиления железобетонных балок.

Ключевые слова: усиление, балка, железобетон, сдвиг, углеродное волокно, прочность, изгиб, полимерный композит, стержень

1. Introduction

Strengthening the structural elements of buildings is an important issue for building maintenance and sustainability [1, 2]. Strengthening the structural members of the building to increase its bearing capacity in the event of the need to increase the design loads or in the event of the building being damaged as a result of external factors. Correct and timely strengthening of building structures can significantly lower costs, increase their useful lives, or prevent accidents and collapses [3, 4].

There are several ways to strengthen the structural elements, including old ones, such as reinforcement using iron structures or steel sheets, as well as modern methods such as using fiber-reinforced polymer (FRP) and carbon fiber bars [5].

One of the disadvantages of using epoxy-bonded external steel panels and building steel jackets is that it increases the self-weight of the building in addition to an increase in the dimensions of the structural elements in addition to distorting the architectural dimensions [6]. However, it is effective in terms of strength, hardness, and ductility [7]. The advantages of reinforcing structural elements using carbon-fiber panels are that they are light in weight, have high resistance to aggressive environments, are not limited in dimensions, have high strength, ease of implementation, do not require equipment, are very good in execution, do not require a long time to implement. Even though the reinforcement with carbon fiber panels is considered expensive if we compare it with traditional methods, it is sometimes economically feasible as it is possible to work in the building without the need to turn it off, and the work does not need a lot of workers, and it is possible to increase the stress by increasing the width of the carbon fiber panels or increase the number of layers [8,9].

Through studies, it has been shown that cracking can occur after strengthening by separation of the external composite reinforcement from the concrete's surface as well as the separation of the protective layer of concrete from the external reinforcement running along the steel bar [10].

Carbon fiber strengthening is the most flexible and increases the rigidity of the structure [1, 11]. It has high physical and mechanical properties that exceed those of steel [12].

The use of the technology of carbon fiber rods installed near the surface is a good technique for strengthening structural elements, especially in areas of negative torque [13]. This technique is more effective in areas where the strengthening is subject to mechanical and environmental damage. Where a groove is made in the desired direction and filled with a special epoxy, carbon fiber rods are installed inside the groove, and the epoxy is settled with the outer surface of the concrete.

2. Problem Research

2.1. Characteristics of the place of practice

An eight-story building of a shopping center, as shown in Fig. 1, it is called (Al Salam Commercial Complex), which was damaged by the war in 2015, was chosen to study the reinforcement of reinforced concrete beams. The building is located in Anbar Governorate, Ramadi city, on Main Street and Cinema Street. The building was damaged, as shown in Fig. 2. The company supervising the restoration of the building was contacted and through them, the architectural and construction plans were obtained, as well as the results of laboratory tests carried out to assess the condition of the concrete parts of the building.

2.2. Material properties and reinforcement details of the concrete beams

We conducted a study on the beam specified in Fig. 3, with a length of 6.95 m and dimensions of 600 * 400 mm, the lower reinforcement (2Ø25+3Ø20), the upper reinforcement (2Ø25), and stirrups (Ø10/200mm) as in Fig. 4.

The laboratory tests obtained from the company supervising the strengthening of the beams in the building, where the hammer test and ultrasound of the above beam, where was the compressive strength of concrete 31,3 MPa.

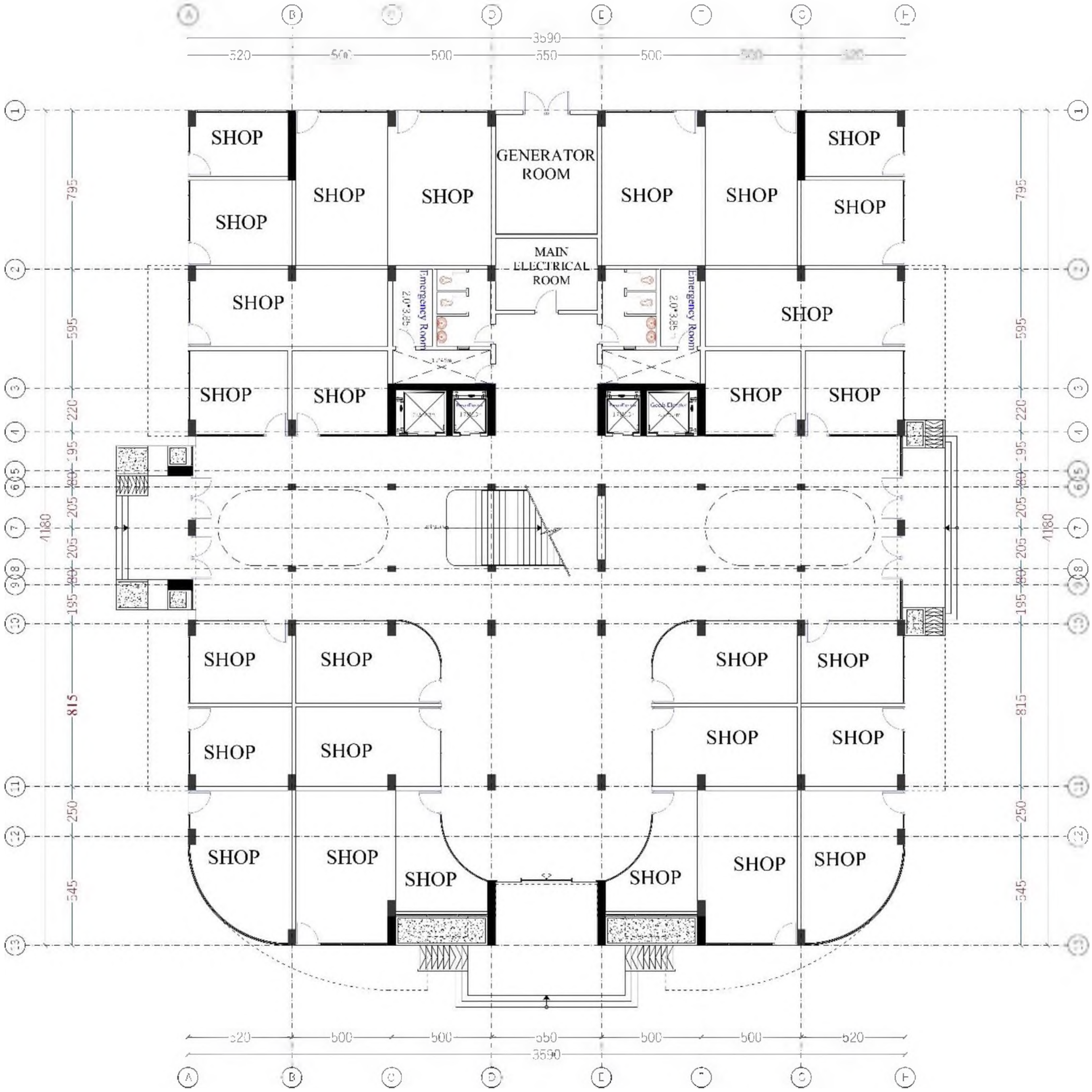

Fig. 1. First floor plan for commercial complex

Fig. 2. The southeast facade of the commercial complex

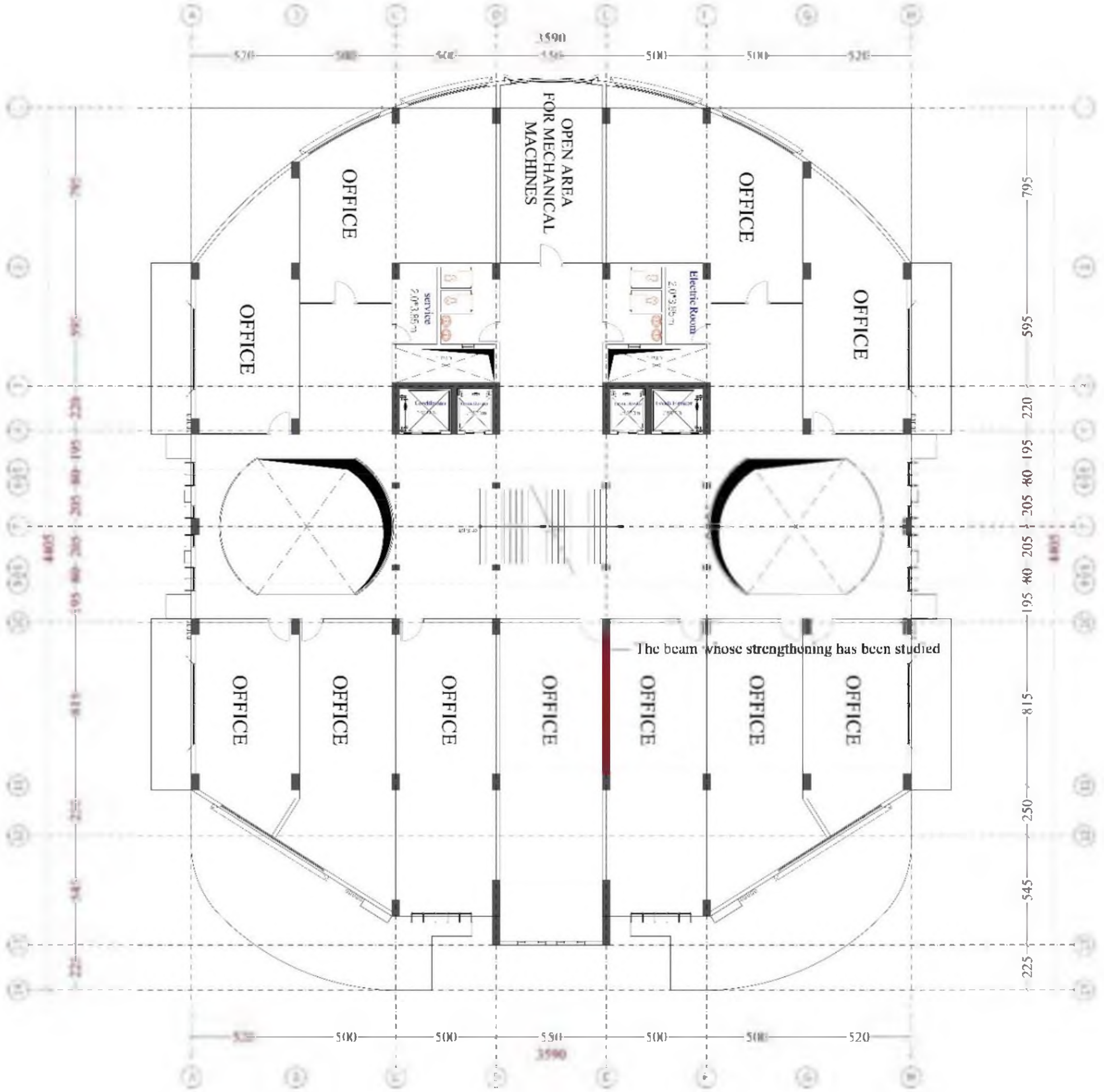

Fig. 3. Plan for the sixth floor Indicates the location of the beam to be studied

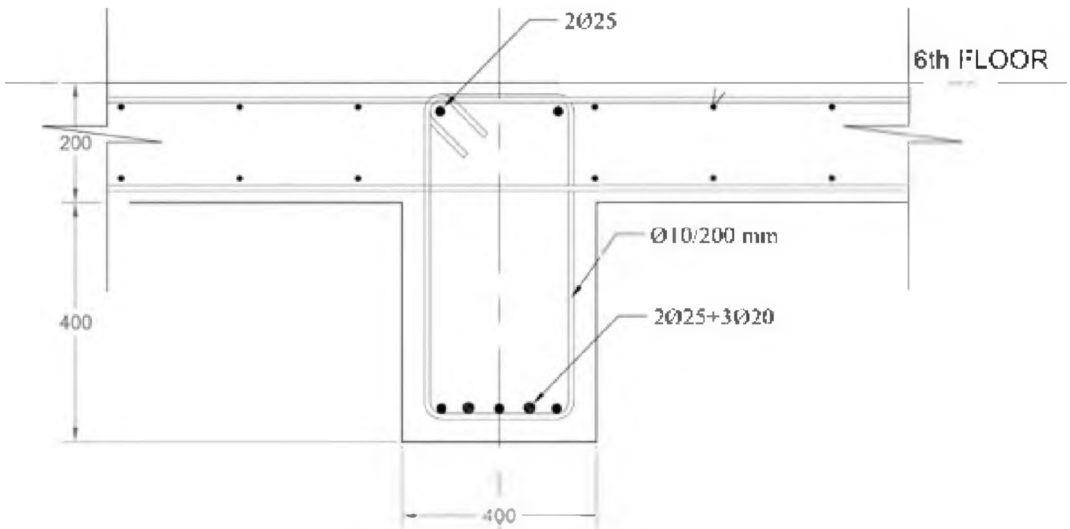

Fig. 4. The section of the beam

2.3. Materials used to strengthen the beam

Carbon fiber plates of the type (Sika® CarboDur® S512) were used, which are pultruded carbon fiber reinforced polymer (CFRP) laminates. According to the properties of material shown in Table 1 [14].

Carbon fiber fabric of the type (SikaWrap®-530C) was used, is a carbon fiber fabric made of unidirectional weaving that is used for wet application. According to the properties of material shown in Table 2 [15].

Carbon fiber fabric of the type (SikaWrap®-301C) was used, is a unidirectional woven carbon fiber fabric for the wet application process. According to the properties of material shown in Table 3 [16].

Carbon fiber bars of the type (Sika® CarboDur® 1/2" rod) were used, and Pultruded carbon fiber reinforced polymer (CFRP) rods are used to reinforce concrete. By placing the rods into grooves carved out of the beam and bonding them with epoxy resin, the Near Surface Mounted (NSM) technique is usually used to attach the rods. According to the properties of material shown in Table 4 [17].

Linking material of type (Sikadur®-330) is a two-part, solvent-free, thixotropic epoxy-based impregnating resin/adhesive. According to the properties of material shown in Table 5 [18].

Table 1

Mechanical and physical Properties of Carbon fiber type Sika® CarboDur® S512

Characteristics name	Units of measurement	Value
Width	mm	50
Thickness	mm	1,2
Strength of Tensile	MPa	3100
Modulus of Elasticity in Tension	MPa	160000
Elongation during Tensile Break	%	1,7

Table 2

Mechanical and physical Properties of Carbon fiber type SikaWrap®-530 C

Characteristics name	Units of measurement	Value
Width	mm	400
Thickness	mm	0,29
Strength of Tensile	MPa	4900
Modulus of Elasticity in Tension	MPa	230000
Elongation during Tensile Break	%	1,7

Table 3

Mechanical and physical Properties of Carbon fiber type SikaWrap®-301 C

Characteristics name	Units of measurement	Value
Width	mm	500
Thickness	mm	0,29
Strength of Tensile	MPa	4900
Modulus of Elasticity in Tension	MPa	230000
Elongation during Tensile Break	%	1,7

Table 4

Mechanical and physical Properties of Carbon fiber type Sika® CarboDur® 1/2" rod

Characteristics name	Units of measurement	Value
Diameter of rod	mm	12
Strength of Tensile	MPa	3100
Modulus of Elasticity in Tension	MPa	142000
Elongation during Tensile Break	%	0,8

Table 5

Mechanical and physical Properties of Carbon fiber type Sika® CarboDur® 1/2" rod

Characteristics name	Units of measurement	Value
Modulus of Elasticity in Flexure	MPa	3800
Strength of Tensile	MPa	30
Modulus of Elasticity in Tension	MPa	4500
Elongation during Tensile Break	%	0,9(7 days at +23°C)

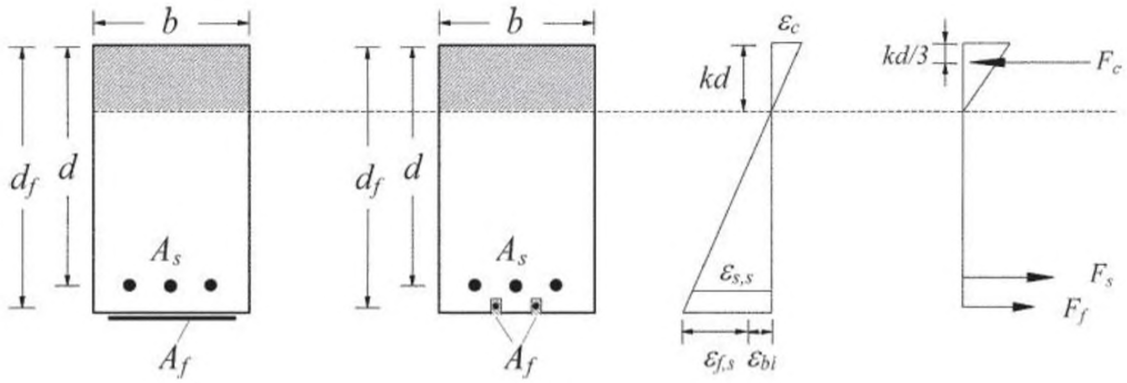

Fig. 5. Strain distribution and force equilibrium conditions for strengthened beams

Modulus of Elasticity in Flexure 3800 MPa, Tensile Strength 30 MPa, Modulus of Elasticity in Tension 4500 MPa and Elongation at Break 0,9 % (7 days at +23°C).

3. Calculation methods and results

3.1. Bending Strengthening

ACI 440.2R-02,08 states that strain compatibility, internal force equilibrium, and governing modes of failure are used to calculate the bending moment of externally bonded FRP beams. For externally strengthened FRP beams, Fig. 5 depicts the strain distribution and force equilibrium conditions [19]. Given that the building is exposed to various environmental conditions for long periods, the properties of the materials used in the strengthening can be reduced by equations (1, 2).

Therefore, the final tensile strength and the design rupture strain must be determined in the design using the environmental reduction factor, according to the type of fiber and the exposure conditions:

$$f_{fu} = C_E f^*_{fu}, \quad (1)$$

$$\varepsilon_{fu} = C_E \varepsilon^*_{fu}, \quad (2)$$

when f_{fu} – design ultimate tensile strength of FRP, MPa;

$f_{fu}{}^*$– ultimate tensile strength of the FRP material as reported by the manufacturer, MPa;

C_E – environmental reduction factor;

ε_{fu}– design rupture strain of FRP reinforcement, mm/mm;
ε_{fu}^{*}– ultimate rupture strain of FRP reinforcement, mm/mm.

The effective strain in FRP reinforcement should be restricted to the strain at which debonding may occur, ε_{fd}, as indicated in equation 3, to prevent intermediate crack-induced debonding failure mode.

$$\varepsilon_{fd} = 0.41\sqrt{\frac{f_c`}{nE_f t_f}} \leq 0.9\varepsilon_{fu}, \quad (3)$$

when ε_{fd} – debonding strain of externally bonded FRP reinforcement, mm/mm;
$f_c`$– specified compressive strength of concrete, MPa;
n – number of plies of FRP reinforcement;
E_f – tensile modulus of elasticity of FRP, MPa;
t_f – nominal thickness of one ply of FRP reinforcement, mm.

Equation 4 can be used to determine the effective strain in the FRP reinforcement at the ultimate limit condition.

$$\varepsilon_{fe} = \varepsilon_{cu}\left(\frac{d_f - c}{c}\right) - \varepsilon_{bi} \leq \varepsilon_{fd}, \quad (4)$$

when ε_{fe}– effective strain in FRP reinforcement attained at failure, mm/mm;
ε_{cu}– the ultimate axial compressive strain of confined concrete corresponding to 0.85fc' ultimate axial compressive strain of confined concrete corresponding to failure in a severely confined member, or failure in a lightly confined member (member confined to recover its concrete design compressive strength);
d_f – effective depth of FRP flexural reinforcement, mm;
c – distance from extreme compression fiber to the neutral axis, mm;
ε_{bi}– strain in the concrete substrate at the time of FRP installation (tension is positive), mm/mm.

Where the following formulas can be used to calculate the values of ε_{bi} and k by equations (5, 6):

$$\varepsilon_{bi} = \frac{M_{DL}(h - kd)}{I_{cr}E_C}, \quad (5)$$

$$k = \sqrt{(\rho_s\frac{E_S}{E_C} + \rho_f\frac{E_f}{E_C})^2 + 2\left(\rho_s\frac{E_S}{E_C} + \rho_f\frac{E_f}{E_C}\left(\frac{h}{d}\right)\right)} - (\rho_s\frac{E_S}{E_C} + \rho_f\frac{E_f}{E_C}), \quad (6)$$

when h – overall thickness or height of a member, mm;
k – ratio of depth of neutral axis to reinforcement Depth measured from extreme compression fiber;
I_{cr} – moment of inertia of cracked section transformed to concrete, mm^4;
E_C – concrete's elasticity modulus, MPa;
E_S – steel's elasticity modulus, MPa;
E_f – elastic tensile modulus of FRP, MPa.

If the FRP behaves exactly elastically, the material's strain, as determined by equation 7, can be used to compute this effective stress.

$$f_{fe} = E_f\varepsilon_{fe}, \quad (7)$$

when f_{fe} – Stress in the FRP that is effective; stress reached during section failure, MPa.

Using strain compatibility, equation 8 can be used to determine the strain in the nonprestressed steel reinforcement based on the strain in the FRP reinforcement.

$$\varepsilon_s = (\varepsilon_{fe} - \varepsilon_{bi})(\frac{d - c}{d_f - c}), \quad (8)$$

when ε_s – strain in nonprestressed steel reinforcement, mm/mm.

Using the steel's presumed elastic-perfectly plastic stress-strain curve, the stress in the steel is calculated from the strain in the steel by equation 9.

$$f_s = E_s\varepsilon_s \leq f_y, \quad (9)$$

when f_s – stress in nonprestressed steel reinforcement, MPa;
f_y – specified yield strength of nonprestressed steel reinforcement, MPa.

Equation 10 can be used to test internal force equilibrium once the stress in the FRP and steel reinforcement has been established for the presumptive neutral axis depth.

$$\alpha_1 f_c \beta_1 bc = A_s f_s + A_f f_{fe}, \qquad (10)$$

when α_1 – multiplier on fc' to determine intensity of an equivalent rectangular stress distribution for concrete;

β_1 – ratio of depth of equivalent rectangular stress block to depth of the neutral axis.

The section with FRP external reinforcement nominal flexural strength is calculated using equation 11. The contribution of the FRP reinforcement to flexural strength is adjusted by an extra FRP reduction factor, ψf. The suggested amount for ψf is 0,85.

$$M_n = A_s f_s \left(d - \frac{\beta_1 c}{2}\right) + \Psi f A f f_{fe} \left(d_f - \frac{\beta_1 c}{2}\right). \qquad (11)$$

3.2. Shear Strengthening

Shear reinforcement for concrete beams is performed as in Fig. 6 [20]. Where the external strengthening of the concrete beam in the compression zone. It can be in the form of laminates or fabrics extending bonded to epoxy, as in Fig. (6. a). Or the epoxy-bonded fabrics are wrapped around the concrete beam as shown in Fig. (6. b).

When studying the shear strength of concrete beam strengthened with an FRP system, the design shear strength must be greater than the required shear strength. According to ACI 318-05, the nominal shear strength should be multiplied by the strength reduction factor φ to determine the design shear strength [21].

By adding the FRP's shear resistance contribution (V_f) that we can find in equation 13 to the steel stirrup contribution (V_s) and the concrete shear resistance (V_c), it is possible to calculate the nominal shear strength of a concrete beam reinforced with FRP by equation 12 [22].

$$V = V_f + V_S + V_C, \qquad (12)$$

where V_c and V_s can be calculated using design guidelines like ACI 318-08.

You can determine the shear contribution of the FRP shear reinforcement by:

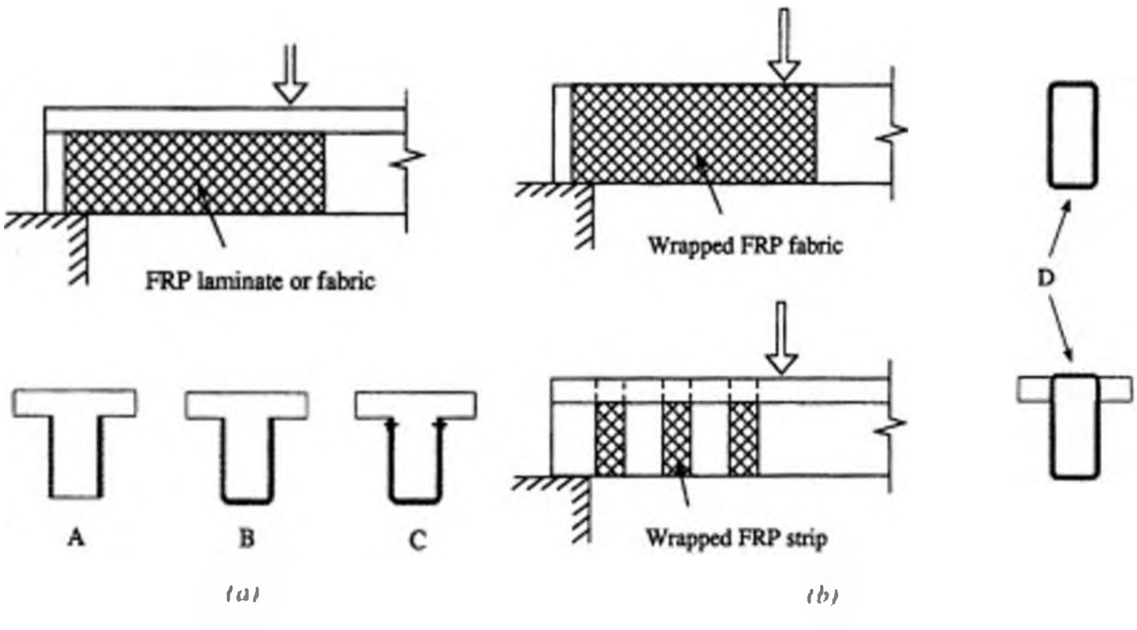

Fig. 6. Concrete shear reinforcement with FRP: a) laminates or textiles (b) strips or bundled textiles

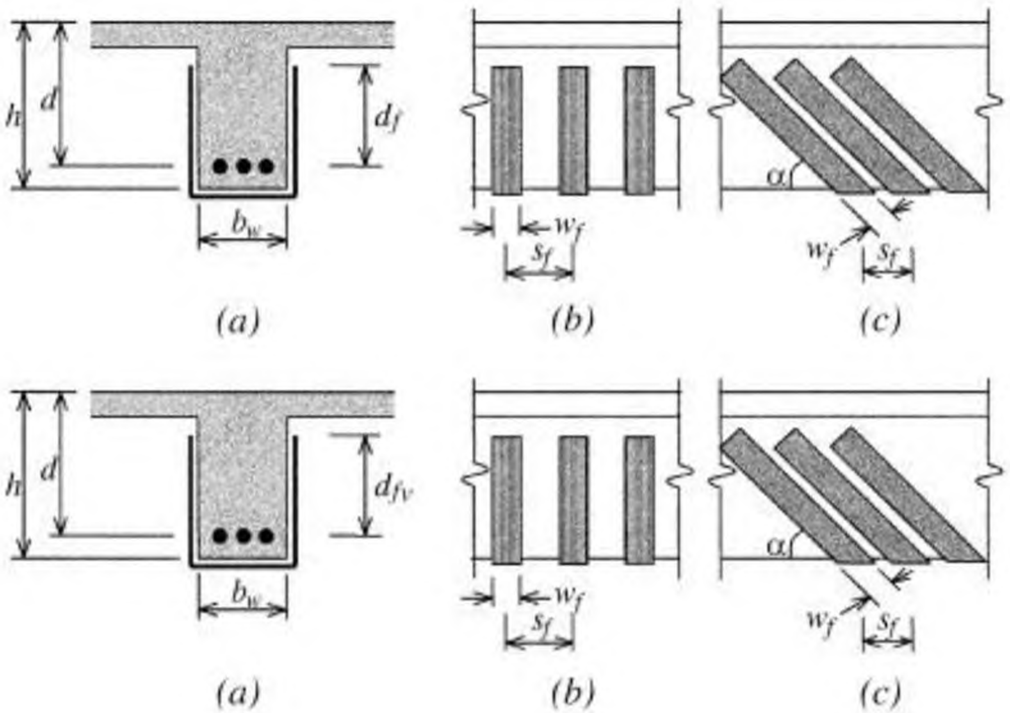

Fig. 7. The dimensions that are taken into account when doing shear-strengthening calculations for FRP laminate repairs, retrofits, or strengthening

$$V_f = \frac{A_f E_f \varepsilon_{fe} (\sin\beta + \cos\beta) d}{S_f}, \quad (13)$$

when A_f – area of FRP external reinforcement, mm² by equation 14;
β – is the inclination angle of the FRP;
S_f – is the width of the FRP, mm.

$$A_f = 2nt_f w_f, \quad (14)$$

when n – the number of FRP sheets;
t_f – the thickness of the FRP, mm;
w_f – width of FRP reinforcing plies, mm.

For applications that are entirely covered in FRP, the maximum strain used in the design should be kept to 0,4% by equation 15.

$$\varepsilon_{fe} = 0.004 \le 0{,}75\varepsilon_{fu}, \quad (15)$$

For systems with U-wrapped or bonded face ply, the FRP does not completely seal the portion. In order to evaluate the utilization and achievable effective strain level, bond stresses should be examined. The strain reduction coefficient K_v can be used to calculate the effective strain for U-wrapped or face plies by equation 16:

$$\varepsilon_{fe} = K_v \varepsilon_{fu} \le 0{,}004, \quad (16)$$

This element is dependent on the strengthening plan, which in turn is dependent on the durability of the concrete, the kind of wrapping technique employed, and the stiffness of the sheets. The strain reduction factor is calculated by equation 17:

$$K_v = \frac{k_1 k_2 l_e}{11900\varepsilon_{fu}} \le 0{,}75, \quad (17)$$

where the FRP sheet's effective length is given by equation 18:

$$l_e = \frac{23300}{(n_f t_f E_f)^{0.58}} \quad (18)$$

Two modification factors, k_1 and k_2, by equation (19, 20) can be used to determine the remaining factors. These two elements are reliant on the wrapping strategy and concrete strength:

$$k_1 = \left(\frac{fc}{27}\right)^{2/3} \quad (19)$$

$$k_2 = \frac{(d - l_e)}{d} \quad (20)$$

3.3. Analysis of Results

After calculating the loads applied to the concrete beam to be reinforced, according to the specifications in (ACI 318M-19) for the live and dead loads, where the live loads were 60 kN and the dead loads were 52 KN. After conducting the analysis of the concrete beam, it was found that the moment ultimate for this beam (øMu) was 397 kN m and the ultimate shear strength (øVu) at (d) was 463,4 KN. We use strengthening with carbon-fiber plates, where carbon-fiber plates type (Sika® CarboDur® S512) were used to reinforce the concrete beam concerning moment strain and shear force. Where moment was obtained after using three layers of carbon fiber plates for strengthening moment strain and two layers for shear forces as in Fig. 8 equal to ultimate moment 397 kN m which is greater than 397 kN m. We got the shear force, we used two layers of carbon fiber plates (Sika® CarboDur® S512) 492,8 kN which is greater than 463,4 kN.

Also, when using carbon fiber fabrics of the type (sika Wrap 301C) as in the Fig. 9 to strengthen the concrete beams in the direction of the moment, a moment of 442,2 kN m was obtained using a layer. Shear strength was obtained by using carbon fiber fabrics type (sika Wrap 530C) in the form of four layers.

We also studied the strengthening using carbon-fiber rods of the type (Sika® CarboDur® BC12) in the direction of the moment as in Fig. 10, and a moment of 443 kN m was obtained when using two of the rods. The shear forces were strengthen using carbon fiber fabrics type (sika Wrap 530C)

Fig 11 shows the comparison between the prices of using composite materials in different ways to strengthening the beams and in Russian rubles.

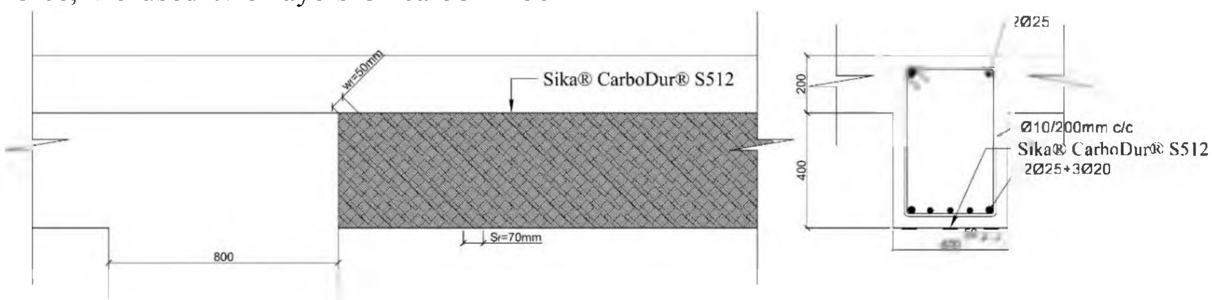

Fig. 8. Strengthening by carbon fiber plates

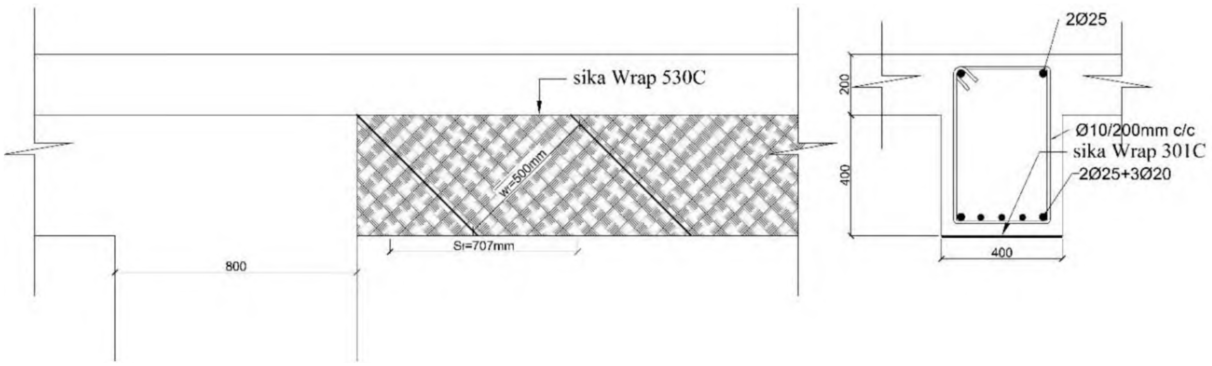

Fig. 9. Strengthening by carbon fiber fabrics

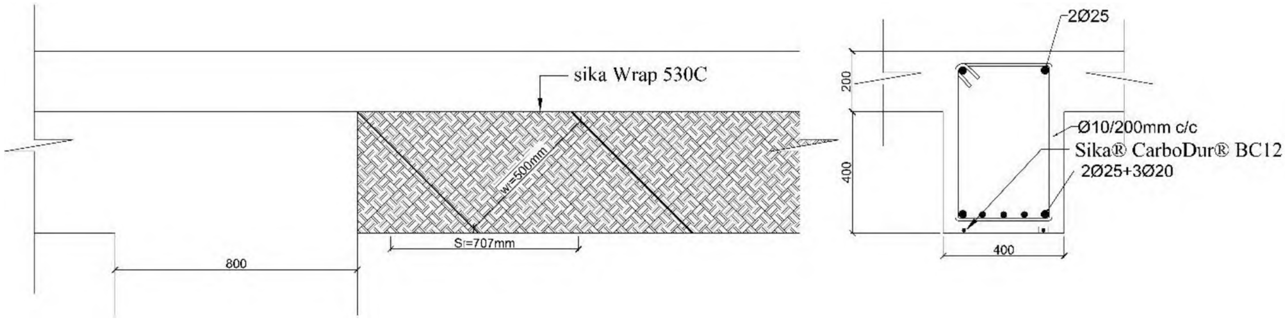

Fig. 10. Strengthening by carbon-fiber rods

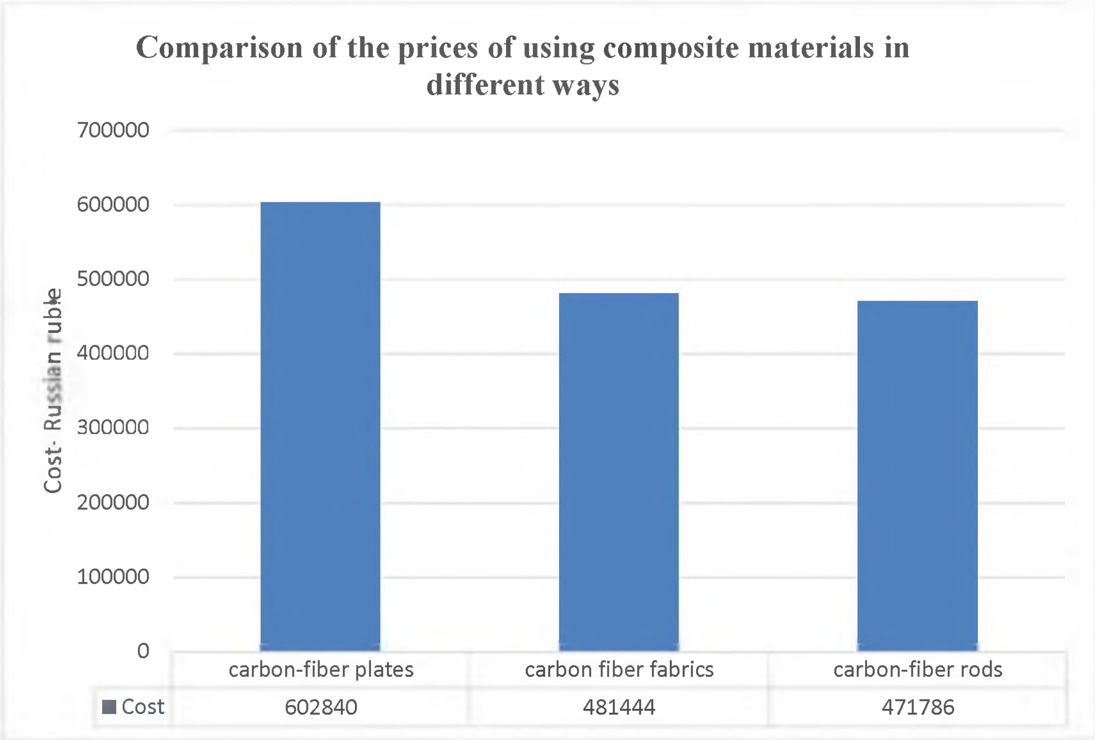

Fig. 11. Comparison of the prices of using composite materials in different ways

4. Conclusions

1. Strengthening of reinforced concrete beams with carbon fiber plates does not require much workers, is easy to install, but at the same time it is the most costly method and remains vulnerable to external mechanical factors.

2. Strengthening using carbon-fiber fabrics and carbon-fiber rods close to the surface, are similar in terms of cost and lower than the cost of reinforcement with carbon fiber plates, but strengthening with carbon-fiber fabrics, is considered easier to implement and does not require a lot of workers, as well as it can be easily formed. The strengthening with carbon fiber rods requires more worker and more skill, and one of its advantages is that it is less susceptible to external mechanical factors.

3. Through the results that have been studied, it turns out that the strengthening using carbon fiber fabrics is the best in terms of price as well as time and effort.

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