

RESEARCH ARTICLE

Examination of parameters impacting flexural and shear strengthening of RC beams

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Abstract

Structural performance of reinforced concrete (RC) structures should be improved due to new design standards, strength reduction, and/or functional changes throughout their service life. To reach a sufficient level of structural performance, the following two options can be considered: reconstruction or strengthening of structures. Although reconstruction has some advantages in terms of using current technological developments, this option can lead to some negative consequences such as interruption of the building's service life, relatively high cost, and sustainability issues. Therefore, strengthening an existing structure mostly stands out as the first choice. The techniques used in strengthening applications can be grouped into two different methods: traditional (addition of new structural members) and non-conventional (seismic base isolation, local retrofitting, and jacketing). Among innovative methods, the fibre-reinforced polymer strengthening method attracts attention due to several advantages including practical applicability, as well as shear and bending capacity increase. Its application to the outer surface of structural members using resin reduces deterioration. Plus, fibres oriented in various directions spread stresses in different directions, therefore, provide effective force distribution. In this study, the effect of carbon fibre reinforced polymer (CFRP) orientation and RC material properties in the strengthening RC beams were investigated using MATLAB software. Accordingly, all stages of the design process are presented for RC beam strengthening considering both flexural and shear effects based on the American Concrete Institute (ACI) 440.2R standard. Through compiling MATLAB code, calculation time reduces, and material characteristics can be obtained more accurately. Plus, using curves obtained by MATLAB coding, shear and bending capacity increases can be observed. According to our findings, the application of one-layer CFRP plate to an RC beam increases the bending capacity by 50.6% and shear capacity by 33.6%. However, as the number of layers increases, the capacity increase rate reduces.

1. Introduction

Improving the seismic performance of a reinforced concrete structure can be done by reducing seismic requirements or increasing the capacity of structural members. Traditional and non-conventional techniques are used in retrofitting applications performed with this purpose. Conventional retrofitting methods are implemented to improve the seismic capacities of existing structures by diminishing the negative effects of

structural design or members. The other approach, non-conventional methods, are also used for structural retrofitting practices [1]. The use of fiber-reinforced polymer (FRP) materials can be implemented as an alternative to conventional strengthening practices for RC structural components which mostly applied by mounting steel plates, increasing sectional areas, and external post-tensioning. In FRP strengthening applications, FRP composite materials are used as EBR (externally-bonded reinforcement) or NSM (near-surface-mounted strengthening material). FRP materials yield several benefits such as being lightweight, easy mounting, and corrosion resistance. Due to the unique properties of FRP materials and the different structural behaviors displayed by FRP-strengthened members, an appropriate guidance is required for the use of these materials [2]. Three types of materials (carbon, glass, aramid) are used in FRP strengthening.

FRP structural strengthening is mostly preferred to enhance the shear, flexural, or seismic performance of structural members. In general, EBR (Externally bonded reinforcement) and NSM-FRP techniques are used for beams strengthened with FRP [3-13]. Ali et al. [3] examined the impact of CFRP mechanical anchorages on the flexural capacity of RC beams externally strengthened using both CFRP sheets and plates. The authors also measured the ductility and load-bearing capacity of the beams. Hawileh et al. [4] investigated the effect of longitudinal CFRP that externally bonded to beams using epoxy adhesives on the shear strength. Karzad et al. [5] examined the shear performance of full-scale CFRP-wrapped RC beams. Sabol and Priganc [6] carried out a study on shear strengthening of RC structures with NSM technique. Mhanna et al. [8] examined the shear performance increase in RC beams using U-wrapped and completely wrapped CFRP sheets. In their study, the authors performed three-point bending tests on their beam samples and they plotted the mid-span load displacement response graphs. Salama et al. [10] measured the flexural performance of RC beams externally strengthened by CFRP sheets. They used side-bonded CFRP sheets with epoxy-based adhesives. The authors compared the obtained performance improvement in the flexural performance of CFRP-sheet strengthened RC beams with those traditionally bottom-bonded strengthened beams. On the other hand, NSM and EBR methods used to increase the flexural performance of RC beams were examined in terms of performance and effectiveness by Khalifa [12]. In that study, RC beams strengthened by various CFRP schemes were examined. According to the test results for the same amount of CFRP, NSM strip strengthened beams yielded a greater ultimate load performance compared to EBR strengthened beams. Moreover, Balamuralikrishnan and Jeyasehar [13] examined the flexural behavior of CFRP strengthened RC beams. A total of ten RC beams were exposed to monotonic and cyclic conditions until failure to measure the flexural strengthening performance. Their results showed that the strengthened beams yielded higher flexural strength performance, better flexural stiffness, and composite action until the collapse state.

Some studies were also reported on whole structure strengthening with CFRP. One of these studies, Sayin and Manisalı [14] examined the key features of interfacial stress distributions in RC beams strengthened with FRP bonded adhesives. They carried out an experimental study followed by a numerical analysis. They found that stress transfer abilities are very effective on the adhesion behavior of epoxy-bonded members. In another study, Sayin et al. [15] used a computer simulation to model the experimental behavior of CFRP-strengthened RC beams. For this purpose, they developed a numerical model based on the polynomial regression method to simulate the CFRP strengthened RC beams under flexural loading. Their model results showed a good agreement with the actual test data. Akcay et al. [16] studied the strengthening of a historical masonry building against seismic effects. In the restoration applications they implemented, volta slabs, exterior and interior walls, as well as door and window openings were strengthened by various methods. They strengthened facade walls using carbon fiber plate and wrap. Sayin et al. [17] presented a strengthening practice for a heritage masonry structure. They evaluated the out-of-plane performance increase in the building exposed to seismic effects by implementing carbon fiber plates/wraps on the exterior walls. Cosgun [18] investigated the impact of CFRP on the performance of RC beams made out of low strength concrete.

Moreover, various estimation methods, such as artificial intelligence and mathematical modeling for simulations are reported in the literature. Barbato [19] presented a new FE model to estimate the load-bearing capacity of RC beams strengthened with externally bonded FRP. Godat et al. [20] developed a versatile numerical tool that can predict the behavior of FRP shear-strengthened beams to determine the debonding failure modes. Tanarslan et al. [21] developed an ANN model to determine the shear performance of RC beams strengthened with wrapped and U-jacketed externally bonded FRP. Martinez et al. [22] proposed a procedure based on a FE formulation that can be used for numerical simulations of FRP strengthened RC structures. Sayin et al. [23] conducted an analytic examination for the moment-curvature relationship of RC beams strengthened with FRP. They examined four FRP strengthened RC beams with different adhesive thicknesses and a reference RC beam model. They added FRP and adhesive modules to a software package developed to examine the moment-curvature relationship and examined stress-strain and moment-curvatures. Yang et al. [24] presented a new method for flexural strengthening of RC beams with CFRP and experimentally tested it on the same specimens. Their method provides self-anchorage and does not require additional anchorage. Ilkhani et al. [25] experimentally examined CFRP-strengthened RC beams bending - torsion loading. Their findings indicated that CFRP plate use increases torsion capacity at the beam edges and delays crack formation time. Zhou et al. [26] examined flexural strength increase in beams using a hybrid strengthening method including the use of both FRP and steel materials. They also introduced a calculation method in that study. Haroon et al. [27] investigated shear strength increase in T beams using CFRP strips. The authors separately examined unidirectional and multidirectional CFRP strip use. Their examinations revealed that the use of unidirectional CFRP strips provided higher shear capacity than using the same number of multidirectional CFRP strips. However, under the same loading conditions, multidirectional CFRP strips provided more uniformly distributed stirrup stresses compared to those unidirectional strips.

In the current study, the capacity increase of a CFRP strengthened RC beam under flexural and shear loading is examined. This RC beam was exposed to a higher load due to a change in the purpose of use. The parameters effective in flexural and shear strengthening of RC beams were also calculated.

2. Methodology

The calculations in the proposed approach will refer to ACI 440.2R. The calculations for the design process were coded in the Matlab software. Matlab [28] is a well-known programming language used in engineering applications. Matlab combines numerical calculations with a high-order programming language that can perform sophisticated calculations and create advanced graphs.

The RC beam examined in this study was exposed to a comparably higher load since the building's purpose has changed. Sectional elevation and cross-section of the RC beam are shown in Fig. 1. We determined that the beam failed under higher loads. Therefore, CFRP material was used to strengthen the RC beam against flexural and shear loading. The material features of the RC beam and FRP are given in Tables 1 and 2, respectively.

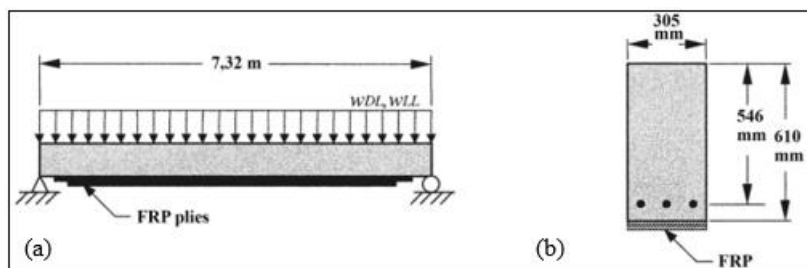


Fig. 1. The examined RC beam (a) Sectional elevation, (b) Cross-section [2]

Table 1. The material features for the RC beam

Parameter	Definition	Value
b	width of beam	305 mm
h	height of beam	610 mm
d	effective depth	546 mm
D_l	diameter of reinforcement	28 mm
D_s	stirrup diameter	10 mm
f'_c	compressive strength of concrete	34.5 MPa
f_y	yield strength of steel	414 MPa
E_s	modulus of elasticity of steel	2.10^5 MPa
l	length of beam	7.32 m
s	reinforcement range	200 mm
w_{DL}	dead loads	14.6 N/mm
w_{LL}	live load	17.5 N/mm

Table 2. The material properties of the FRP

Parameter	Definition	Value
t_f	thickness of one ply of FRP	1 mm
E_f	modulus of elasticity of FRP	37000 MPa
ϵ_{fu}^*	ultimate rupture strain of FRP	0.015 mm/mm
ψ_f	FRP strength reduction factor	0.85
ϕ	strength reduction factor	0.9
C_E	environmental reduction factor	0.95

2.1. Design stages for flexural strengthening

In this stage, the ultimate flexural capacity M_u of the beam should be checked to determine whether the lowest limit value (Munstrengthened,limit) given in the ACI 440.2R is exceeded. If the current flexural capacity does not exceed the limit value, FRP strengthening is now allowed. This is because FRP's strengthening role will be limited in this scenario. The moment values were calculated using the Eqs. 1-4 given below.

$$\text{Dead-load moment} \quad : \quad M_{DL} = \frac{w_{DL} \times l^2}{8} \quad (1)$$

$$\text{Live-load moment} \quad : \quad M_{LL} = \frac{w_{LL} \times l^2}{8} \quad (2)$$

$$\text{Non-strengthened moment limit} \quad : \quad M_{nonstrengthened} = 1.1 \times M_{DL} + 0.75 \times M_{LL} \quad (3)$$

$$\text{Factored moment} \quad : \quad M_u = 1.2 \times M_{DL} + 1.6 \times M_{LL} \quad (4)$$

$M_u > M_{nonstrengthened}$ means the current capacity of the beam is sufficient for strengthening and further calculations are performed. If $M_u < M_{nonstrengthened}$, FRP strengthening is now allowed since the current capacity of the beam does not meet the lowest limit value given in the Guide. Concrete and rebar properties can be calculated using Eqs. 5-9.

$$\text{Modulus of elasticity of concrete} : E_c = 4700\sqrt{f'_c} \quad (5)$$

$$\text{Area of FRP} : A_f = n \times t_f \times b \quad (6)$$

$$\text{Rebar area (m, rebar number)} : A_s = m \frac{\pi D^2}{4} \quad (7)$$

$$\text{Rebar ratio} : \rho_s = \frac{A_s}{b \times d} \quad (8)$$

$$\text{Modular ratio} : n_s = \frac{E_s}{E_c} \quad (9)$$

Moment of inertia of cracked (transformed) section to concrete is calculated by using Eq.10.

$$M_{DL} = \frac{\varepsilon_{bi} \times (I_{cr} \times E_c)}{d_f - k \times d} \quad (10)$$

where

$$k = \sqrt{(\rho_s \times n_s)^2 + 2 \times (\rho_s \times n_s)} - \rho_s \times n_s, \quad I_{cr} = \frac{b \times c^3}{3} + n_s \times A_s \times (d - c)^2 \quad \text{and} \quad c = k \times d$$

2.1.1. Limit value control

To avoid collapse due to debonding, ε_{fd} should be equal or less than 0.9 times the deformation at the break time (Eq.11).

$$\varepsilon_{fd} = 0.41 \sqrt{\frac{f_c}{n \times E_f \times t_f}} \leq 0.9 \times \varepsilon_{fu} \quad (11)$$

According to the ACI 440.2R, neutral axis depth c can be defined 0.2 times the effective height as a presupposition (Eq.12):

$$c = 0.2 \times d \quad (12)$$

2.1.2. Effective deformation of FRP

ε_{fe} should be equal or less than ε_{fd} . If $\varepsilon_{fe} > \varepsilon_{fd}$, ε_{fe} should be accepted as $\varepsilon_{fe} = \varepsilon_{fd}$. Deformation values of the FRP, concrete, and rebar are calculated using Eqs. 13-15.

$$E_c = 4700\sqrt{f'_c} \quad (13)$$

$$A_f = n \times t_f \times b \quad (14)$$

$$A_s = m \frac{\pi D^2}{4} \quad (15)$$

2.1.3. Stress in non-prestressed steel reinforcement

f_s should be equal or less than f_y . If $f_s > f_y$, f_s should be accepted as $f_s = f_y$. $f_s = E_s \times \varepsilon_s \leq f_y$, $f_{fe} = E_f \times \varepsilon_{fe}$, $\varepsilon'_c = \frac{1.7 \times f_c}{E_c}$, $\beta_1 = \frac{4 \times \varepsilon'_c - \varepsilon_c}{6 \times \varepsilon'_c - 2 \times \varepsilon_c}$, $\alpha_1 = \frac{3 \times \varepsilon'_c \times \varepsilon_c - \varepsilon_c^2}{3 \times \beta_1 \times (\varepsilon'_c)^2}$, and $c = \frac{A_s \times f_s + A_f \times f_{fe}}{\alpha_1 \times f_c \times \beta_1 \times b}$.

If the pre-determined $c = (0.2) \times d$ value does not equal or close to c , a new c value between these two values is determined and the calculations after the ε_{fe} are repeated. This procedure is repeated until the determined c value is equal to the calculated c value. The latest calculated c , α , and β values are used in the Eqs. 16-18 and the calculations are continued.

$$\text{Contribution of the rebar} \quad : \quad M_{ns} = A_s \times f_s \left(d - \frac{\beta_1 \times c}{2} \right) \quad (16)$$

$$\text{Contribution of the FRP} \quad : \quad M_{nf} = A_f \times f_{fe} \left(d_f - \frac{\beta_1 \times c}{2} \right) \quad (17)$$

$$\text{Flexural capacity} \quad : \quad \phi M_n = \phi \times (M_{ns} + \psi_f \times M_{nf}) \quad (18)$$

If $\phi M_n \geq M_u$, strengthening is needed. If $\phi M_n < M_u$, calculations should be repeated with higher number of plies. The number of plies is increased until the condition $\phi M_n \geq M_u$ is met. The calculations are stopped when the condition is met.

2.2. Design stages for shear strengthening

The beam for shear calculations has the same properties as the beam considered in flexural effect calculations (Table 1). The features of the FRP plate are given in Table 3.

As the RC beam exposed to higher loads, shear effects on the beam increased. Therefore, it was decided to strengthen the beam with FRP to have adequate shear strength. The contribution of the rebar and concrete to the shear capacity can be calculated by Eqs. 19 and 20, respectively. The total shear strength capacity is calculated using Eq. 21.

Table 3. Features of FRP plate

Parameter	Definition	Value
C_E	environmental reduction factor	0.95
d_{fv}	effective depth of FRP shear reinforcement	440 mm
E_f	modulus of elasticity of FRP	37000 MPa
f_{fu}^*	ultimate tensile strength of FRP	621 MPa
s_f	span between each sheet	305 mm
t_f	thickness of one ply of FRP	1.02 mm
w_f	width of each sheet	228 mm
α	angle of application of primary FRP	90°
ε_{fu}^*	ultimate rupture strain of FRP	0.015 mm/mm
ψ_f	strength reduction factor for FRP	0.85
ϕ	strength reduction factor	0.75

$$\text{Rebar's contribution to the shear strength} : V_s = \frac{A_v \times f_y \times (\sin \alpha + \cos \alpha) \times d}{s}, \text{ where } A_v = \frac{\pi D^2}{4} \quad (19)$$

$$\text{Concrete's contribution to the shear strength} : V_c = \frac{\sqrt{f_c} \times b \times d}{6} \quad (20)$$

$$\text{Non-strengthened shear strength} : V_{nonstrengthened} = \phi \times (V_s + V_c) \quad (21)$$

Design rupture strain and active bond length of FRP are obtained using Eqs. 22 and 23, respectively.

$$f_{fu} = C_E \times f_{fu}^*, \varepsilon_{fu} = C_E \times \varepsilon_{fu}^* \quad (22)$$

$$L_e = \frac{2300}{(n \times t_f \times E_f)^{0.58}} \quad (23)$$

2.2.1. Limit value control

To prevent a collapse, k_v should be equal or less than 0.75.

$$\varepsilon_{fe} = k_v \times \varepsilon_{fu} \leq 0.004 \quad (24)$$

where $k_v = \frac{k_1 \times k_2 \times L_e}{1900 \times \varepsilon_{fu}} \leq 0.75$, and coefficients $k_1 = \left(\frac{f_c}{27}\right)^{2/3}$ and $k_2 = \frac{d_{fv} - L_e}{d_{fv}}$.

2.2.2. Contribution of FRP to shear force

$$V_f = \frac{A_{fv} \times f_{fe} \times (\sin \alpha + \cos \alpha) \times d_f}{s_f} \quad (25)$$

where $A_{fv} = 2 \times n \times t_f \times w_f$ and $f_{fe} = \varepsilon_{fe} \times E_f$

2.2.3. Shear force capacity after strengthening

After strengthening, the shear performance of the beam is calculated by Eq. 26.

$$\phi \times V_n = \phi \times (V_c + V_s + \psi_f \times V_f) \quad (26)$$

If $V_{nonstrengthened} < V_u$, strengthening should be performed and further calculations are continued. If $V_{nonstrengthened} > V_u$, strengthening is not needed.

If $\phi V_n \geq V_u$, strengthening can be performed. If $\phi V_n < V_u$, the calculations should be repeated by increasing number of plies. The number of plies is increased until the $\phi V_n \geq V_u$ condition is met. The calculations are stopped when the condition is met.

3. Results and discussion

In this section, the properties of the FRP and concrete used in the flexural and shear strengthening are discussed.

3.1. The effect of ply number

The change in the flexural and shear strength with the number of FRP plies are given in Fig. 2 and Table 4. Application of only one layer of ply increased the flexural and shear strength of the beam by 50.7% and 33.6%, respectively. However, for both flexural and shear strengths, the increasing effect of ply decreased

as the number of plies increase. The most effective capacity increase was obtained with 2 plies which yield a cumulative flexural and shear strength increase by 5.8% and 14.4%, respectively.

3.2. Effect of plate thickness

The effect of the FRP ply thickness on the RC beam strength was also examined. Accordingly, the changes in the flexural and shear strengths were determined for FRP application of different thicknesses varying from 1 to 1.5 mm. The flexural and shear strengths for the ply number and thickness are given in Table 5. Accordingly, a 0.1 mm increase in the thickness caused a 0.8% and 1.5% increase in the flexural and shear capacities, respectively. In this case, the maximum increase in the flexural and shear strengths with an 0.5 mm increase in the thickness was 1.13% and 2.5%, respectively. Moreover, the capacity increases were obtained with 2 plies of 1.5 mm thick FRP and one ply of 3 mm thick FRP. Accordingly, our findings indicate that for the same amount of FRP, similar capacity increases are obtained for different ply numbers and thicknesses.

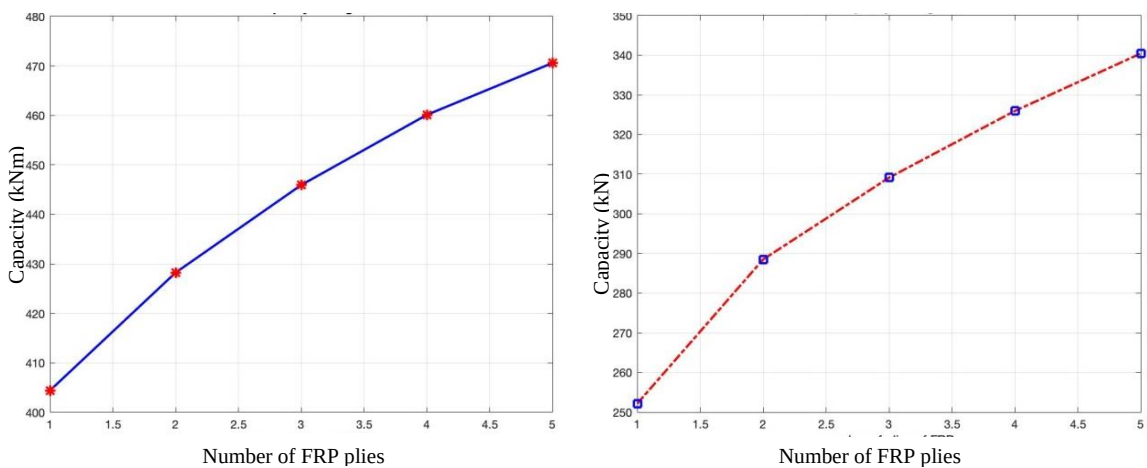


Fig. 2. The relationship of ply number vs. capacity. Flexural (left), Shear (right)

Table 4. The change in the flexural and shear strengths according to the ply number

Number of FRP plies	Flexural strength (kNm)	Increase in moment (%)	Shear strength (kN)	Increase in shear strength (%)
none	268.3	—	188.8	—
1	404.4	50.7	252.2	33.6
2	428.2	5.8	288.5	14.4
3	445.9	4.1	309.1	7.1
4	460.1	3.2	326.0	5.5
5	470.6	2.3	340.4	4.4

The thickness of the FRP was considered 1 mm.

Table 5. The relationship of ply number vs plate thickness

Ply number (<i>n</i>)	Plate thickness (<i>t</i>)	Flexural moment (kNm)	Increase in flexural strength (%)	Shear capacity (kN)	Increase in shear capacity (%)
1	1.0	404.4	–	250.9	–
	1.1	407.3	0.70	257.1	2.5
	1.2	410.1	0.68	263.3	2.4
	1.3	412.5	0.59	269.2	2.2
	1.4	415.0	0.60	272.2	1.1
	1.5	417.4	0.57	275.0	1.0
2	1.0	428.2	–	287.6	–
	1.1	431.1	0.68	292.1	1.6
	1.2	434.6	0.81	296.4	1.5
	1.3	437.9	0.76	300.4	1.3
	1.4	441.0	0.71	304.3	1.3
	1.5	444.0	0.68	308.0	1.2
3	1.0	445.9	–	308.0	–
	1.1	448.3	0.54	313.4	1.8
	1.2	453.4	1.13	318.4	1.6
	1.3	456.4	0.66	323.2	1.5
	1.4	461.3	1.07	327.8	1.4
	1.5	464.3	0.65	332.2	1.3
4	1.0	460.1	–	324.7	–
	1.1	462.5	0.52	330.7	1.8
	1.2	467.2	1.08	336.4	1.7
	1.3	468.2	0.21	341.8	1.6
	–	–	–	346.9	1.5
5	1.0	470.6	–	–	–

3.3. Effect of concrete compressive strength

The effect of concrete compressive strength on FRP strengthened RC beams was also examined. For this purpose, the flexural and shear strength values were obtained for three different concrete strengths (Table 6).

As seen in Table 6, for a concrete strength of 20.7 MPa, a single-ply FRP application yielded a flexural performance increase by 28.8%. The single-ply FRP application increased the flexural capacity by 41.9% and 50.7% for concrete strengths of 27.6 MPa and 34.5 MPa, respectively. We found that for all different concrete strengths, the capacity increase rate decreased as the number of plies increased. The capacity increase rate varied between 2-8% for each additional ply.

For the concrete strength of 20.7 MPa, the application of a single-ply FRP increased the shear strength by 31.4%. For concrete strengths of 27.6 MPa and 34.5 MPa, the capacity increase with the single-ply FRP was 35.0% and 33.6%, respectively. Like the flexural strength calculations, the capacity increase rate decreased as the number of plies increased for different concrete strengths. The increases in the shear capacity varied between 4-14% for each additional ply. This result indicates that the increase in ply number is more effective for shear strength than concrete strength.

Table 6. The relationships of ply number vs concrete strength

Concrete Strength (MPa)	Number of plies (<i>n</i>)	Flexural strength (kNm)	Increase in flexural strength (%)	Shear strength (kN)	Increase in shear strength (%)
20.7	0	268.3	–	161.3	–
	1	345.7	28.8	212.0	31.4
	2	357.5	3.4	232.2	9.5
	3	364.2	1.8	246.9	6.3
	4	379.4	4.1	258.8	4.8
	5	409.4	7.9	269.1	4.0
27.6	0	268.3	–	175.9	–
	1	380.7	41.9	237.4	35.0
	2	409.5	7.6	261.8	10.3
	3	425.6	3.9	279.6	6.8
	4	437.2	2.7	294.1	5.2
	5	447.9	2.4	306.6	4.2
34.5	0	268.3	–	188.8	–
	1	404.4	50.7	252.2	33.6
	2	428.2	5.9	288.5	14.4
	3	445.9	4.1	309.1	7.1
	4	460.1	3.2	326.0	5.5
	5	470.6	2.3	340.4	4.4

The effect of concrete strength was examined considering different ply numbers. Accordingly, for one-ply-FRP, increase in flexural and shear strengths with different concrete strengths were between 6-12%. For ply numbers between 2-5, the effect of concrete strength is shown in Table 7. Accordingly, the increases in flexural and shear strengths were varied between 4-13%. The findings presented in Table 7 also indicate that the concrete strength had a greater impact on flexural strength than shear.

3.4. Effect of rebar number

The effect of longitudinal rebar number on flexural strength was also examined for. For this purpose, Flexural capacities were calculated for two different numbers of rebar. The flexural capacity increases for different numbers of rebar and ply are shown in Table 8. The results in Table 8 indicate that the rebar number is effective on the flexural capacity increase. However, the effect of rebar decreases as ply number increases.

4. Conclusions

The use of fiber-reinforced plastic (CFRP) laminate stands out as a rapid and economic strengthening method recently. Many experimental studies examined the repair and strengthening of the current structural members with FRP. However, such examinations require more time and labor. In this regard, modeling behaviors of these members offer serious benefits in terms of time and economy. However, many parameters affect FRP behaviors. For an accurate simulation of structural behaviors, the impacts of these parameters should be precisely determined. The current paper, therefore, presents a numerical determination of effective parameters in CFRP strengthening for RC beams considering flexural and shear effects. The parameters considered in calculations are CFRP thickness, CFRP ply number, concrete strength, and rebar number.

Table 7. The flexural and shear values for three concrete strengths

Number of plies (<i>n</i>)	Flexural			Shear		
	20.7	27.6	34.5	20.7	27.6	34.5
1	345.7	380.7	404.4	212.0	237.4	252.2
Increase (%)		10.1	6.2		12.0	6.2
2	357.5	409.6	428.2	232.2	261.8	288.5
Increase (%)		14.6	4.5		12.7	10.2
3	379.4	412.6	445.9	246.9	279.6	309.1
Increase (%)		8.7	8.1		13.2	10.6
4	364.4	437.2	460.1	258.8	294.1	326.0
Increase (%)		20.0	5.2		13.6	10.8
5	409.4	447.9	470.6	269.1	306.6	340.4
Increase (%)		9.4	5.1		13.9	11.2

Table 8. The relationships of ply number vs. rebar number

Number of FRP plies (<i>n</i>)	Number of rebar*	Flexural capacity (kNm)	Increase in flexural capacity (%)
1	2	292.2	–
	3	404.4	38.4
2	2	319.7	–
	3	428.2	33.9
3	2	338.4	–
	3	445.9	31.8
4	2	354.5	–
	3	460.1	29.8
5	2	368.3	–
	3	470.6	27.8

*The longitudinal rebar has the same area for all cases

The key findings of this study are:

- The first-ply applied to the RC beam provided a significant increase in flexural and shear capacity (%50.6 and %33.6, respectively). This finding indicates that FRP is an important strengthening technique.
- Although increases in the ply number and CFRP thickness increased the flexural and shear capacities, the increase rate decreased. Especially the effectivity of CFRP decreased after the fourth ply. Based on this result, it can be argued that the maximum CFRP ply number should be three for strengthening practices.
- For ply numbers of 1-5, increases in the flexural and shear capacities varied between 5-15% corresponding to an increase in the concrete strength. This result indicates that concrete strength has an important role in strengthening applications.
- For ply number 1-5, higher number of rebars increased the flexural strength by 27.8-38.4%. This finding showed that rebar is effective in strengthening. Thus, the rebar area in existing RC beams affects the CFRP amount needed.

Through calculations on MATLAB compiler, the required number of FRP layers to achieve the desired bending capacity and shear capacity were determined separately. Our findings indicate that five-layer-FRP should be used to achieve each desired bending capacity and shear capacity. However, the common practice is to use a maximum of three layers of FRP. Furthermore, the findings of the current study showed that although the effect of single-layer FRP on the capacity increase is significant, the capacity increase rate decreases as the number of FRP layers increases. So, if the desired capacity could not be achieved by increasing the number of FRP layers, other strengthening methods should be used.

Consequently, we determined that CFRP is an effective method in strengthening of RC beams against flexural and shear effects. Moreover, the results presented in this paper indicate that the properties of FRP and concrete components are effective in strengthening performance. The approach introduced in this study provides an accurate and fast determination of whether a strengthening work provides the required capacity increase.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Notation

A_f	area of FRP external reinforcement	M_{ns}	contribution of steel reinforcement to nominal flexural strength
A_{fv}	area of FRP shear reinforcement with spacing	M_{nf}	contribution of FRP reinforcement to nominal flexural strength
A_s	area of non-prestressed steel reinforcement	n	number of plies of FRP
A_v	area of stirrup	n_s	modular ratio
b	width of beam	s	reinforcement range
c	distance from extreme compression fibre to the neutral axis	s_f	centre-to-centre spacing of FRP strips
C_E	environmental reduction factor	V_c	nominal shear strength provided by concrete with steel flexural reinforcement
d	effective depth	V_f	nominal shear strength provided by FRP stirrups
D	diameter of reinforcement	V_s	nominal shear strength provided by steel stirrups
d_f	effective depth of FRP flexural reinforcement	t_f	nominal thickness of one ply of FRP reinforcement
d_{fv}	effective depth of FRP shear reinforcement	w_f	width of FRP reinforcing plies
E_c	modulus of elasticity of concrete	α	angle of application of primary FRP reinforcement direction relative to longitudinal axis of member
E_f	tensile modulus of elasticity of FRP	α_1	multiplier on f'_c to determine intensity of an equivalent rectangular stress distribution for concrete
E_s	modulus of elasticity of steel	β_1	ratio of depth of equivalent rectangular stress block to depth of the neutral axis
f'_c	specified compressive strength of concrete	ϵ_{bi}	strain in concrete substrate at time of FRP installation
f_{fe}	effective stress in the FRP	ϵ_c	strain in concrete
f_{fu}	design ultimate tensile strength of FRP	ϵ'_c	compressive strain of unconfined concrete corresponding to f'_c
f_{fu}^*	ultimate tensile strength of the FRP material as reported by the manufacturer	ϵ_{fd}	debonding strain of externally bonded FRP reinforcement
f_s	stress in non-prestressed steel reinforcement	ϵ_{fe}	effective strain in FRP reinforcement attained at failure
f_y	specified yield strength of non-prestressed steel reinforcement	ϵ_{fu}	design rupture strain of FRP reinforcement
h	height of a beam	ϵ_{fu}^*	ultimate rupture strain of FRP reinforcement
I_{cr}	moment of inertia of cracked section transformed to concrete	ϵ_s	strain in non-pre-stressed steel reinforcement
k_1	modification factor applied to n_v to account for concrete strength	ϕ	strength reduction factor
k_2	modification factor applied to n_v to account for wrapping scheme	ψ_f	FRP strength reduction factor
k_v	bond reduction coefficient	ρ_s	ratio of non-prestressed reinforcement
M_{DL}	dead-load moment		
M_{LL}	live-load moment		
L_e	active bond length of FRP laminate		

Appendix: MATLAB Codes

Flexural Strengthening of Beam

```

clear all, clc, clf
b = input('enter the beam width: ')
h = input('enter the height of the beam: ')
d = input('enter the effective depth of beam: ')
l = input('enter beam distance: ')
fc_prime = input('enter the compressive strength of the concrete: ')
fy = input('enter the yield strength of steel: ')
w_DL = input('enter the dead load of the beam: ')
w_LL = input('enter the live load of the beam: ')
tf = input('enter the thickness of FRP ')
D = input('enter the diameter of the reinforcement: ')
x = input('enter the number of reinforcement: ')
Es = input('enter the modulus of elasticity of reinforcement: ')
Ef = input('enter the modulus of elasticity of FRP: ')
eps_fu_asterisk = input('enter the ultimate rupture strain of FRP:')
psi_f = input('enter the FRP strength reduction factor: ')
fi = input('enter the strength reduction factor: ')
CE = input('enter the environmental reduction factor: ')
df=h;
%Design rupture strain of FRP
eps_fu = CE*eps_fu_asterisk;
%Dead-load moment:
M_DL = (w_DL*l^2/8)*10^6;
%Live-load moment:
M_LL = (w_LL*l^2/8)*10^6;
%Unstrengthened moment limit:
M_unstrengthened = (1.1*M_DL + 0.75*M_LL)*10^(-6)
%Factored moment:
Mu = (1.2*M_DL + 1.6*M_LL)*10^(-6)
if M_unstrengthened < Mu
    disp('Strengthening Required')
else
    disp('Strengthening is not recommended')
end
fi_vekt = [];
n=1;
while n<6
    %Modulus of elasticity of concrete
    Ec = 4700*sqrt(fc_prime);
    %FRP Area
    Af = n*tf*b;
    %Reinforcement Area
    As = x*(pi*(D^2)/4);
    %Reinforcement ratio
    ro_s = As/(b*d);
    %Modular ratio
    ns = Es/Ec;
    k = sqrt((ro_s*ns)^2 + 2*ro_s*ns) - ro_s*ns;
    c = k*d;
    %Moment of inertia of cracked section transformed to concrete
    Icr = (b*c^3)/3 + ns*As*((d-c)^2);
    eps_bi = (M_DL*(df-(k*d)))/(Icr*Ec);
    %Debonding deformation of FRP
    eps_fd = 0.41*sqrt(fc_prime/(n*Ef*tf));
    %Limit Limit Value Control
    if eps_fd <= 0.9*eps_fu

```

```

        disp('Limit Limit Value Control: Appropriate');
    elseif eps_fd > 0.9*eps_fu
        ('Limit Limit Value Control: Collapse');
    end
    %Initial value selected for c
    c = 0.2*d;
    %Effective deformation of FRP
    eps_fe = 0.003*(df-c)/c - eps_bi;
    if eps_fe <= eps_fd
        eps_fe = 0.003*(df-c)/c - eps_bi;
    elseif eps_fe > eps_fd
        eps_fe = eps_fd;
    end
    %Compatibility equation
    eps_c = (eps_fe + eps_bi)*(c/(df-c));
    eps_s = (eps_fe + eps_bi)*((d-c)/(df-c));
    fs = Es*eps_s;
    if fs <= fy
        fs = Es*eps_s;
    elseif fs>fy
        fs=fy;
    end
    f_fe=Ef*eps_fe;
    eps_c_prime = (1.7*fc_prime)/Ec;
    betal = (4*eps_c_prime - eps_c)/(6*eps_c_prime - 2*eps_c);
    alfa1 = (3*eps_c_prime*eps_c - eps_c^2)/(3*betal*eps_c_prime^2);
    c1 = (As*fs+Af*f_fe)/(alfa1*fc_prime*betal*b);
    c = floor(c);
    c1 = floor(c1);
    if c == c1
        disp('iteration completed')
        c=c1;
    elseif c~=c1
        ci = c;
        while (ci <= c1-1)
            eps_fe = 0.003*(df-ci)/ci - eps_bi;
            if eps_fe <= eps_fd
                eps_fe = 0.003*(df-ci)/ci - eps_bi;
            elseif eps_fe > eps_fd
                eps_fe = eps_fd;
            end
            eps_c = (eps_fe + eps_bi)*(ci/(df-ci));
            eps_s = (eps_fe + eps_bi)*((d-ci)/(df-ci));
            fs = Es*eps_s;
            if fs <= fy
                fs = Es*eps_s;
            elseif fs>fy
                fs=fy;
            end
            f_fe=Ef*eps_fe;
            eps_c_prime = (1.7*fc_prime)/Ec;
            betal = (4*eps_c_prime-eps_c)/(6*eps_c_prime - 2*eps_c);
            alfa1 = (3*eps_c_prime*eps_c-eps_c^2)/(3*betal*eps_c_prime^2);
            c = (As*fs+Af*f_fe)/(alfa1*fc_prime*betal*b);
            c = floor(c);
            if ci==c
                break
            end
            ci = ci + 1;
        end
    end
end

```



```

end
c;
%Contribution of steel reinforcement
M_ns = As*fs*(d-((beta1*c)/2));
%Contribution of FRP reinforcement
M_nf = Af*f_fe*(df-((beta1*c)/2));
fi_Mn = fi*(M_ns + psi_f*M_nf)*10^(-6)
if fi_Mn >= Mu
    disp('Suitable Strengthening')
    break
end
if fi_Mn < Mu
    disp('FRP s number of layers should be increased')
    n=n+1
end
fi_vekt = [fi_vekt; fi_Mn];
end
Fi = [(fi_vekt)' fi_Mn]
N = 1:n;
plot(N,Fi, 'b-', 'LineWidth',2, 'Marker', '*', 'MarkerEdgeColor',...
      'r', 'MarkerSize',8)

title('Flexural Capacity Change Chart'), grid on
xlabel('number of plies of FRP')
ylabel('capacity')

```

Shear Strengthening of Beam

```

clear all, clc, clf
b = input('enter the beam width: ')
h = input('enter the height of the beam: ')
d = input('enter the effective depth of beam: ')
fc_prime = input('enter the compressive strength of the concrete: ')
fy = input('enter the yield strength of steel: ')
tf = input('enter the thickness of FRP: ')
D = input('enter the stirrup diameter: ')
Ef = input('enter the modulus of elasticity of FRP: ')
eps_fu_asterisk = input('enter the ultimate rupture strain of FRP:')
f_fu_asterisk = input('enter the ultimate tensile strength of FRP ')
s = input('enter the reinforcement range: ')
wf = input('enter the width of the FRP: ')
sf = input('enter the center-to-center spacing of FRP strips: ')
Vu = input('enter the required shear capacity: ')
fi = input('enter the strength reduction factor: ')
d_fv = input('enter the effective shear reinforcement depth of FRP: ')
alfa = input('enter the anglle of primary FRP reinforcement: ')
psi_f = input('enter the FRP strength reduction factor: ')
CE = input('enter the environmental reduction factor: ')
%Contribution of concrete
Av = pi*(D^2)/4;
Vc = ((sqrt(fc_prime)*b*d)/6)*10^(-3);
%Contribution of reinforcement
Vs = (Av*(fy*10^(-3))*(sind(alfa)+cosd(alfa))*d)/s;
V_unstrengthened = fi*(Vc + Vs)
if V_unstrengthened < Vu
    disp('Strengthening Required')
else
    disp('Strengthening is not recommended')
end
df=h;
%Design ultimate tensile strength of FRP

```

```

f_fu = CE*f_fu_asterisk;
%Design rupture strain of FRP
eps_fu = CE*eps_fu_asterisk;
fi_vekt = [];
n=1;
while n<6
    %Active bond length of FRP laminate
    Le = 23300 / (n*tf*Ef)^(0.58);
    %Coefficients
    k1 = (fc_prime/27)^(2/3);
    k2 = (d_fv-Le)/d_fv;
    %Bond reduction coefficient
    kv = (k1*k2*Le)/(11900*eps_fu);
    %Limit control
    if kv <= 0.75
        disp('Limit Value Control: Appropriate')
    else
        disp('Limit Value Control: Insufficient')
    end
    eps_fe = kv*eps_fu;
    if eps_fe <= 0.004
        eps_fe = kv*eps_fu;
    else
        eps_fe = 0.004;
    end
    %The contribution of FRP to shear force
    Afv = 2*n*tf*wf;
    f_fe = eps_fe*(Ef*10^(-3));
    Vf = (Afv*f_fe*(sind(alfa)+cosd(alfa))*d_fv)/sf;
    %Contribution of reinforcement
    Vs = (Av*(fy*10^(-3))*(sind(alfa)+cosd(alfa))*d)/s;
    %Contribution of concrete
    Av = pi*(D^2)/4;
    Vc = ((sqrt(fc_prime)*b*d)/6)*10^(-3);
    fi_Vn = fi*(Vc + Vs + psi_f*Vf)
    if fi_Vn >= Vu
        disp('Suitable Strengthening')
        break
    end
    if fi_Vn < Vu
        disp('FRP s number of layers should be increased')
        n=n+1
    end
    fi_vekt = [fi_vekt; fi_Vn];
end
Fi = [(fi_vekt)' fi_Vn]
N = 1:n;
plot(N,Fi, 'r-.', 'LineWidth',2, 'Marker', 'square', 'MarkerEdgeColor',...
      'b', 'MarkerSize',8)

title('Shear Capacity Change Chart'), grid on
xlabel('number of plies of FRP')
ylabel('capacity')

```