Scientific Research Publishing

World Journal of Engineering and Technology, 2023, 11, 281-292
https://www.scirp.org/journal/wjet
ISSN Online: 2331-4249
ISSN Print: 2331-4222

Shear Strengthening of Reinforced Concrete (RC) with FRP Sheets Using Different Guidelines

Bashir H. Osman

Civil Engineering Department, College of Engineering, University of Sinnar, Sinnar, Sudan
Email: bashir00@yahoo.com

How to cite this paper: Osman, B.H. (2023) Shear Strengthening of Reinforced Concrete (RC) with FRP Sheets Using Different Guidelines. *World Journal of Engineering and Technology*, **11**, 281-292.
https://doi.org/10.4236/wjet.2023.112020

Received: February 11, 2023
Accepted: May 9, 2023
Published: May 12, 2023

Abstract

The aim of this study is to investigate the influence of fiber reinforcement polymer (FRP) on shear behavior of reinforcement concrete (RC) beams with various guidelines. The FRP thickness, beam depth and concrete strength at ultimate load are considered as main strength parameters. A finite element (FE) by using ANSYS computer program was used to analyze the reinforced concrete beams. The numerical models were used to investigate the effect of beam depth, concrete strength, CFRP sheet configuration, and CFRP sheet thickness on the behavior of reinforced concrete beams strengthened with CFRP sheets compared with different guidelines. The results from ACI guideline show little difference compared with FE, which make it suitable for RC beams strengthened with FRP sheets.

Keywords

FRP Sheets, Strengthening, RC Beams, ANSYS, ACI

1. Introduction

In the last decade, the use of Fiber-Reinforced Polymer (FRP) composites in strengthening and repairing of structures has continuously increased because it has several advantages over other materials. Beside low weight and an economical way, epoxy resin and FRP composites provide high resistance to corrosion and mechanical strengths of structures repair or rehabilitation ([1] [2] [3]).

Over the last two decades, many researches were carried out on the strengthening of RC beams using FRP composites using different methods such as externally strengthening, near-surface mounted (NSM) strengthening, and embedded section (internal strengthening) ([4] [5] [6] [7] [8]). Furthermore, some studies [9] [10] [11] [12] investigate the flexural behavior of pre-damaged reinforced concrete (RC) beams repaired by using grids and engineered cementitious composite (ECC) and carbon fiber reinforced polymer (CFRP) under sustained load. Their results showed that most of the beams failed by debonding. Furthermore, the proposed repairing technique was effective in enhancing the flexural stiffness and bearing capacity of pre-damaged RC beams. Moreover, they proposed a mathematical model to calculate the flexural capacities of the repaired beams and the results were in accordance with excremental results. Six RC beams strengthened with CFRP sheets under static and fatigue loading were studied by Min, *et al.* [13] to show the failure mechanism. The results showed that acceleration the fatigue failure of the specimens is due to coupling of stresses between accumulated fatigue damage in the steel reinforcement and fatigue debonding of the CFRP plate. Jia, J., *et al.* [14] used the novel models of Extreme Learning Machine (ELM) in co-operation with Particle Swarm Optimization (PSO), Teaching-Learning based Optimization (TLBO), and gray wolf optimizer (GWO) to investigate the debonding strength of FRP. The results predicted from ELM-GWO showed the best performance compared with ELM-PSO and ELM-TLBO.

2. Material Properties and Codes of Practice Used in This Study

Based on this study, a prediction model was proposed by considering all common parameters that influence the ultimate shear capacity of a strengthened beam including concrete strength (f_c'), effective height of the beam (*d*), FRP thickness (t_f), and strengthening configuration (completely wrapped, U-jacketing, and side bonding). The obtained results were compared with that recommended design guide given by different guidelines ([13] [14] [15] [16] [17]). Beam geometry and materials properties were illustrated in **Figure 1** and **Table 1**, respectively.

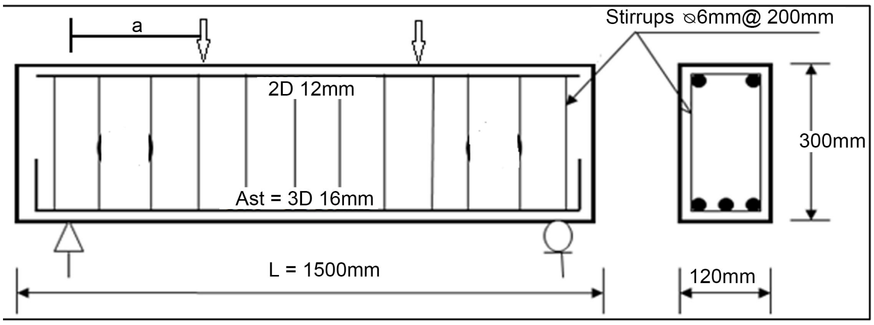


Figure 1. Geometrical details of proposed RC beams.

Table 1. The properties of materials used in this study.

f_y	f_{yv}	w_f	F_c'	E_f	S_f	d_f	ε_{fu}	f_{fu}	b
460	250	100	35	223,500	50	300	0.018	3000	120

3. FE Model Description

Numerical Modeling

A finite element analysis (FEA) by using ANSYS [18] computer program was used to analysis the reinforced concrete beams. SOLID65 element, was used to model the concrete as this element is capable of modeling cracking in tension and crushing in compression. An eight nodes three degrees of freedom at each node: translations of the nodes in x, y, and z-directions used to define the element.

Steel reinforcement was modeled using link 8 element and which consists of two nodes with three degrees of freedom in each node. The FE model for the rebar was assumed to be a bilinear isotropic, elastic-perfectly plastic material, and identical in tension and compression. Solid element with an eight-node, solid 45, was used to simulate the plates in the supports and the loading points. This element has defined with eight nodes of three degrees of freedom at each node translation in the nodal *y*-, *x*-, and *z*-directions.

FRP sheet was modeled using Shell41 element. This element allows for different material layers with different orientations and orthotropic material properties in each layer. Since the FRP materials considered as orthotropic materials, they showed different properties in each direction. The relationship between v_{xy} and v_{yx} is illustrated in Equations (1) and (2) ([15] [18] [19]):

$$1-v_{xy}^2\left(\frac{E_y}{E_x}\right)-v_{yz}^2\left(\frac{E_z}{E_y}\right)-v_{xz}^2\left(\frac{E_z}{E_x}\right)-2v_{xy}v_{yz}v_{xz}\left(\frac{E_z}{E_x}\right)=\text{Positive} \tag{1}$$

$$G_{xy}=G_{xz}=\frac{E_xE_y}{E_x+E_y+2v_{xy}E_x},G_{yz}=\frac{E_z\text{ or }E_y}{2\left(1+v_{yz}\right)}\text{ and }v_{yx}=\frac{E_y}{E_x}v_{xy} \tag{2}$$

In this study, Poisson's ratios of: 0.22, 0.22 and 0.30 are used for v_{xy}, v_{xz}, and v_{yz}, respectively, which are widely used in the related published literature based on this subject. Contact elements TARGE170 and CONTA174 are used to model the contact between concrete and FRP. To study the contact between two elements, the surface of one element is considered as a contact surface (e.g. FRP) and the other body surface considered as a target surface (e.g. concrete). The contact and target pair concepts has been widely used in finite element models. As used in this study, the FRP was considered as the contact surface which is associated with the deformable body; the concrete was considered as the target surface which must be the rigid surface [20].

4. Comparison of Different Method with Design Guidelines

Following the previous discussion on the behavior of FRP shear-strengthened beams, it is of interest to see how the measured shear capacity compares with the predictions from available design guidelines. Three design guidelines are considered in this study which compared with American Concrete Institute (ACI) (2008) such as Traintafillou and Anton 2000, carolin and taljsten 2005 and Zhichao and cheng 2005. The equations used in this part of this study related with below guides:

4.1. ACI Equation

Simplified method: the above equation is not so simple to use as a design equation, the ACI code permits use of below equation:

$$V_c = \frac{1}{6}\sqrt{f_c'}b_w d \tag{3}$$

For beams with shear reinforcement, the ACI consider nominal shear strength, V_n as flow:

$$V_n = V_c + V_s \tag{4}$$

Which V_c = shear strength of concrete; V_s = shear strength of shear reinforcement. Shear strength for inclined stirrup at an angle α with horizontal suggested as:

$$V_s = \frac{A_v f_{yv}(\sin\alpha + \cos\alpha)d}{s} \tag{5}$$

Which A_v, f_{yv} are area of shear reinforcement in distance s and is the yield strength of shear reinforcement respectively.

When $\alpha = 90^\circ$ (vertical stirups are used) the above equation reduces to

$$V_s = \frac{A_v f_{yv} d}{s}\text{, but } \varnothing V_s \geq V_s \tag{6}$$

The nominal shear strength of an FRP-strengthened concrete member can be determined by adding the contribution of the FRP external shear reinforcement to the contributions from the reinforcing steel (stirrups, ties, or spirals) and the concrete. An additional reduction factor ψ_f is applied to the contribution of the FRP system.

$$\varphi V_n = \varphi\left(V_c + V_s + \psi_f V_f\right) \tag{7}$$

The reduction factor ψ_f of 0.85 is recommended for the three-sided FRP U-wrap or two-opposite-sides strengthening schemes. Insufficient experimental data exist to perform a reliability analysis for fully-wrapped sections; however, there should be less variability with this strengthening scheme as it is less bond independent, and therefore, the reduction factor ψ_f of 0.95 is recommended. Figure 2 illustrates the dimensional variables used in shear-strengthening calculations for FRP laminates. The contribution of the FRP system to shear strength of a member is based on the fiber orientation and an assumed crack pattern. The shear strength provided by the FRP reinforcement can be determined by calculating the force resulting from the tensile stress in the FRP across the assumed crack. The shear contribution of the FRP shear reinforcement is then given by:

$$V_f = A_{fv} f_{fe}(\sin\alpha + \cos\alpha)d_{fv}/s_f \tag{8}$$

where: $A_{fv} = 2nt_f w_f$

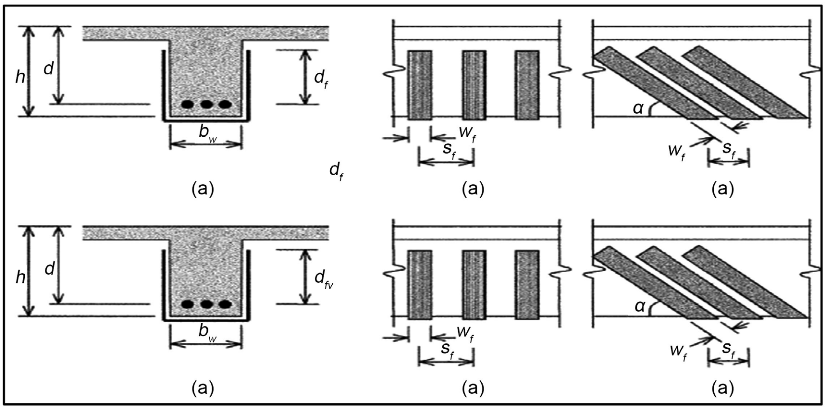


Figure 2. Illustration of the dimensional variables used in shear-strengthening calculations for repair, retrofit, or strengthening using FRP laminates.

For reinforced concrete column and beam members completely wrapped by FRP

$$\varepsilon_{fe} = 0.004 \le 0.75\varepsilon_{fu}$$

FRP systems that do not enclose the entire section (two- and three-sided wraps) have been observed to delaminate from the concrete before the loss of aggregate interlock of the section. For this reason, bond stresses have been analyzed to determine the usefulness of these systems and the effective strain level that can be achieved. The effective strain is calculated using a bond-reduction coefficient κ_v applicable to shear:

$\varepsilon_{fe} = \kappa_v \varepsilon_{fu} \le 0.004$, The bond-reduction coefficient can be computed from:

$$K_v = k_1 k_2 L_e / 11900\varepsilon_{fu} \le 0.75$$

The active bond length Le is the length over which the majority of the bond stress is maintained. This length is given by:

$$L_e = \frac{23300}{\left(n_f t_f E_f\right)^{0.58}}$$

The bond-reduction coefficient also relies on two modification factors, k_1 and k_2, that account for the concrete strength and the type of wrapping scheme used, respectively. Expressions for these modification factors are given in:

$$k_1 = \left(\frac{f'_c}{27}\right)^{2/3}, \quad k_1 = \begin{cases} \dfrac{d_{fv} - L_e}{d_{fv}} & \text{for U warps} \\[2ex] \dfrac{d_{yv} - 2L_e}{d_{yv}} & \text{for two sides bonded} \end{cases}$$

4.2. Traintafillou and Anton 2000 Equation for FRP Contribution

$$\rho_f = \frac{2w_f * t_f}{b * s_f}$$

$$\varepsilon_{fe} = 0.17\left(f_c^{2/3} / E_f \rho_f\right)^{0.3} \varepsilon_{fu} \quad \text{for full warp}$$

$$V_f = \left(2w_f t_f E_f \varepsilon_{fe} d_f\right) / s_f$$

$$\begin{aligned}
&\Gamma_f = \left(E_f \rho_f\right) \big/ f_c^{2/3} \left(\frac{a}{d}\right) \\
&\varepsilon_{fe} = 0.72 \varepsilon_{fu} \mathrm{e}^{-0.0431 \Gamma_f} \quad \text{for three or two sides or} \\
&\varepsilon_{fe} = 0.00065 \left(\frac{f_c^{2/3}}{E_f \rho_f}\right)^{0.56}
\end{aligned} \tag{9}$$

4.3. Carolin and Taljsten 2005 Equation

$$V_f = \left(\eta \varepsilon_{cr} E_f t_f r_f z \cos\theta\right) \big/ \sin\alpha ,\ \varepsilon_{fe} = \eta \varepsilon_{cr} ,\ \eta = 0.6,\ r_f = b_f \big/ s_f ,\ \varepsilon_{fe} = \varepsilon_{cr} \tag{10}$$

4.4. Zhichao and Cheng 2005 Equation

$$\begin{aligned}
&V_f = \left(2 w_f t_f E_f \varepsilon_{fe} d_f\right) \big/ s_f ,\ \ \varepsilon_{fe} = R \varepsilon_{fu} \\
&\rho_f = (2 w_f t_f) / b s_f \\
&R = 1.4871 \left(\rho_f E_f / f_c\right)^{-0.7488} \quad \text{or} \\
&R = 0.5622 \left(\rho_f E_f\right)^2 - 1.2188 \left(\rho_f E_f\right) + 0.778 \quad \text{which is small} \\
&R = \left(0.0042 \left(f_c\right)^{2/3} w_f\right) \big/ \left(E_f t_f\right)^{0.58} \varepsilon_{fu} d_f
\end{aligned} \tag{11}$$

4.5. Zhichao and Cheng 2005

$$\begin{aligned}
&V_f = \left(2 w_f * t_f * E_f * \varepsilon_{fe} * d_f\right) \big/ s_f ,\ V_c = \left(f_c\right)^{0.5} * b * d / 6 \\
&R = \left(0.0042 \left(f_c\right)^{2/3} * w_f\right) \big/ \left(E_f * t_f\right)^{0.58} * \varepsilon_{fu} * d_f \\
&\varepsilon_{fe} = R * \varepsilon_{fu} ,\ \ p_f = \left(2 w_f * t_f\right) \big/ b * s_f
\end{aligned} \tag{12}$$

5. Results and Discussion

The main goal for this work is to study the influence of fiber reinforcement polymer (FRP) on shear behavior of RC beams with various guidelines. The purpose was also to study the strength parameters such as, FRP thickness, beam depth and concrete strength at ultimate load.

5.1. FRP Thickness

Table 2 shows the effect of FRP thickness on the shear strength, which plotted in Figure 3.

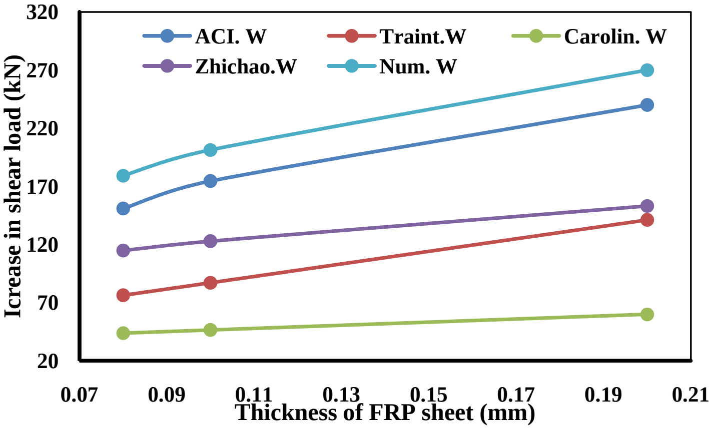
Table 2 and Figure 3 show that the FRP thickness has a grater effects on concrete strength, the results predicted from Carolin equation showed under estimation compared with those from FE program. Furthermore, the ACI guideline showed acceptable differences compared with the other guidelines when compared with FE.

5.2. Effect of Concrete Strength

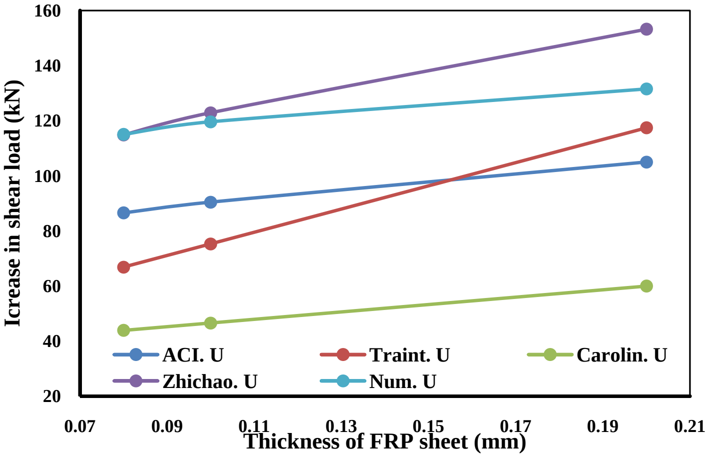
Table 3 shows the effect of FRP thickness on the shear strength, which plotted in Figure 4.

5.3. Effect of Beam Depth

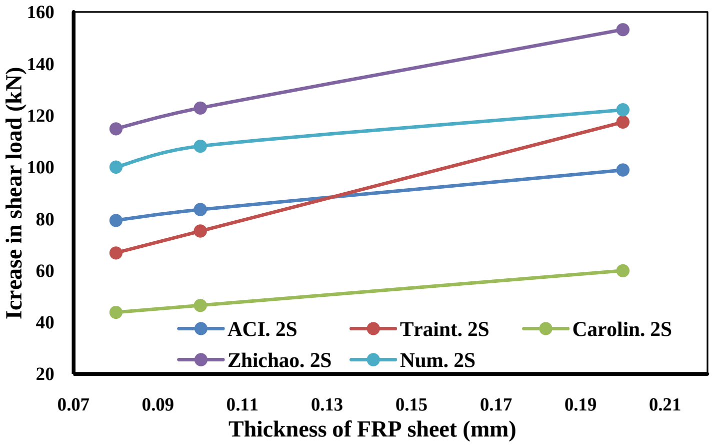
Table 4 shows the effect of FRP thickness on the shear strength, which plotted in Figure 5.



(a) Full warp



(b) U warp



(c) 2s warp

Figure 3. Effect of FRP thickness on beams strength using different configurations (a) Full warp (b) U-warp (c) 2 sides warp.

Table 2. Effect of FRP thickness on the strength.

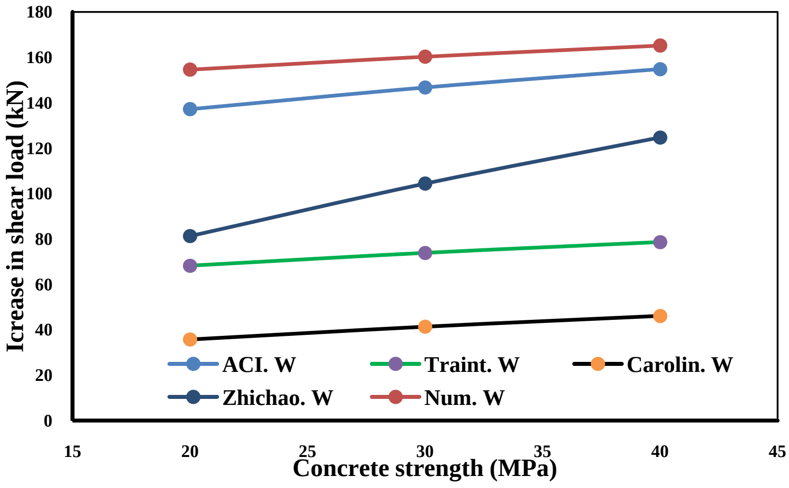
	Full			U			Side		
t_f	**0.08**	**0.1**	**0.2**	**0.08**	**0.1**	**0.2**	**0.08**	**0.1**	**0.2**
Numerical	179.22	201.34	270	115	119.6	131.54	100	108.13	122.15
ACI	150.94	174.59	239.99	86.52	90.43	104.99	79.4	83.589	98.8666
Traintaf.	76.35197	87.15745	141.1848	66.83981	75.26725	117.4044			
Carolin	43.85954	46.54191	59.95377						
Zhichao	114.8425	122.8709	153.1969						

Table 3. Effect of concrete strength on shear strength.

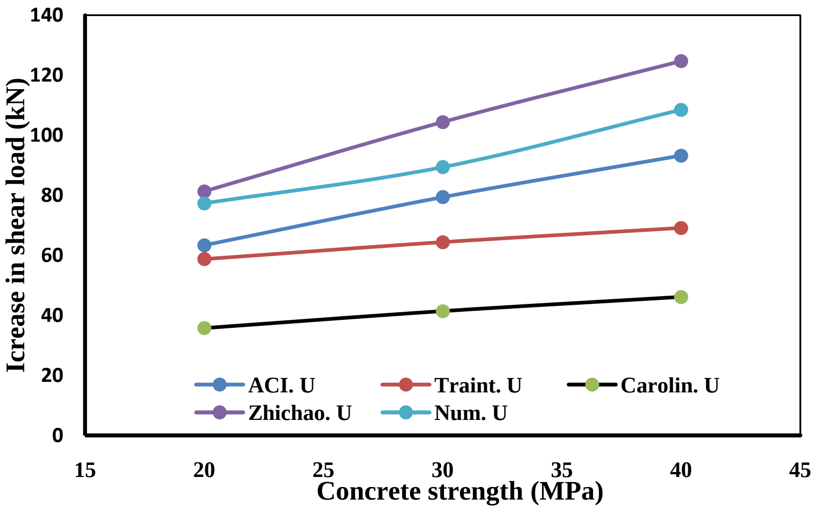
	Full			U			Side		
Strength	40	30	20	40	30	20	40	30	20
Numerical	165.2	160.3	154.6	108.5	89.4	77.32	93.67	85.08	69.5
ACI	154.83	146.764	137.195	93.2211	79.393	63.371	85.467	72.993	58.485
Traintaf.	78.63943	73.89438	68.26588	69.12727	64.38222	58.75372			
Carolin	46.147	41.40195	35.77345						
Zhichao	124.7377	104.4046	81.31203						

Table 4. Effect of beam depth on shear strength.

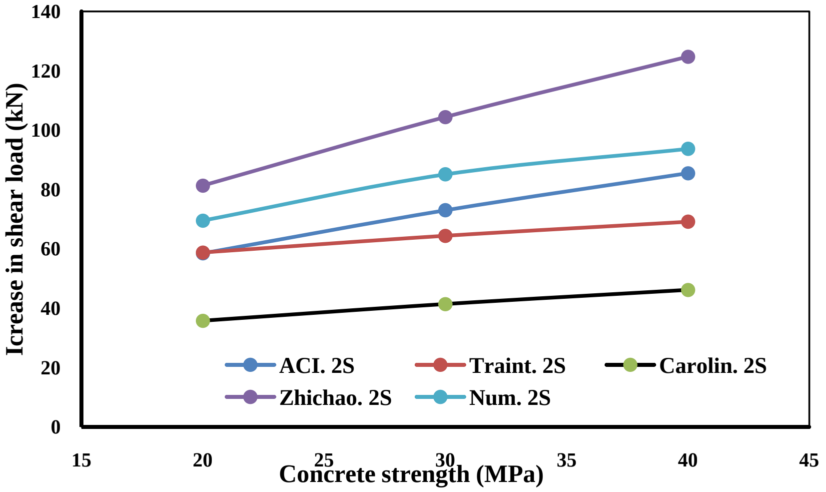
	Full			U			Side		
Depth	250	280	320	250	280	320	250	280	320
Numerical	150.1	163.5	185.4	82	98.5	108.34	76.25	91	107.3
ACI	134.77	150.94	172.51	76.49	86.52	99.894	69.397	79.43	92.8
Traintaf.	68.1714	76.35197	87.25939	59.6784	66.83981	76.38835			
Carolin	40.30989	43.85954	48.5924						
Zhichao	121.0983	114.8425	109.3613						



(a)

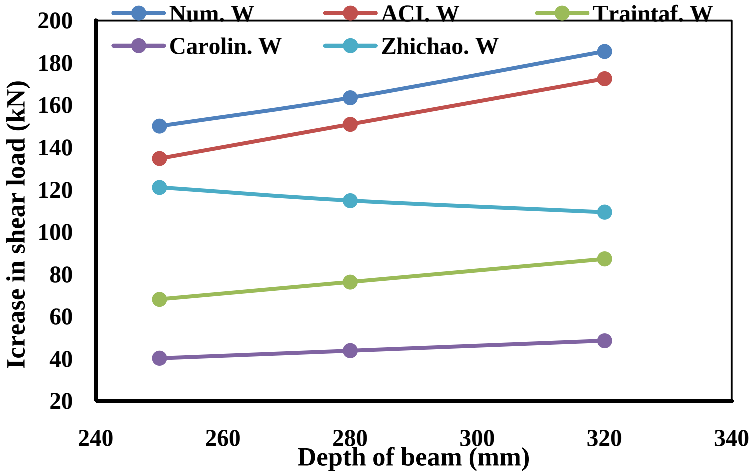


(b)

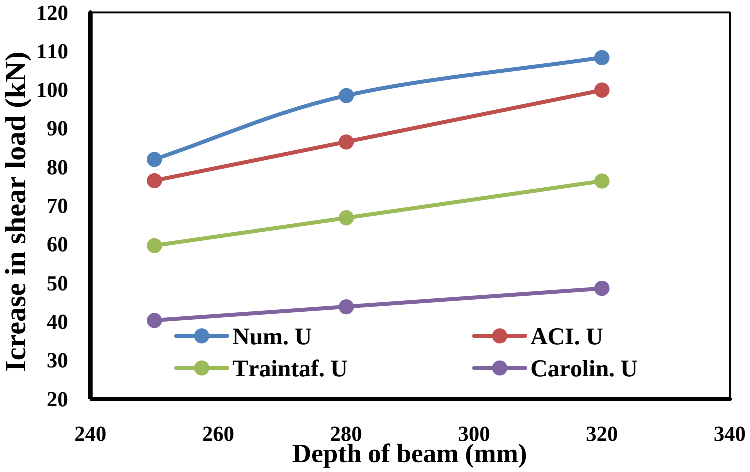


(c)

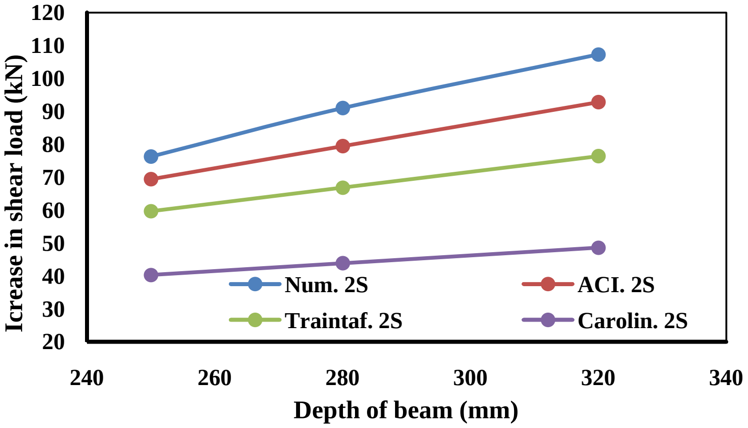
Figure 4. Effect of concrete strength on beams strength using different configurations (a) Full warp (b) U-warp (c) 2 sides warp.



(a)



(b)



(c)

Figure 5. Effect of beam depth on beams strength using different configurations (a) Full warp (b) U-warp (c) 2 sides warp.

6. Conclusions

Based on the results of analysis using ANSYS software and different design guidelines on reinforced concrete RC beams strengthened with fiber reinforcement polymer (FRP) and reported in literature the following conclusions are:

1) The use of FRP strengthening has greater effect in the stiffness of the concrete.

2) The finite element models were able to accurately predict the load capacities for the simulated RC beams. This confirms the validity of the developed FE models and reliability of the FE simulation.

3) For the FRP shear contribution, the ACI equation is believed to be the most appropriate for practical design. However, for the fully wrapped scheme, the ACI method appears to predict the FRP shear contribution with a relatively high discrepancy.

4) The ACI model predicted the ultimate capacity of RC beams based on the beam geometry and concrete compressive strength without considering the ef-

fect of the longitudinal reinforcement.

5) The theoretical prediction of ultimate shear strength on the basis of methods used in this study gives results over estimate compared with the other design guidelines values in most of the beams.

6) Use ACI assumptions because it gives results with more reliable safety factors than other theorems according to results on the previous literature of RC beams in case of using analytical theorems in RC beams analysis.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Barnes, R.A. and Mays, G.C. (1999) Fatigue Performance of Concrete Beams Strengthened with CFRP Plates. *Journal of Composites for Construction*, **3**, 63-72. https://doi.org/10.1061/(ASCE)1090-0268(1999)3:2(63)

[2] Aboutaha, R.S. (2002) Ductility of CFRP Strengthened Concrete Flexural Members. In: Wendichansky, D. and Paumarada-O'Neill, L.F., Eds., *Rehabilitating and Repairing the Buildings and Bridges of Americas*: *Hemispheric Workshop on Future Directions*, ASCE, Reston. https://doi.org/10.1061/40613(272)1

[3] Danraka, M.N., Mahmod, H.M., Oluwatosin, O.K.J. and Student, P. (2017) Strengthening of Reinforced Concrete Beams Using FRP Technique: A Review. *International Journal of Engineering Science*, **7**, 13199-13213.

[4] Uji, K. (1992) Improving Shear Capacity of Existing Reinforced Concrete Members by Applying Carbon Fiber Sheets. *Transactions of the Japan Concrete Institute*, **14**, 253-266.

[5] Triantafillou, T.C. (1998) Shear Strengthening of Reinforced Concrete Beams Using Epoxy-Bonded FRP Composites. *ACI Structural Journal*, **95**, 107-115. https://doi.org/10.14359/531

[6] Khalifa, A., Gold, W.J., Nanni, A. and Aziz, A. (1998) Contribution of Externally Bonded FRP to Shear Capacity of RC Flexural Members. *Journal of Composites for Construction*, **2**, 195-203. https://doi.org/10.1061/(ASCE)1090-0268(1998)2:4(195)

[7] Yang, Z.J., Chen, J.F. and Proverbs, D. (2003) Finite Element Modelling of Concrete Cover Separation Failure in FRP Plated RC Beams. *Construction and Building Materials*, **17**, 3-13. https://doi.org/10.1016/S0950-0618(02)00090-9

[8] Galal, K. and Mofidi, A. (2010) Shear Strengthening of RC T-Beams Using Mechanically Anchored Unbonded Dry Carbon Fibre Sheets. *Journal of Performance of Constructed Facilities*, **24**, 31-39. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000067

[9] Yan, Y., Lu, Y., Zhao, Q. and Li, S. (2023) Flexural Behavior of Pre-Damaged and Repaired Reinforced Concrete Beams with Carbon Fiber Reinforced Polymer Grid and Engineered Cementitious Composite. *Engineering Structures*, **277**, Article ID: 115390. https://doi.org/10.1016/j.engstruct.2022.115390

[10] Min, X., Zhang, J., Li, X., Wang, C., Tu, Y., Sas, G. and Elfgren, L. (2022) An Experimental Study on Fatigue Debonding Growth of RC Beams Strengthened with Prestressed CFRP Plates. *Engineering Structures*, **273**, Article ID: 115081. https://doi.org/10.1016/j.engstruct.2022.115081

[11] Aksoylu, C. (2022) Shear Strengthening of Reinforced Concrete Beams with Minimum CFRP and GFRP Strips Using Different Wrapping Technics without Anchoring Application. *Steel and Composite Structures*, **44**, 831-851.

[12] Zhang, Z.C. and Hsu, C.-T.T. (2005) Shear Strengthening of Reinforced Concrete Beams Using Carbon-Fiber-Reinforced Polymer Laminates. *Journal of Composites for Construction*, **9**, 158-169. https://doi.org/10.1061/(ASCE)1090-0268(2005)9:2(158)

[13] Osman, B.H., Wu, E., Ji, B. and Abdulhameed, S.S. (2016) Effect of Reinforcement Ratios on Shear Behavior of Concrete Beams Strengthened with CFRP Sheets. *HBRC Journal*, **14**, 253-263. https://doi.org/10.1016/j.hbrcj.2016.04.002

[14] Jia, J., Zandi, Y., Rahimi, A., Pourkhorshidi, S., Khadimallah, M.A. and Ali, H.E. (2022) Numerical Performance Evaluation of Debonding Strength in Fiber Reinforced Polymer Composites Using Three Hybrid Intelligent Models. *Advances in Engineering Software*, **173**, Article ID: 103193. https://doi.org/10.1016/j.advengsoft.2022.103193

[15] ANSYS (2004) User's Manual Version 14.5. Swanson Analysis System Inc. (SASI), Houston.

[16] Carolin, A. and Täljsten, B. (2005) Experimental Study of Strengthening for Increased Shear Bearing Capacity. *Journal of Composites for Construction*, **9**, 488-496. https://doi.org/10.1061/(ASCE)1090-0268(2005)9:6(488)

[17] Carolin, A. and Täljsten, B. (2005) Theoretical Study of Strengthening for Increased Shear Bearing Capacity. *Journal of Composite for Construction*, **9**, 497-506. https://doi.org/10.1061/(ASCE)1090-0268(2005)9:6(497)

[18] Kachlakev, D.I. and McCurry Jr., D. (2000) Simulated Full Scale Testing of Reinforced Concrete Beams Strengthened with FRP Composites: Experimental Results and Design Model Verification. Final Report FHWA-OR-RD-00-19. Oregon Department of Transportation and U.S. Department of Transportation Federal Highway Administration, Salem.

[19] American Concrete Institute (2008) ACI Committee 440. Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures (ACI 440.2R-02). American Concrete Institute, Farmington Hills.

[20] American Concrete Institute (ACI) (2008) Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures. ACI 440.2R-08.