Investigation of the Experimental Shear Resistance of RC T-beams after Strengthening with Carbon Fiber-Reinforced Polymer (CFRP) Bars

Hussain Hassan Alhilli
Department of Civil Engineering, College of Engineering, University of Baghdad, Iraq
hussain.hasan2001m@coeng.uobaghdad.edu.iq (corresponding author)

Mahdi Hameed Al-Farttoosi
Department of Civil Engineering, College of Engineering, University of Baghdad, Iraq
mahdi_farttoosi@coeng.uobaghdad.edu.iq

Received: 31 October 2023 | Revised: 14 November 2023, 17 November 2023, and 23 November 2023 | Accepted: 1 December 2023

ABSTRACT

This study investigates the stiffness and shear resistance of T-reinforced concrete beams that have been strengthened against shear using the embedded through-section approach. The beams were exposed to a monotonic one-point load until failure. The experimental methodology included the investigation of 12 T beams made of reinforced concrete, consisting of 2 reference beams that were not subjected to any strengthening measures and 10 reinforced beams. The 12 beams were classified into two primary categories: those with stirrups and those without stirrups. The primary factors from each group encompassed the spacing and angle of inclination pertaining to the Carbon Fiber-Reinforced Polymer (CFRP) bars placed along the central axis of the section. Various configurations were used, including varied spacing intervals and degrees of inclination. The results showed that the ratio of the CFRP shear resistance to the total section (Vf / Vsec) ranged between 10 to 21% in group one (with stirrups). This means that the Embedded Through Section (ETS) technique with CFRP bars is useful in increasing the shear resistance of reinforced concrete beams. For group two (without stirrups), this ratio ranged between 56 to 58.5%. That is, ETS with CFRP bars significantly increases the shear resistance of reinforced concrete beams without stirrups.

Keywords-shear resistance; stiffness; Embedded Through Section (ETS); CFRP bars; reinforced concrete T-beams

I. INTRODUCTION

During the recent years, there has been a growing interest in the use of Carbon Fiber Reinforced Polymer (CFRP) composites for reinforcing concrete parts to rehabilitate infrastructure. The use of CFRP reinforcement demonstrates a diverse array of applications, entailing the construction of innovative structures and the rehabilitation of pre-existing ones [1-7]. The shear strength of Reinforced Concrete (RC) beams is influenced by many factors [8-10]. These factors include the compressive strength of the concrete (f'c), the ratio of main steel (ρ), the dimensions of the beam, the ratio of shear span to effective depth (a/d), and the ratio of shear reinforcement (ρv). Several studies have attempted to define the bond behavior at the interface where premature failures originate [11-14]. Authors in [15] conducted a thorough analysis and practical study of RC T-beams that were strengthened in shear using Embedded Through-Section (ETS) Fiber-Reinforced Polymer (FRP). The study examined the impact of various factors on the performance of FRP bars, including the influence of the surface coating on FRP bars, the effect of internal transverse steel reinforcement on FRP shear contribution, the influence of FRP bar spacing, the impact of FRP rod diameter, and the efficiency of the embedded through-section FRP rod method. Novel design equations were introduced to compute the shear contribution of FRP for beams reinforced using the ETS FRP method. The design equations were verified using data obtained from the experimental portion of the present research investigation. The proposed model exhibits a satisfactory correlation with the experimental findings. Authors in [16] examined 14 RC beams strengthened in shear by CFRP textiles bonded with cement-based adhesive CBA. The experimental results demonstrated that the CBA-bonded CFRP textiles substantially enhanced the shear capacity of the RC members. The structural performance of RC columns strengthened in shear with ETS Glass Fiber Reinforced Polymer (GFRP) bars was experimentally and analytically investigated in [17]. The results showed that the configuration and specifics of the anchorage system should be carefully considered before formulating unified specifications. Authors in [18] presented a comprehensive investigation of the shear behavior of the RC beams reinforced with a small-diameter FRP bar-reinforced geopolymer matrix (FRGM) system. The findings indicated that utilizing steel fibers in the geopolymer matrix further inhibited the formation of shear fractures and enhanced shear capacity. Using 18 shear-deficient RC beams strengthened with Near Surface Mounted (NSM) CFRP bars, authors in [19] conducted an experimental analysis to determine the bars impact on the shear strength of the RC beams. The reinforced beams were found to have a shear capacity that was up to 35% higher than that of the control beams. It was also noted that, compared to beams with higher strength concrete, those with standard strength concrete showed a greater increase in shear strength.

According to the literature review, and to the best of our knowledge, no research has been conducted on the shear behavior of reinforced concrete T-beams strengthened by CFRP bars using the ETS technique.

II. EXPERIMENTAL PROGRAM

The experimental program included testing a total of 12 RC T-beams, consisting of 2 reference beams not subjected to any strengthening measures and 10 beams that were strengthened with the ETS Technique with CFRP bars. The 12 beams were classified into 2 primary categories, namely those with stirrups and those without stirrups, with the latter involving just 3 beams for steel bar support. The primary factors under investigation were the CFRP bars' spacing and inclination degree. The reinforced beams exhibited enhanced resistance to shear forces by inserting 12 mm CFRP bars along the beam central axis, using various spacing intervals and inclination degrees. An experimental investigation was carried out to investigate the impact of spacing and inclination angle of CFRP bars on several factors, including failure load, fracture distribution, load-strain relation, and load-deflection relationship. All beams within each group exhibited uniform characteristics, encompassing a consistent length of 2200 mm, exact cross-sectional dimensions, and equivalent reinforcing. The beams in question were exposed to a unidirectional single-point load applied at the midpoint until reaching the point of failure, as seen in Figures 1 and 2. The tested beams were designed according to ACI-318-19 [20] and ACI440-17 [21]. Table I illustrates the configuration and designation of the tested beams.

Concrete's properties, such as its modulus of elasticity, and tensile and compressive strengths, were calculated. The properties of the concrete (after 28 days), CFRP bars, and steel reinforcements employed in this study are illustrated in Table II. Figure 3 shows the ETS shear strengthening technique using CFRP bars, while Figure 4 shows a tested T-beam.

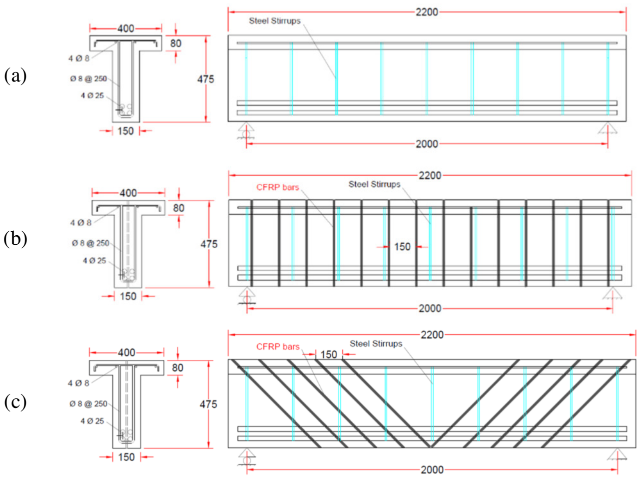

Fig. 1. Details of the beams for group one (with stirrups) (all dimensions in mm): (a) Un-strengthened reference beam, (b) strengthened beam, (c) strengthened beam with inclined CFRP bars.

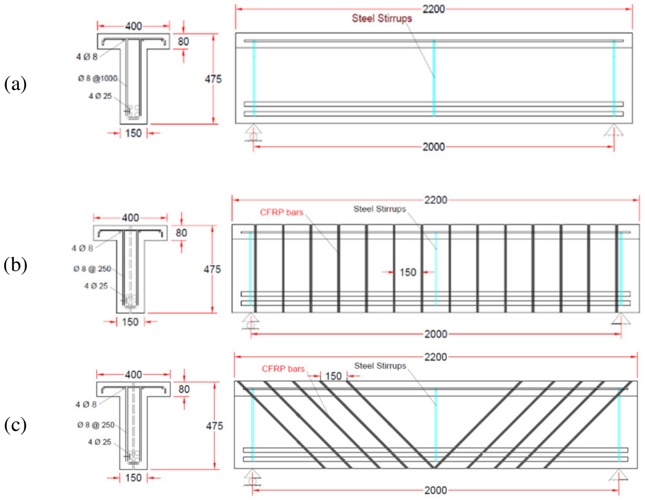

Fig. 2. Details of the beams for group two without stirrups (just 3 for support) (all dimensions in mm): (a) Un-strengthened reference beam, (b) strengthened beam with vertical CFRP bars, (c) strengthened beam with inclined CFRP bars.

TABLE I. DETAILS OF THE TESTED BEAMS.

Group	Beam-ID	Angle of inclination of CFRP bar (deg.)	CFRP bar spacing (mm)
Group one (with stirrups)	G1-B1-Ref	–	–
	G1-B2-R-S10	90	100
	G1-B3-R-S15	90	150
	G1-B4-R-S20	90	200
	G1-B5-I-S10	45	100
	G1-B6-I-S15	45	150
	G1-B7-I-S20	45	200
Group two (without stirrups)	G2-B1-Ref	–	–
	G2-B2-R-S10	90	100
	G2-B3-R-S15	90	150
	G2-B4-I-S10	45	100
	G2-B5-I-S15	45	150

TABLE II. MATERIAL PROPERTIES

Properties	**Steel bars**		**Concrete**	**CFRP bar (12mm)**
	8 mm	**25 mm**		
Tensile yield (MPa)	522.5	553.8	-	-
Tensile strength (MPa)	661.5	701	3.73	3100
Modulus of elasticity (GPa)	200		28.645	148
Compressive strength (MPa)	-	-	45.3	-

Fig. 3. ETS shear strengthening using CFRP bars.

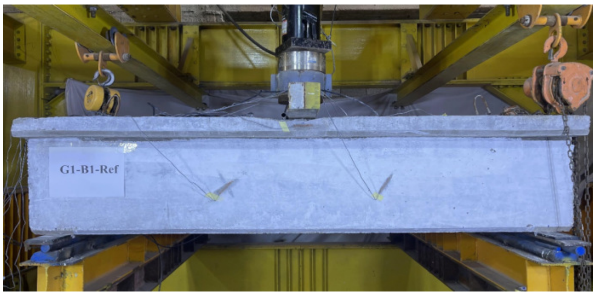

Fig. 4. A tested T beam.

III. RESULTS AND DISCUSSION

A comparative analysis was conducted on the test findings and on the reinforced specimens behavior in relation to the control T-beams, both with and without stirrups. The study also examined the impact of the spacing and angle of inclination of the CFRP bars on shear strength.

A. Beam Stiffness (k)

The serviceability limit used for this study was regulated by dividing the experimental ultimate load by a factor of 1.7, a recommendation supported by previous researchers such as [22]. This criterion was applied due to the absence of any unwanted cracking or deformation seen at this particular load level. Tables III and IV provide a comprehensive overview of the tested beams stiffness at the service stage for groups 1 and 2, respectively.

Table III shows that the beams stiffness of group one (with stirrups) with vertical CFRP bars and spacing of 100, 150, and 200 mm increased by 35.6, 22, and 11.9%, respectively. In comparison, the stiffness of the beams of group one with inclined CFRP bars (45°) and spacing of 100, 150 and 200 mm increased by 50.8, 27, and 17%, accordingly with respect to the reference beam. This finding indicates that the spacing of the CFRP bars is inversely proportional to the beam stiffness for the exact inclination angle. It is also seen that the inclined CFRP bars (45°) perform better than the vertical ones.

TABLE III. STIFFNESS k OF THE BEAMS OF GROUP ONE

Beam ID	**At service loading Ps**				**Failure load (kN)**
	Load (kN)	**Deflection (mm)**	**k (kN/mm)**	**% increase in k**	
G1-B1-Ref	265.3	4.5	59	Ref.	451
G1-B2-R-S10	335.3	4.22	80	35.6	570
G1-B3-R-S15	314.7	4.4	72	22	535
G1-B4-R-S20	294.7	4.49	66	11.9	501
G1-B5-I-S10	344.1	3.85	89	50.8	585
G1-B6-I-S15	324.7	4.31	75	27	552
G1-B7-I-S20	306.5	4.45	69	17	521

k=Load/Deflection

TABLE IV. STIFFNESS k OF THE BEAMS OF GROUP TWO

Beam ID	**At service loading Ps**				**Failure load (kN)**
	Load (kN)	**Deflection (mm)**	**k (kN/mm)**	**% increase in k**	
G2-B1-Ref	130	2.9	44.8	Ref.	221
G2-B2-R-S10	305.3	4.12	74	65.2	519
G2-B3-R-S15	295.3	4.48	66	47.3	502
G2-B4-I-S10	313	3.8	82.4	84	532
G2-B5-I-S15	300	4.14	72.5	61.8	510

k=Load/Deflection

Table IV shows that the beams stiffness of group two (without stirrups) with vertical CFRP bars and spacing of 100, and 150 mm increased by 65.2 and 47.3%, respectively, while the stiffness of the beams of group two with inclined CFRP bars (45°) and spacings of 100 and 150 mm augmented by 84 and 61.8%, respectively, concerning the reference beam. This finding shows that the spacing of the CFRP bars is inversely proportional to the beam stiffness for the exact angle of inclination in this group. It is clear that the impact of CFRP bars was more effective on group two than on group one because the beams of group two have no shear stirrups. Figure 5 shows the stiffness of all the beams.

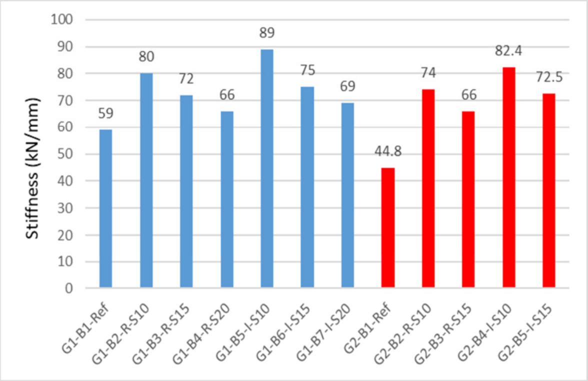

Fig. 5. Stiffness of all the tested beams.

B. Experimental Shear Resistance

The shear resistance of concrete (Vc) was taken as the half of the ultimate load of set two control beam (without stirrups), i.e. G2-B1-REF. While the shear resistance of steel (Vs) was taken as the half of the difference between the ultimate load of the control beam of set two (without stirrups) G2-B1-REF and the set one reference beam (with stirrups) G1-B1-REF. Table V shows the additional shear resistance of CFRP bars (Vf) for each beam. So, the calculated values were:

$V_c = 0.5 \times 221 = 110.5$ kN

$V_s = 0.5(451-221) = 115$ kN

$V_f = V_{sec.} - (V_c+V_s)$ …… (1)

$V_{sec.} = 0.5 \times P_u$ (for each beam) (2)

TABLE V. SHEAR RESISTANCE OF THE TESTED BEAMS.

Group	Specimens	Ultimate load	Vsec (kN)	Vc (kN)	Vs (kN)	Gain attributable to CFRP (%)	Vf (kN)	Vf / Vsec. (%)	Vf / Vc (%)
Group1	G1-B1-Ref	451	225.5	110.5	115	Ref.	-	-	-
	G1-B2-R-S10	570	285	110.5	115	26.39	59.5	21	54
	G1-B3-R-S15	535	267.5	110.5	115	18.6	42	16	38
	G1-B4-R-S20	501	250.5	110.5	115	11.1	25	10	27
	G1-B5-I-S10	585	292.5	110.5	115	29.7	67	23	61
	G1-B6-I-S15	552	276	110.5	115	22.4	50.5	18.3	46
	G1-B7-I-S20	521	260.5	110.5	115	15.5	35	13.4	32
Group2	G2-B1-Ref	221	110.5	110.5	-	Ref.	-	-	-
	G2-B2-R-S10	519	259.5	110.5	-	135	149	57.4	135
	G2-B3-R-S15	502	251	110.5	-	127	140.5	56	127
	G2-B4-I-S10	532	266	110.5	-	141	155.5	58.5	141
	G2-B5-I-S15	510	255	110.5	-	131	144.5	56.7	131

Table V shows that the ultimate beams load of group one (with stirrups) with vertical CFRP bars and spacings of 100, 150, and 200 mm increased by 26.39, 18.6, and 11.1%, respectively. On the contrary, the beams stiffness of group one with inclined CFRP bars (45°) and spacings of 100, 150, and 200 mm increased by 29.7, 22.4, and 15.5%, respectively, with regard to the reference beam. This suggests that there is an inverse relationship between the spacing of the CFRP bars and the ultimate load of the beam, specifically for the given inclination angle. Furthermore, this discovery suggests that inclined CFRP bars at 45° have superior performance compared to the vertical bars. Table V also shows that the ultimate load of the group tow beams (without stirrups) with vertical CFRP bars and spacings of 100 and 150 mm grew by 135 and 127%, respectively. The stiffness of group two beams, with inclined CFRP bars (45°) and spacings of 100 and 150 mm, though, increased by 141 and 131%, correspondingly, regarding the reference beam. This finding indicates that the increasing spacing of the CFRP bars is inversely proportional to the beam stiffness for the exact angle of inclination in this group. It is clear that CFRP bars presence was more effective in group two than in group one because group two beams have no shear stirrups. Figures 6 to 17 describe the failure mechanism and fracture patterns of every single T-beam.

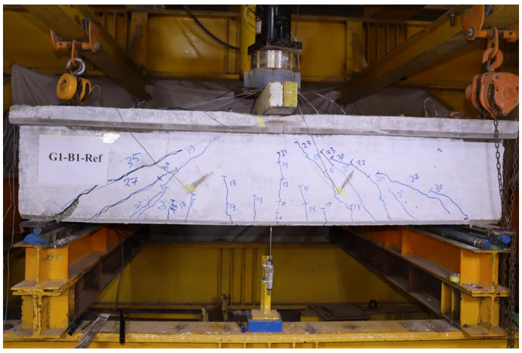

Fig. 6. Failure crack pattern of specimen G1-B1-REF.

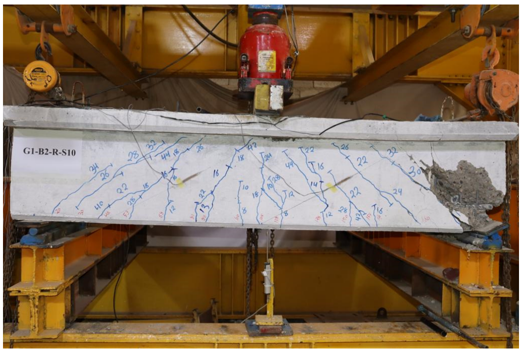

Fig. 7. Failure crack pattern of specimen G1-B2-R-S10.

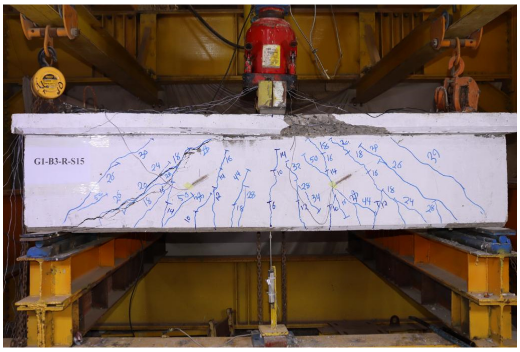

Fig. 8. Failure crack pattern of specimen G1-B3-R-S15.

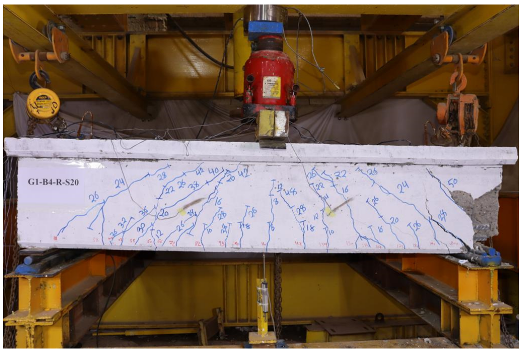

Fig. 9. Failure crack pattern of specimen G1-B4-R-S20.

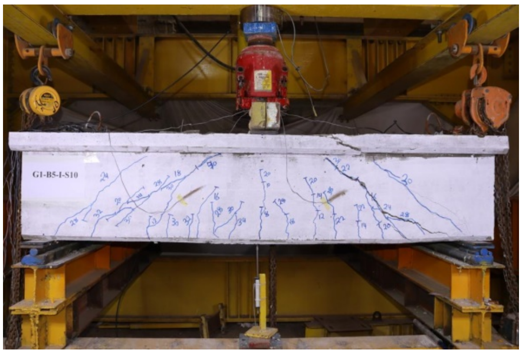

Fig. 10. Failure crack pattern of specimen G1-B5-I-S10.

Fig. 11. Failure crack pattern of specimen G1-B6-I-S15.

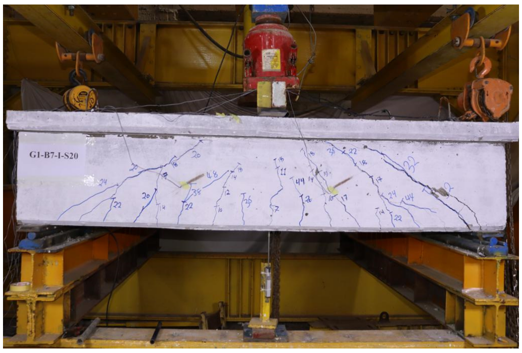

Fig. 12. Failure crack pattern of specimen G1-B7-I-S20.

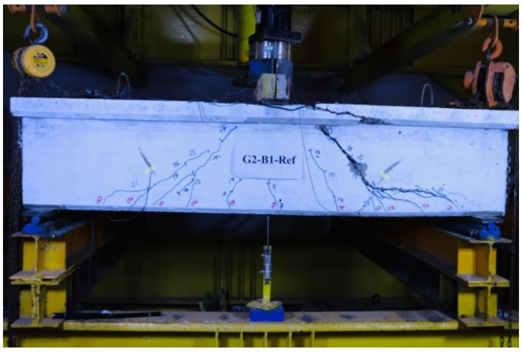

Fig. 13. Failure crack pattern of specimen G2-B1-REF.

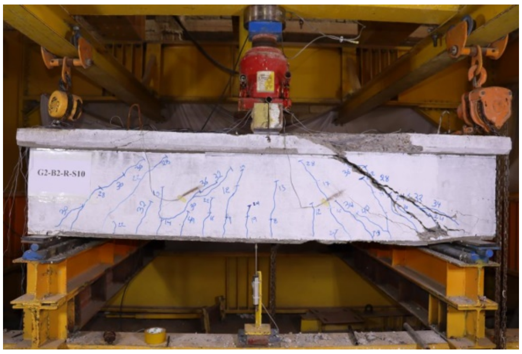

Fig. 14. Failure crack pattern of specimen G2-B2-R-S10.

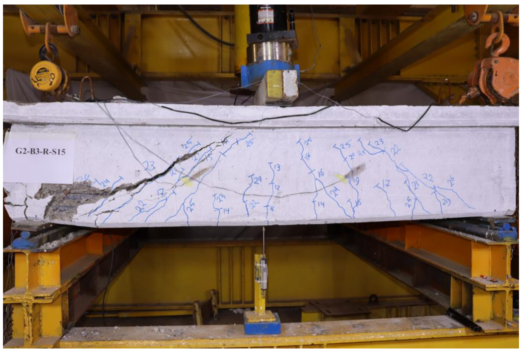

Fig. 15. Failure crack pattern of specimen G2-B3-R-S15.

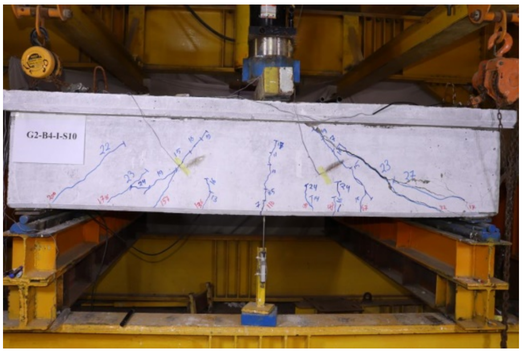

Fig. 16. Failure crack pattern of specimen G2-B4-I-S10.

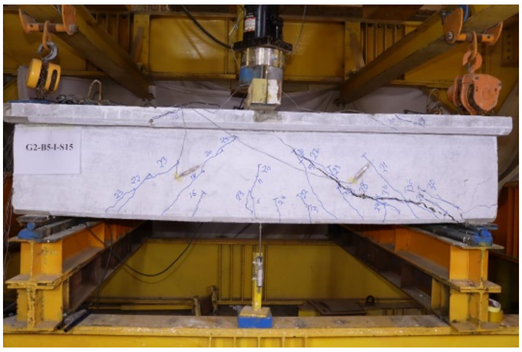

Fig. 17. Failure crack pattern of specimen G2-B5-I-S15.

IV. CONCLUSION

This paper investigates two essential properties of the RC beam, i.e. stiffness and shear resistance, because these properties give a good indicator of the RC beams shear behavior after strengthening with CFRP bars. Based on the experimental results, we can obtain the following conclusions:

- The stiffness of group one beams (with stirrups) with vertical CFRP bars and spacing of 100, 150, and 200 mm increased by 35.6, 22, and 11.9%, respectively, whereas the stiffness of group one beams with inclined CFRP bars (45°) and spacing of 100, 150, and 200 mm rose by 50.8, 27, and 17%, correspondingly, with regard to the reference beam. It is concluded that CFRP bars spacing is inversely proportional to the beam stiffness for the exact inclination angle.
- The inclined CFRP bars (45°) perform better than the vertical ones.
- The stiffness of group two beams (without stirrups) with vertical CFRP bars and spacing of 100 and 150 mm increased by 65.2, and 47.3%, accordingly, whereas the stiffness of group two beams with inclined CFRP bars (45°) and spacing of 100 and 150 mm increased by 84 and 61.8%, respectively. The CFRP bars influence was more effective on group two than group one because group two beams have no shear stirrups.
- The ultimate load of group one beams (with stirrups) with vertical CFRP bars and spacing of 100, 150, and 200 mm augmented by 26.39, 18.6, and 11.1%, respectively, whereas the stiffness of group one beams with inclined CFRP bars (45°) and spacing of 100, 150, and 200 mm increased by 29.7, 22.4, and 15.5 %, correspondingly, with regard to the reference beam. This suggests an inverse relationship between the CFRP bars spacing and the ultimate load of the beam, specifically for the given inclination angle.
- Inclined CFRP bars at a 45° angle perform better than vertical bars.
- The ultimate load of group two beams (without stirrups) with vertical CFRP bars and spacing of 100 and 150 mm increased by 135, and 127%, respectively, whereas the stiffness of group two beams with inclined CFRP bars (45°) and spacing of 100 and 150 mm rose by 141 and 131%, respectively with regard to the reference beam.
- The ratio of the CFRP shear resistance to concrete (Vf / Vc) ranged between 27 to 61% in group one (with stirrups). For group two (without stirrups), this ratio ranged between 1.27 to 1.41%.
- The ratio of the CFRP shear resistance to the total section (Vf / Vsec.) ranged between 10 to 21% in group one (with stirrups). This means that the ETS technique with CFRP bars is useful in increasing the shear resistance of RC beams. For group two (without stirrups), this ratio ranged between 56 to 58.5%, which means that ETS with CFRP bars significantly increases the shear resistance of RC beams without stirrups.

Recommendations for future research work: Investigation of the behavior of strengthened T-RC beams with CFRP bars under repeated load and studying the behavior of prestressed strengthened T-reinforced concrete beams with CFRP bars.

REFERENCES

[1] H. A. Al-Baghdadi and A. S. Sabah, "Behavior of RC Beams Strengthened with NSM-CFRP Strips Subjected to Fire Exposure: A Numerical Study," *Engineering, Technology & Applied Science Research*, vol. 11, no. 6, pp. 7782–7787, Dec. 2021, https://doi.org/10.48084/etasr.4493.

[2] A. J. Daraj and A. H. Al-Zuhairi, "The combined strengthening effect of CFRP wrapping and NSM CFRP laminates on the flexural behavior of Post-Tensioning concrete girders subjected to partially strand damage," *Engineering, Technology & Applied Science Research*, vol. 12, no. 4, pp. 8856–8863, Aug. 2022, https://doi.org/10.48084/etasr.5008.

[3] S. I. Ali and A. A. Allawi, "Effect of Web Stiffeners on The Flexural Behavior of Composite GFRP- Concrete Beam Under Impact Load," *Journal of Engineering*, vol. 27, no. 3, pp. 76–92, Feb. 2021, https://doi.org/10.31026/j.eng.2021.03.06.

[4] B. F. Abdulkareem, A. F. Izzet, and N. Oukaili, "Post-Fire Behavior of Non-Prismatic Beams with Multiple Rectangular Openings Monotonically Loaded," *Engineering, Technology & Applied Science Research*, vol. 11, no. 6, pp. 7763–7769, Dec. 2021, https://doi.org/10.48084/etasr.4488.

[5] A. M. Kareem and S. D. Mohammed, "The experimental and theoretical effect of fire on the structural behavior of laced reinforced concrete deep beams," *Engineering, Technology & Applied Science Research*, vol. 13, no. 5, pp. 11795–11800, Oct. 2023, https://doi.org/10.48084/etasr.6272.

[6] A. A. Abdulhameed and A. I. Said, "Behaviour of Segmental Concrete Beams Reinforced by Pultruded CFRP Plates: an Experimental Study," *Journal of Engineering*, vol. 25, no. 8, pp. 62–79, Aug. 2019, https://doi.org/10.31026/j.eng.2019.08.11.

[7] R. M. Abbas and R. K. Rakaa, "Structural performance of lightweight fiber reinforced polystyrene aggregate Self-Compacted concrete beams," *Engineering, Technology & Applied Science Research*, vol. 13, no. 5, pp. 11865–11870, Oct. 2023, https://doi.org/10.48084/etasr.6217.

[8] A. W. Naqe and A. H. Al-zuhairi, "Strengthening of RC Beam with Large Square Opening Using CFRP," *Journal of Engineering*, vol. 26, no. 10, pp. 123–134, Oct. 2020, https://doi.org/10.31026/j.eng.2020.10.09.

[9] A. F. Izzat, "Retrofitting of Reinforced Concrete Damaged Short Column Exposed to High Temperature," *Journal of Engineering*, vol. 21, no. 3, pp. 34–53, Mar. 2015, https://doi.org/10.31026/j.eng.2015.03.03.

[10] A. Y. Turki and M. H. Al-Farttoosi, "Flexural Strength of Damaged RC Beams Repaired with Carbon Fiber-Reinforced Polymer (CFRP) Using Different Techniques," *Fibers*, vol. 11, no. 7, Jul. 2023, Art. no. 61, https://doi.org/10.3390/fib11070061.

[11] H. N. Ghadhban, "Effect of Beam Size on Shear Strength of Reinforced Concrete Normal Beams," *Journal of Engineering and Development*, vol. 11, no. 1, pp. 152–168, Mar. 2007.

[12] H. Chen, W.-J. Yi, Z. J. Ma, and H.-J. Hwang, "Shear Strength of Reinforced Concrete Simple and Continuous Deep Beams," *Structural Journal*, vol. 116, no. 6, pp. 31–40, Nov. 2019, https://doi.org/10.14359/51718003.

[13] N. K. Tuma, A. H. Al-Ahmed, and M. H. Al-Farttoosi, "The shear strengthening of reinforced concrete beams by embedded through section technique -analytical study-," *IOP Conference Series: Materials Science and Engineering*, vol. 888, no. 1, Apr. 2020, Art. no. 012039,https://doi.org/10.1088/1757-899X/888/1/012039.

[14] H. H. Mhanna, R. A. Hawileh, and J. A. Abdalla, "Shear Strengthening of Reinforced Concrete Beams Using CFRP Wraps," *Procedia Structural Integrity*, vol. 17, pp. 214–221, Jan. 2019, https://doi.org/10.1016/j.prostr.2019.08.029.

[15] A. Mofidi, O. Chaallal, B. Benmokrane, and K. W. Neale, "Experimental tests and design model for RC beams strengthened in shear using the embedded Through-Section FRP method," *Journal of Composites for Construction*, vol. 16, no. 5, pp. 540–550, Oct. 2012, https://doi.org/10.1061/(asce)cc.1943-5614.0000292..

[16] D. Alwash, R. Kalfat, R. Al-Mahaidi, and H. Du, "Shear strengthening of RC beams using NSM CFRP bonded using cement-based adhesive," *Construction and Building Materials*, vol. 301, Sep. 2021, Art. no. 124365, https://doi.org/10.1016/j.conbuildmat.2021.124365.

[17] L. V. H. Bui, C. Klippathum, T. Prasertsri, P. Jongvivatsakul, and B. Stitmannaithum, "Experimental and Analytical Study on Shear Performance of Embedded Through-Section GFRP-Strengthened RC Beams," *Journal of Composites for Construction*, vol. 26, no. 5, Oct. 2022, Art. no. 04022046, https://doi.org/10.1061/(ASCE)CC.1943-5614.0001235.

[18] K.-D. Peng, J.-Q. Huang, B.-T. Huang, L.-Y. Xu, and J.-G. Dai, "Shear strengthening of reinforced concrete beams using geopolymer-bonded small-diameter FRP bars," *Composite Structures*, vol. 305, Feb. 2023, Art. no. 116513, https://doi.org/10.1016/j.compstruct.2022.116513.

[19] R. A. Hawileh, R. B. Saleh, E. I. Saqan, and J. A. Abdalla, "Contribution of Longitudinal NSM-CFRP Bars on the Shear Strength of RC Beams with Varying Depths and Concrete Strengths," *Journal of Composites for Construction*, vol. 26, no. 3, Jun. 2022, Art. no. 04022025, https://doi.org/10.1061/(ASCE)CC.1943-5614.0001212.

[20] ACI Committee 318, *318-19 Building Code Requirements for Structural Concrete and Commentary*. Farmington Hills, MI, USA: American Concrete Institute, 2019.

[21] ACI Committee 440, *ACI PRC-440.2-17: Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*. Farmington Hills, MI, USA: ACI, 2017.

[22] M. A. Mansur, L. M. Huang, K. H. Tan, and S. L. Lee, "Deflections of Reinforced Concrete Beams With Web Openings," *Structural Journal*, vol. 89, no. 4, pp. 391–397, Jul. 1992, https://doi.org/10.14359/3019.