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Orientation-Dependent Performance of Externally Bonded CFRP for Shear Strengthening of Reinforced Concrete Beams

Robert B. A.[1], John A. T.[1,] * and Biebelemo J. J.[2]

[1]Department of Civil Engineering, Niger Delta University, Bayelsa State, Nigeria
[2]Department of Agric/Environmental Engineering, Niger Delta University, Bayelsa State, Nigeria
*Corresponding Author: johntrustgod@ndu.edu.ng

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ABSTRACT

This study examined the optimal orientation of Carbon Fibre Reinforced Polymer (CFRP) strips for the shear strengthening of Reinforced Concrete (RC) beams. A total of eighteen (18) RC beams, each measuring 100 × 225 × 1400 mm, were cast comprising three (3) control beams (CA-B) and fifteen (15) beams strengthened with CFRP strips bonded using epoxy resin. The strengthening configurations included vertical strips (A2), 45° diagonal strips from bottom left to top right (A3), 45° diagonal strips in reverse (A4), a cross-diagonal "X" arrangement with upward 45° strips from both bottom corners (A5), and downward 45° strips from both top corners (A6). Three samples were produced for each configuration, and the CFRP strips were applied and cured before testing under two-point loading to record mid-span deflection. For each set of three samples, the average value was computed. The CFRP sheets possessed an ultimate tensile strength of approximately 3,964 MPa, a modulus of elasticity of 237 GPa, and a thickness of 0.167 mm, while the epoxy adhesive had a tensile strength of about 20 MPa and a modulus of 3300 GPa. Results showed that CFRP application delayed crack initiation, with first-crack loads increasing from 3.4 kN for the control beam to between 7.3 kN and 7.5 kN. The ultimate load capacity also improved significantly, reaching 43.9 to 47.7 kN compared to 36.7 kN for the control, confirming enhanced flexural strength in all strengthened beams. However, increased stiffness resulted in lower ductility, with the control beam having the highest ductility index (1.78) and diagonal configurations showing the lowest (about 1.40). Vertical and top-to-bottom orientations achieved the greatest strength gains, while diagonal arrangements offered a better balance between strength and ductility. Overall, CFRP strengthening proved effective, lightweight, and non-corrosive, though limited by epoxy cost, environmental sensitivity, and the laboratory scale of testing.

Keywords: Concrete, beam, Shear, Orientation, CFRP, Shear Resistance, Ductility

1.0. Introduction

Reinforced Concrete (RC) beams are critical structural elements designed to resist bending and shear forces in buildings, bridges, and other civil infrastructure (Bahij et al., 2020; Hung et al., 2021). Although concrete possesses high compressive strength, its tensile and shear capacities are relatively low, making it prone to cracking and eventual failure under significant transverse loads (Abouni, 2023; Jiang et al., 2024; Sarfaraz & Harish, 2025). Traditional shear reinforcement, typically in the form of steel stirrups, enhances load-carrying capacity (Luo et al., 2021); however, poor detailing, steel corrosion, overloading, and long-term material degradation can compromise performance. Consequently, the need for effective retrofitting and strengthening methods has become increasingly vital to ensure structural safety and serviceability (Şimşek et al., 2023).

In recent decades, Fiber Reinforced Polymer (FRP) composites, particularly Carbon Fiber Reinforced Polymer (CFRP), have emerged as promising materials for structural rehabilitation due to their high tensile strength-to-weight ratio, corrosion resistance, and ease of application (Diniță et al., 2023; Vijayan et al., 2023). CFRP systems have been successfully employed for both flexural and shear strengthening of RC beams, providing a lightweight, durable, and non-intrusive alternative to conventional repair techniques (Hassani et al., 2023; Zhang et al., 2023). Nevertheless, the effectiveness of CFRP in shear strengthening is influenced not only by its material properties but also by the configuration and orientation of the fibers relative to the principal stress directions (Mohamed & Abdelbary, 2023).

Previous studies (Han et al., 2021; Mohamed & Abdelbary, 2023) have shown that CFRP applied at various orientations such as vertical, inclined, or horizontal interacts differently with shear cracks. Inclined orientations can intercept diagonal tension cracks more effectively, while vertical alignments may better complement conventional steel stirrups. However, these outcomes are often inconsistent, as they depend on parameters such as beam geometry, loading type, concrete strength, and internal reinforcement detailing. Furthermore, the interaction between CFRP orientation and the resulting failure modes requires further exploration (Abadel et al., 2022; Bounjoum et al., 2024). Certain orientations delay shear cracking and enhance ultimate load capacity, whereas others may be limited by premature debonding or stress concentration at anchorage zones (Eslami et al., 2020; Ryan, 2022).

Given the growing need for efficient and sustainable strengthening techniques in civil infrastructure, it is essential to understand precisely how the orientation of Carbon Fibre Reinforced Polymer (CFRP) strips affects the shear behavior of Reinforced Concrete (RC) beams. Therefore, this study experimentally investigates the influence of various CFRP fiber orientations, specifically vertical, diagonal at 45 degrees in both directions, and cross-diagonal (X) arrangements, on the load-carrying capacity, crack propagation, stiffness, and ductility of RC beams subjected to shear loading. The objective is to determine the most effective CFRP configuration that maximizes shear strength enhancement while maintaining adequate ductility and preventing premature failure. The findings are expected to provide practical guidance for optimizing CFRP application in the retrofitting and rehabilitation of RC structural members, thereby improving their structural resilience, durability, and service life.

2.0. Methodology

2.1. Materials

The materials used in this study included crushed stone coarse aggregates (maximum size 12 mm) sourced from Ore, Ondo State, and river sand fine aggregates (maximum size 4.75 mm) from Amassoma, Bayelsa State, both conforming to BS EN 933-1 (2012). Portland limestone cement grade 42.5 N, compliant with BS EN 197-1 (2011), and potable water from the Civil Engineering Laboratory meeting BS 3148:1980 requirements were used, with a water–cement ratio of 0.5. Beam formworks were constructed from plywood in accordance with BS 1881-209:1983. Steel reinforcement, designed per EN 1992, comprised 2Φ10 mm tensile bars, 2Φ8 mm hanger bars, and Φ6 mm links at 350 mm spacing with 10 mm cover. The beams were designed to fail in shear. For strengthening, unidirectional Carbon Fiber Reinforced Polymer (CFRP) fabrics (300 g/m², 0.167 mm thick) from Shanghai Horse Construction Technology Co., Ltd. were applied using Sikadur®-31 epoxy resin, a high-performance two-part adhesive ensuring effective bonding and stress transfer between CFRP and concrete surfaces. The CFRP sheets possessed an ultimate tensile strength of approximately 3,964 MPa, a modulus of elasticity of 237 GPa, and a thickness of 0.167 mm, while the epoxy adhesive had a tensile strength of about 20 MPa and a modulus of 3300 GPa.

2.2. Methods

2.2.1 Beam Configuration

The sample IDs in Tables 1 are described as follows: CA-B represents the control beam, while beams A2, A3, A4, A5, and A6 are beams strengthened using epoxy resin as the bonding agent. Each type of beam has a different orientation of CFRP, as illustrated in Figure 1 The beam configurations in this study comprised six variations: CA-B, identified as the control beam with no CFRP strengthening; A2, containing vertically oriented CFRP strips evenly spaced and perpendicular to the beam's longitudinal axis; A3, with CFRP strips inclined at 45° from the bottom-left to the top-right; A4, with CFRP strips inclined at 45° in the opposite direction, from the bottom-right to the top-left; A5, incorporating a cross-diagonal ("X") arrangement with 45° strips running from both bottom-right and bottom-left towards the top; and A6, featuring 45° strips oriented downward, running from both top-right and top-left towards the bottom.

Table 1: Geometric of CFRP fabric, Epoxy and Beam section

Beam Type	Bond thickness (mm)	Beam cross-section		CFRP fabric thickness
		b_w (mm)	h (mm)	t_f (mm)
CA-B	-	100	225	-
A2	2	100	225	0.167
A3	2	100	225	0.167
A4	2	100	225	0.167
A5	2	100	225	0.167
A6	2	100	225	0.167

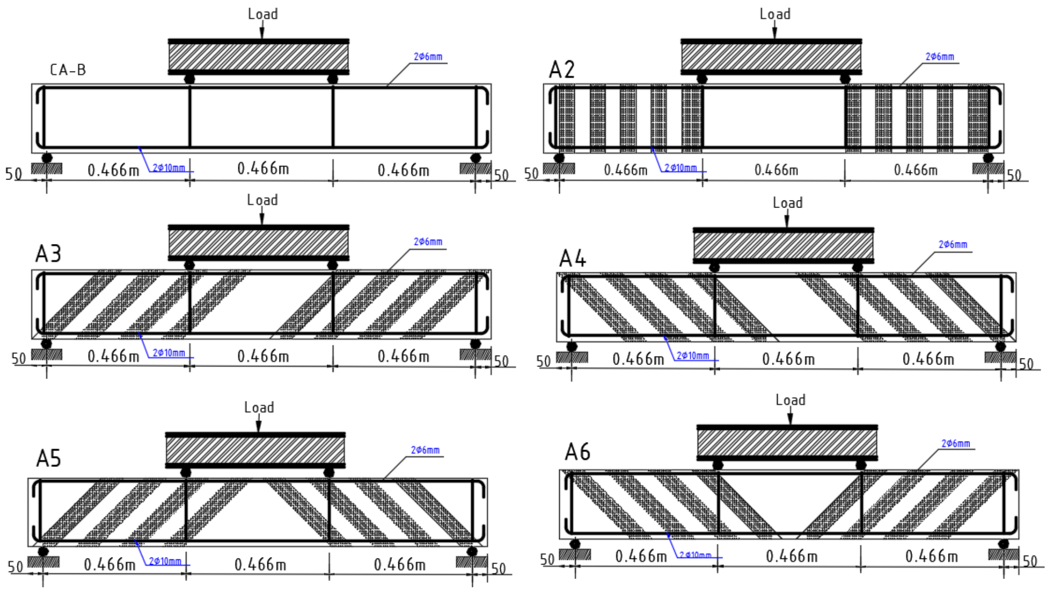

Figure 1: Beam samples

2.2.2 Production of Concrete Beams

A total of eighteen (18) RC beams, each measuring 100 × 225 × 1400 mm, were cast comprising three (3) control beams (CA-B) and fifteen (15) beams strengthened with CFRP strips bonded using epoxy resin. The beams were cast in marine plywood moulds at the Niger Delta University's concrete laboratory, as depicted in Plate 1(a). The beam dimensions were selected to achieve a shear span-to-effective depth ratio of 2.3.

The same concrete mix, in a 1:2:4 ratio, was used for both the beams and standard 150 mm cube specimens. After casting, all specimens were cured in a water bath for at least 28 days, in line with BS 1881-209:1983. On the testing day, the concrete cubes were tested for compressive strength at the same time as the beams, using a universal compression machine, as shown in Plate 1(b).

(a) (b)

Plate 1: (a) RC Beam; (b) Universal Compression Machine

2.2.3 Lateral Beams Surface Preparation

The lateral surfaces of the reinforced concrete (RC) beams were carefully roughened to remove the superficial layer of cement paste as recommended by ACI 440.2R-17 (2017), thereby enhancing the substrate condition for optimal bonding of the carbon fiber reinforced polymer (CFRP), as depicted in Plate 2(a). This surface preparation exposed the underlying aggregate rich concrete, a critical requirement for developing a durable and high-strength adhesive interface between the CFRP and the beam. Following the roughening procedure, the prepared surfaces were thoroughly cleaned with compressed air to remove all loose particles, dust, and debris that could compromise the integrity of the bond.

2.2.4 Strengthening process

The CFRP fabric strips were cut to the specified dimensions and thoroughly cleaned prior to bonding onto the RC beams using Sikadur®-31 epoxy adhesive, according to ACI 440.2R-17 (2017). The prepared epoxy resin was uniformly applied to the concrete surface at an approximate thickness of 2 mm. The CFRP strips were then precisely aligned in position, and pressure was applied using a roller to ensure intimate contact and effective adhesion between the concrete substrate and the reinforcement strips. Any excess adhesive was removed during the process. The bonded specimens were allowed to cure for a minimum of seven days at ambient temperature as illustrated in Plate 2(b) before testing as recommended ACI 503.4-04 (Reapproved 2003).

(a) (b)

Plate 2: (a) Application of Concrete (b) Surface preparation

2.2.5 Test Setup

A total of eighteen RC beams, incorporating control and various CFRP configurations, were tested under simple support conditions in accordance with the provisions of ASTM C78/C78M-18 and BS EN 12390-5:2019 for loading arrangements. Loading was applied at two discrete points, each located 467 mm from the respective supports and spaced 467 mm apart, as depicted in Plate 2(b). The loads were applied by a 1,000 kN hydraulic jack through a rigid steel plate, ensuring uniform force distribution to two rigid steel cylinders positioned at the designated loading points. The hydraulic jack was mounted securely onto a rigid steel loading frame. The beams were supported on two rigid steel cylinders anchored to steel bearing plates, which were in turn fixed to a robust foundation. One support was designed to permit horizontal translation, thereby replicating simple support boundary conditions. A dial gauge positioned at mid-span was employed to precisely measure the vertical deflection throughout the loading process. For each set of three samples, the average value was computed.

The ductility of the samples was measured by computing the ductility index, which is calculated as follows:

$$Ductility\ Index = \frac{Deflection\ at\ Failure}{Deflection\ at\ yield} \qquad (1)$$

3.0. Results and Discussion

3.1 Results of Load-Carrying capacity

The Table 2 presents the results of six reinforced concrete beams with different CFRP configurations, including a control specimen (CA-B), under flexural loading. The parameters considered first crack load, yield load, and ultimate (failure) load along with their corresponding mid-span deflections, provide critical insights into the influence of CFRP orientation on the beams' stiffness, cracking behaviour, and ultimate load-carrying capacity.

Table 2: Load-Carrying capacity

Sample ID	First Crack Load (kN)	Deflection @ First Crack (mm)	Yield Load (kN)	Deflection @ Yield Load (mm)	Failure Load (kN)	Deflection @ Failure Load
CA-B	3.4	0.04	27.5	0.45	36.7	0.8
A2	7.3	0.3	35.8	2.9	47.7	4.4
A3	7.5	0.4	33.3	2.4	44.4	3.35
A4	3.7	0.16	33.4	2.35	43.9	3.74
A5	3.8	0.13	33.8	2.2	45.4	3.43
A6	3.6	0.18	33.6	2.8	44.5	3.9

3.1.1 Control Specimen (CA-B)

The control beam, without CFRP strengthening, exhibited the lowest first crack load (3.4 kN) and a correspondingly small deflection at cracking (0.04 mm), indicating an early onset of tensile cracking in the concrete. The yield and ultimate loads reached 27.5 kN and 36.7 kN, respectively, with moderate ductility up to failure (0.8 mm deflection). This specimen forms the baseline for evaluating the performance enhancements achieved through CFRP application.

3.1.2 Vertically Oriented CFRP (A2)

Beam A2 demonstrated a substantial improvement in performance compared to the control, with the first crack load more than doubling to 7.3 kN. The deflection at cracking (0.3 mm) indicates that the vertical CFRP strips were effective in delaying crack initiation, likely by restraining tensile strain perpendicular to the longitudinal axis. The yield and ultimate loads also increased significantly to 35.8 kN and 47.7 kN, respectively, accompanied by large deflections (2.9 mm at yield and 4.4 mm at failure), suggesting improved ductility and post-yield energy absorption. These results were similar to that of Bahij et al. (2020).

3.1.3 Single-Diagonal CFRP (A3 and A4)

For beams with 45° inclined CFRP strips, the first crack loads varied markedly with orientation A3, oriented bottom-left to top-right, achieved 7.5 kN, closely matching A2, while A4 (bottom right to top-left) reached only 3.7 kN comparable to the control beam. This disparity implies that CFRP inclination relative to the principal tensile crack direction has a significant effect on the ability to arrest early cracking which was similar to results reported by Murad, (2018). Both A3 and A4 exhibited similar yield (33.3 to 33.4 kN) and ultimate loads (44.4 to 43.9 kN), suggesting that once cracking commenced, the contribution of CFRP was primarily in providing additional tensile resistance rather than altering the ultimate capacity substantially. However, A3 maintained higher ductility at both yield (2.4 mm) and failure (3.35 mm) compared to A4, indicating better crack-bridging efficiency in its orientation.

3.1.4 Cross-Diagonal Configuration (A5)

The X-shaped CFRP arrangement in A5 resulted in a first crack load (3.8 kN) similar to A4 and only marginally above the control, suggesting that although the configuration provides multidirectional crack restraint, its ability to delay initial crack formation is limited. However, the yield (33.8 kN) and ultimate loads

(45.4 kN) were consistent with other inclined configurations, confirming that diagonal reinforcement enhances ultimate performance despite earlier cracking.

3.1.5 Reverse Diagonal (A6)

Beam A6, with strips inclined from top-left/right toward the bottom, exhibited a slightly lower first crack load (3.6 kN) than A5 but achieved high ductility at yield (2.8 mm) and failure (3.9 mm). This indicates that while this orientation did not substantially improve initial crack resistance, it provided effective post-cracking confinement, allowing significant deformation before failure.

From a structural engineering perspective, the results reveal that vertical (A2) and favourably oriented diagonal (A3) CFRP strips significantly enhance first crack resistance by effectively countering tensile strains perpendicular to the beam axis, while unfavourable orientations (A4, A5, A6) perform similarly to the control in delaying crack initiation. All CFRP-strengthened beams demonstrated notable gains in ultimate load capacity, ranging from approximately 43.9 to 47.7 kN compared to 36.7 kN for the control which is similar to Murad, (2018)'s results, confirming that CFRP application consistently improves flexural strength irrespective of orientation. In terms of energy dissipation, A2 and A6 exhibited the highest deflections at failure, indicating superior crack-bridging capacity and post-yield deformation, attributes particularly beneficial for seismic or dynamic loading scenarios where deformation capacity is as critical as peak strength. Overall, the findings confirm that while CFRP orientation significantly influences early crack behaviour, its contribution to ultimate flexural performance remains consistently positive, with vertical and favourable diagonal configurations offering the most balanced enhancements in both strength and ductility.

3.2 Ductility Index

The ductility results presented in Table 3 reveal a clear strength ductility trade-off in CFRP-strengthened RC beams, where increased stiffness from external reinforcement generally reduces post-yield deformation capacity. The control beam (CA-B) achieved the highest ductility index (1.78), reflecting its greater ability to undergo inelastic deformation despite lower strength. Among strengthened specimens, A4 (1.59) and A5 (1.56) offered a relatively balanced performance, providing moderate strength gains without severely restricting ductility. In contrast, vertical (A2, 1.52), favourable diagonal (A3, 1.40), and especially reverse diagonal (A6, 1.39) configurations showed the greatest ductility reductions, indicating stiffer responses that limit deformation capacity. Structurally, these findings highlight the need to balance strength enhancement with adequate ductility, particularly in seismic or dynamic load applications where deformation capacity is critical to structural resilience.

Table 3: Ductility effect

Sample ID	Deflection @ Yield Load (mm)	Deflection @ Failure Load (mm)	Ductility Index
CA-B	0.45	0.8	1.78
A2	2.9	4.4	1.52
A3	2.4	3.35	1.40
A4	2.35	3.74	1.59
A5	2.2	3.43	1.56
A6	2.8	3.9	1.39

3.3 Load-Deflection behaviour

In investigating the behaviour of RC beam strengthened externally, the load deflection behaviour responds of the beam is a necessary tool. Figure 2 illustrates the load-deflection behavior of six beams (CA-B, A2, A3, A4, A5, and A6), offering insights into their stiffness, strength, and ductility. CA-B stands out with the steepest initial slope, indicating the highest stiffness in the elastic range and superior resistance to deformation under low loads. However, it peaks at a lower load (~35 kN) and experiences a sharp drop post-peak, reflecting brittle behavior and limited energy absorption capacity. This suggests that while CA-B is highly effective at resisting early-stage deformation, it lacks the resilience needed to sustain significant deformation beyond its peak load.

In contrast, beam A2 achieved the highest load of 47.7 kN and demonstrates excellent ductility, maintaining load-bearing capacity even as deflection increases. Its gradual post-peak decline indicated strong energy absorption, making A2 the strongest and most resilient among the beams. Beams A3, A4, A5, and A6 showed comparable performance, with moderate stiffness, peak loads ranging from 40 to 45 kN, and good ductility. Their ability to sustain deformation without sudden failure makes them well-suited for applications where a balance between stiffness and deformability is critical. This behavior is consistent with studies such as those by Rahal and Al Refai (2018), which emphasized the benefits of balanced stiffness and ductility in structural elements.

Overall, CA-B is ideal for applications prioritizing high stiffness in the elastic range but may not be suitable for scenarios requiring sustained strength under large deformations. On the other hand, A2 and the other beams are better choices for structures where strength and the ability to deform without abrupt failure are crucial. These findings confirm the importance of tailoring structural elements to specific performance requirements, as highlighted by Neville, (2011).

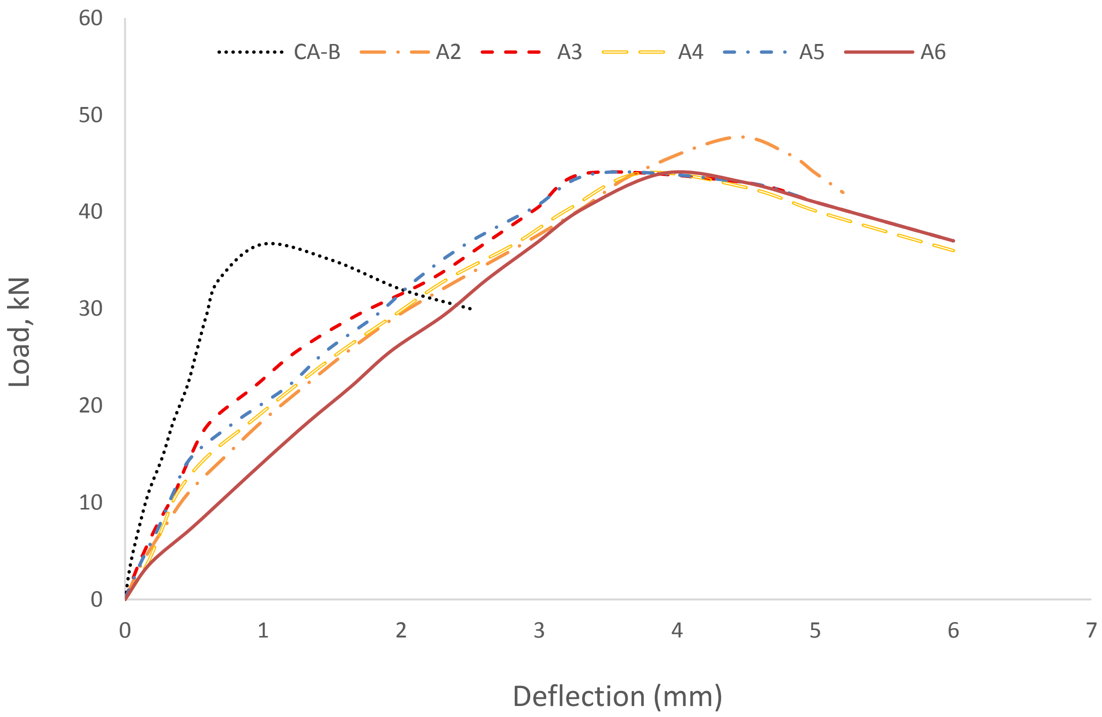

Figure 2: Load-deflection response

4.0. Conclusion

This study has demonstrated that the orientation of CFRP fibers plays a significant role in influencing the shear performance of reinforced concrete beams. Proper alignment of CFRP strips relative to the direction of principal tensile stresses enhances the effectiveness of crack control and load transfer, thereby improving the overall structural behavior. The investigation confirms that CFRP retrofitting provides a lightweight, noncorrosive, and efficient technique for strengthening existing concrete members with minimal disruption to service. Nonetheless, the improvement in stiffness observed with certain orientations suggests a potential reduction in ductility, highlighting the importance of selecting configurations that balance strength enhancement with deformation capacity. Among the various arrangements examined, diagonally oriented and cross-diagonal patterns appear most favourable for applications where both load resistance and flexibility are required. Nevertheless, as the findings are based on small scale laboratory specimens and rely on epoxy resin bonding, which may be cost sensitive or environmentally affected, further studies on full scale beams and long-term performance are recommended to validate and extend these observed trends.

References

Abadel, A., Abbas, H., Almusallam, T., Alshaikh, I. M., Khawaji, M., Alghamdi, H., & Salah, A. A. (2022). Experimental study of shear behavior of CFRP strengthened ultra-high-performance fiber-reinforced concrete deep beams. *Case Studies in Construction Materials, 16*, e01103. https://doi.org/10.1016/j.cscm.2022.e01103

ACI Committee 440. (2017). *ACI 440.2R-17: Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures*. American Concrete Institute.

ACI Committee 503. (2019). *ACI 503.4-04 (Reapproved 2019): Standard specification for repairing concrete with epoxy mortars*. American Concrete Institute.

Bahij, S., Omary, S., Feugeas, F., & Faqiri, A. (2020). Structural strengthening/repair of reinforced concrete (RC) beams by different fiber-reinforced cementitious materials: A state-of-the-art review. *Journal of Civil & Environmental Engineering, 10*(4). https://doi.org/10.37421/2165-784X.2020.10.376

Bounjoum, Y., Hamlaoui, O., Hajji, M. K., Essaadaoui, K., Chafiq, J., & El Fqih, M. A. (2024). Exploring damage patterns in CFRP reinforcements: Insights from simulation and experimentation. *Polymers, 16*(14), 2057. https://doi.org/10.3390/polym16142057

British Standards Institution. (1980). *BS 3148:1980: Methods of test for water for making concrete*. British Standards Institution.

British Standards Institution. (1983). *BS 1881-209:1983: Testing concrete—Recommendations for the measurement of flexural strength*. British Standards Institution.

British Standards Institution. (2011). *BS EN 197-1: Cement—Specification and conformity criteria*. British Standards Institution.

British Standards Institution. (2012). *BS EN 933-1: Tests for geometrical properties of aggregates—Determination of particle size distribution (Sieving method)*. British Standards Institution.

Dehn, F., Kurz, J., & Raffel, P. (2013). Influence of recycled aggregates on concrete properties. *Construction and Building Materials, 44*, 234–241. https://doi.org/10.1016/j.conbuildmat.2013.02.076

Diniță, A., Ripeanu, R. G., Ilincă, C. N., Cursaru, D., Matei, D., Naim, R. I., & Portoacă, A. I. (2023). Advancements in fiber-reinforced polymer composites: A comprehensive analysis. *Polymers, 16*(1), 2. https://doi.org/10.3390/polym16010002

Eslami, A., Moghavem, A., Shayegh, H. R., & Ronagh, H. R. (2020). Effect of FRP stitching anchors on ductile performance of shear-deficient RC beams retrofitted using FRP U-wraps. *Structures, 23*, 407–414. https://doi.org/10.1016/j.istruc.2019.09.023

Han, L., Zhang, J., Liu, Y., & Sun, T. (2021). Effect of fiber orientation on depth sensing intra-laminar failure of unidirectional CFRP under nano-scratching. *Composites Part B: Engineering, 224*, 109211. https://doi.org/10.1016/j.compositesb.2021.109211

Hassani, S., & Dackermann, U. (2023). A systematic review of advanced sensor technologies for non-destructive testing and structural health monitoring. *Sensors, 23*(4), 2204. https://doi.org/10.3390/s23042204

Hung, C. C., El-Tawil, S., & Chao, S. H. (2021). A review of developments and challenges for UHPC in structural engineering: Behavior, analysis, and design. *Journal of Structural Engineering*, *147*(9), 03121001. https://doi.org/10.1061/(ASCE)ST.1943-541X.0003124

Jiang, Z., Zhu, Z., & Accornero, F. (2024). Tensile-to-shear crack transition in the compression failure of steel-fibre-reinforced concrete: Insights from acoustic emission monitoring. *Buildings*, *14*(7), 2039. https://doi.org/10.3390/buildings14072039

Luo, G., Li, X., Zhou, Y., Sui, L., & Chen, C. (2021). Replacing steel stirrups with natural fiber reinforced polymer stirrups in reinforced concrete beams: Structural and environmental performance. *Construction and Building Materials*, *275*, 122172. https://doi.org/10.1016/j.conbuildmat.2020.122172

Mohamed, Y. S., & Abdelbary, A. (2023). Theoretical and experimental study on the influence of fiber orientation on the tensile properties of unidirectional carbon fiber/epoxy composite. *Alexandria Engineering Journal*, *67*, 693–705. https://doi.org/10.1016/j.aej.2023.06.024

Murad, Y. (2018). The influence of CFRP orientation angle on the shear strength of RC beams. *The Open Construction & Building Technology Journal*, *12*(1). https://doi.org/10.2174/1874836801812010051

Neville, A. M. (2011). *Properties of concrete* (5th ed.). Pearson Education.

Rahal, K., & Al Refai, R. (2018). Mechanical properties of recycled aggregate concrete. *Construction and Building Materials*, *180*, 143–155. https://doi.org/10.1016/j.conbuildmat.2018.05.260

Ryan, P. J. (2022). *Detailing of carbon fiber reinforced polymer anchorage for shear strengthening* [Master's thesis, University of Ottawa]. University of Ottawa Library.

Sabouni, A. R. (2023). Advances in reinforced concrete integrity and failure. In *Advances in Structural Integrity and Failure*. IntechOpen. https://doi.org/10.5772/intechopen.113963

Sarfaraz, A., & Harish, K. V. (2025). Experimental study on the fatigue performance of deep reinforced concrete beams subjected to simultaneous reinforcement corrosion. *International Journal of Fatigue*, *193*, 108779. https://doi.org/10.1016/j.ijfatigue.2024.108779

Şimşek, A., Yurdakul, Ö., Duran, B., Tunaboyu, O., Yıldırım, S., & Avşar, Ö. (2023). Effectiveness of structural walls in improving the serviceability of a seismically-retrofitted RC building. *Bulletin of Earthquake Engineering*, *21*(12), 5545–5571. https://doi.org/10.1007/s10518-023-01710-1

Vijayan, D. S., Sivasuriyan, A., Devarajan, P., Stefańska, A., Wodzyński, Ł., & Koda, E. (2023). Carbon fibre-reinforced polymer (CFRP) composites in civil engineering application: A comprehensive review. *Buildings*, *13*(6), 1509. https://doi.org/10.3390/buildings13061509

Zhang, T., Mahdi, M., Issa, M., Xu, C., & Ozevin, D. (2023). Experimental study on monitoring damage progression of basalt-FRP reinforced concrete slabs using acoustic emission and machine learning. *Sensors*, *23*(20), 8356. https://doi.org/10.3390/s23208356

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