Review On Comparative Study on RC Beams Retrofitted with BFRP Laminates with and without Anchorages

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Abstract— **Reinforced concrete (RC) beams tend to lose their structural efficiency over time due to environmental exposure, corrosion of reinforcement, and increased service loads. Strengthening of such members has therefore become essential in modern civil engineering practice. Among the available techniques, Fiber Reinforced Polymer (FRP) systems have gained significant attention, with Basalt Fiber Reinforced Polymer (BFRP) emerging as a promising alternative due to its cost-effectiveness and durability. However, the performance of externally bonded BFRP laminates is often limited by premature debonding at the interface between the laminate and concrete surface. This issue is primarily caused by stress concentration near the laminate ends. To address this limitation, anchorage systems are introduced to enhance bonding performance and delay failure. This study presents a comprehensive review of RC beams strengthened using BFRP laminates under both anchored and unanchored conditions. The findings indicate that anchorage systems significantly improve bond behaviour, enhance load transfer, delay debonding, and increase overall strength and crack resistance. As a result, the use of anchorage systems leads to a more reliable and efficient strengthening solution.**

Index Terms— **Anchorage systems, BFRP laminates, Bond behavior, Flexural strength, RC beams.**

I. INTRODUCTION

Structural members made of reinforced concrete are used in buildings and bridges, mainly designed to resist bending and shear forces. Their performance reduces over time due to factors like corrosion, environmental exposure, and increased loads.

The need to strengthen existing structures has increased, but traditional methods such as steel plates have drawbacks like corrosion and added weight. FRP composites offer a better alternative due to their high strength and durability. Among the available strengthening materials, BFRP is receiving growing attention because of its cost-effectiveness and excellent chemical resistance.

The effectiveness of BFRP depends on proper bonding with concrete, but early debonding is a major issue, often occurring near laminate ends due to stress concentration.

Fig 1: BFRP Fabrics

To overcome premature debonding, anchorage systems are used to improve the bond between Basalt FRP and concrete. These systems enhance load transfer, delay failure, and improve the overall structural behavior of strengthened beams.

In recent practice, composite materials have become a preferred choice for strengthening RC structures because they offer strength without adding significant weight. BFRP, in particular, is becoming popular due to its affordability, high tensile strength, resistance to chemicals, and eco-friendly nature.

The performance of BFRP laminates mainly depends on the bond quality between the laminate and concrete surface. Weak bonding can lead to early separation, which is a critical failure mode usually caused by stress concentration near the ends of the laminate.

II. LITERATURE REVIEW

This section discusses previous studies on the strengthening of RC beams. Different approaches and materials explored by various researchers are briefly considered. Greater importance is given to studies involving BFRP laminates, with and without the use of anchorage systems. The collected information helps in recognizing major observations and also indicates where additional work is still required.

Monier et al., (2017) [1] investigated the flexural strengthening of reinforced concrete (RC) beams using basalt FRP (BFRP) grids bonded with polymer cement mortar (PCM) as an alternative to epoxy-bonded systems. The results showed effective bond performance from double shear tests, with interfacial fracture energy higher than FRP sheets reported in the literature. The ultimate load of strengthened beams increased by 47.60–63.65% compared to the reference beam. The stress–strain response was compatible with flexural theory. Additionally, PCM demonstrated better bonding performance than epoxy putty, particularly with increasing fiber content, indicating its suitability as a durable and efficient strengthening material.

Ibrahim et al., (2019) [2] conducted a numerical investigation on shear-deficient reinforced concrete (RC) beams strengthened using externally bonded BFRP composites with various wrapping configurations. The results showed that all BFRP-strengthened beams exhibited improved strength and ductility compared to control beams. Fully wrapped configurations achieved a strength increase of 37.7%, while diagonally wrapped beams showed the highest ductility improvement of 298.5%. Additionally, strengthened beams demonstrated increased deflection at given load levels, indicating enhanced stiffness. Overall, the study confirmed that BFRP wrapping, particularly full and diagonal configurations, is effective in improving the structural performance of shear-deficient RC beams.

Rajvi et al., (2019) [3] evaluated the behaviour of reinforced concrete beams using basalt fiber-reinforced polymer (BFRP) bars as an alternative to steel reinforcement to address corrosion issues. Pull-out tests conducted on 10 mm and 12 mm BFRP bars indicated bond characteristics comparable to conventional steel reinforcement. Tensile tests showed slipping of BFRP specimens at a load of 7000 kg, without complete failure. In flexural behaviour, BFRP-reinforced beams exhibited higher deflection under lower loads compared to steel-reinforced beams. The final deflection values were 11.6 mm and 11.2 mm for BFRP beams, compared to 10.5 mm and 10.1 mm for steel beams with 10 mm and 12 mm bars, respectively.

Surwase et al., (2019) [4] conducted an experimental investigation on flexural behaviour of reinforced concrete (RC) T-beams strengthened using BFRP sheets through experimental analysis. The results showed that all strengthened beams exhibited improved ultimate load-carrying capacity compared to the control beam. Initial flexural cracks appeared at higher loads in strengthened beams, indicating enhanced performance. The maximum increase in load capacity was 37.5% for Beam 4 compared to the control beam, and 6.5% and 4.4% higher than Beams 2 and 5, respectively. Additionally, Beam 6, retrofitted in the web region over a 1 m length, showed minimum deflection under similar loads, demonstrating improved stiffness.

Diab et al., (2020) [5] aimed to improve the performance of reinforced concrete (RC) T-beams carry shear forces more effectively by utilizing Near Surface Mounted (NSM) BFRP bars in combination with BFRP sheets and a non-mechanical anchorage system. The study demonstrated that beams lacking anchorage achieved shear strength improvements between 8% and 46%, while those provided with anchorage demonstrated significantly higher gains ranging from 39.6% to 81.6%, along with improved strain utilization. The findings indicate that the proposed anchorage method effectively reduces the occurrence of premature debonding and improves the overall efficiency of the strengthening system. In summary, the study emphasizes the importance of anchorage techniques in enhancing shear performance and extending the durability of BFRP-strengthened RC elements.

Wang et al., (2020) [6] investigated the effect of specimen thickness on water absorption and tensile properties of BFRP laminates under hygrothermal ageing (60 °C water and alkaline solution up to 180 days). The results showed that water absorption increased initially, reached a peak, and then decreased with immersion duration, while tensile properties degraded, especially in alkaline conditions. Specimen thickness significantly influenced performance, where water absorption decreased initially and then increased with thickness, whereas tensile strength retention continuously increased with thickness. An accelerated ageing method based on thickness was proposed, showing good agreement with experimental results and effectively predicting long-term performance.

Alkhraisha et al., (2020) [7] did an experimental and numerical investigation on behaviour of BFRP-reinforced concrete beams under environmental exposure, including ultraviolet radiation, humidity, and rain. The results showed that exposure had no significant impact on cracking or ultimate moment capacity, with experimental cracking and ultimate moments exceeding predicted values by 0.5–10.5% and 12–30%, respectively. The average bond-dependent coefficient (kb = 0.61) was lower than ACI recommendations but closer to CSA values. Increasing reinforcement ratio improved stiffness and crack distribution but did not proportionally increase moment capacity. Finite element analysis confirmed that reduced tensile strength significantly affects flexural capacity in under-reinforced beams.

Panahi et al., (2021) [8] numerically investigated the flexural performance of reinforced concrete (RC) beams strengthened using externally bonded (EB), near-surface mounted (NSM), and combined EB–NSM FRP techniques using ABAQUS 6.11. The results showed that flexural capacity and stiffness significantly increased, while mid-span deflection at failure decreased compared to the control beam. Ultimate bending moment and stiffness increased with material strength and embedded length. For equal FRP area, 1Φ12 showed higher capacity than 2Φ6, while ductility decreased with increasing diameter. Load–deflection behavior exhibited a tri-linear response. Increased FRP sheet width enhanced load capacity but reduced ductility.

Nikil et al., (2021) [9] investigated the flexural behaviour of hybrid reinforced concrete beams incorporating BFRP bars and PVA fibers to address corrosion issues. The results showed that beams with PVA fibers exhibited more ductile behaviour compared to pure FRPRC and hybrid beams without fibers. The inclusion of PVA fibers enhanced both cracking load and load-carrying capacity. The ultimate moment capacity increased by 42.99% and 211.2% at 0.125% PVA dosage compared to hybrid beams without fibers and pure BFRP beams, respectively. Additionally, ductility improved by 65% at an optimum 0.25% PVA content, highlighting the effectiveness of fiber inclusion in improving structural performance.

Chhorn et al., (2022) [10] focused on assessing the fatigue behavior of BFRP laminates over an extended period, subjected to cyclic loading while varying the orientation of fibers. Fatigue experiments were conducted at a frequency of 10 Hz with a stress ratio of 0.1, and S–N relationships were established using Weibull statistical analysis to assess fatigue life. The findings revealed that both fiber orientation and stacking sequence have a strong influence on fatigue strength, stiffness reduction, and overall durability of the laminates. The study outcomes give a better idea of the response of basalt fiber reinforced polymer composites to cyclic loading and suggest their effectiveness in improving the durability of such structures. They also emphasize the need to optimize laminate configurations to achieve better fatigue performance.

Kadhim et al., (2022) [11] investigated the flexural performance of reinforced concrete (RC) beams strengthened with basalt fibre-reinforced polymer (BFRP) under four-point bending. The results showed that cracking capacity increased by ≥50%, yield capacity by ≥28%, and ultimate strength by 37–51%. With vertical extensions of 25, 75, and 105 mm, ultimate strength increased by 37%, 44%, and 52%, respectively. Initial stiffness remained 90–105% of the reference beam. Ductility decreased by 33% (soffit only) and 25–29% (side extensions). Beams with U-strips showed ~10% increase, while combined strengthening showed ~39% increase. Toughness improved by 8–78%.

Zhu et al., (20122) [12] evaluated the flexural behaviour of BFRP-reinforced concrete beams incorporating steel fibers under cyclic loading. The results showed that adding 1.5% steel fibers significantly enhanced performance, increasing service load moment by 103.3% while reducing deflection and residual deflection by 48.18% and 30.36%, respectively. Deflection increased by 11% after initial loading cycles and 8% in subsequent cycles. Higher BFRP reinforcement ratio and concrete strength improved stiffness and serviceability. Additionally, a new analytical model for deflection prediction was developed, which showed better agreement with experimental results compared to existing models.

Manibalan et al., (2023) [13] investigated the response of BFRP-strengthened beams, retrofitted through external bonding, was analyzed by subjecting them to repeated loading cycles. Test results indicated that the retrofitted specimens carried higher ultimate loads, showing improvements of 24.32%, 21.05%, and 15% over the control beams. Additionally, reductions in mid-span deflection of 17.63%, 14%, and 6.13% were recorded, respectively. The strengthened beams also demonstrated improved ductility, achieving a maximum ductility factor of 3.583, along with enhanced stiffness during both the cracking phase and post-yield behavior.Numerical analyses carried out using ANSYS showed strong agreement with the experimental observations, thereby validating the results. Overall, the study demonstrates that BFRP laminates in RC components leads to better performance under cyclic loading and supports a longer structural lifespan.

Saribiyik et al., (2023) [14] presented both experimental and finite element analyses to assess the bond behaviour of basalt fibre-reinforced polymer (BFRP), strips externally attached to notched reinforced concrete (RC) beams. Premature debonding was identified as a major constraint in FRP-strengthened systems, and The study considered several influencing aspects, including bond length, surface condition, anchorage layout, and thickness of the strips.The findings showed that proper surface preparation improved the load-carrying capacity by about 17%, while increasing the bond length beyond 100 mm had little effect on strength.

It was also observed that providing anchorage systems contributed to better structural response. Steel anchorage systems exhibited the highest effectiveness, delivering an enhancement of approximately 24–26% over other anchorage types and as much as 43% relative to unanchored specimens.These systems delayed debonding and enabled more uniform stress distribution. Unanchored beams mainly failed due to debonding, whereas anchored beams exhibited rupture of the BFRP strip, indicating better utilization of the material capacity. The numerical analysis closely matched the experimental observations and revealed that concrete layer thickness had a greater influence than adhesive length. In general, the results suggest that incorporating anchorage systems, Better structural behavior in BFRP-strengthened beams is achieved by using steel anchors rather than extending the bond length.

Hawileh et al., (2023) [15] evaluated the impact of different quantities of FRP spike anchors related to bending performance of FRP-strengthened RC beams under four-point bending conditions. The results revealed a substantial improvement in strain utilization of the FRP laminates, increasing from 27% in beams without anchorage to 61% and 99% in beams provided with two and four anchors, respectively. The inclusion of anchors significantly postponed premature debonding and improved the overall flexural behavior, leading to increased load-bearing capacity and enhanced ductility. The study determined that the use of at least two spike anchors offers an effective approach to enhance bond characteristics and strengthening efficiency. Overall, the findings highlight the critical role of anchorage systems in controlling premature laminate separation and improving structural performance.

Wdowiak Postulak et al., (2023) [16] investigated the bending performance of glulam beams strengthened by pre-stressed BFRP bars using the technique involving near-surface placement (NSM) under quasi-static bending conditions. From the study, it was found that the use of BFRP markedly improved the ultimate load capacity by up to 35.88% and increased stiffness by around 23% compared to unreinforced specimens. In addition, the reinforcement contributed to a reduction in both tensile and compressive stresses within the timber, thereby enhancing its overall bending performance. The numerical simulations closely matched the experimental outcomes, confirming the reliability of the NSM BFRP strengthening technique. Overall, the study demonstrates that pre-stressed BFRP bars are an effective and promising solution for contributing to better overall behavior of laminated timber structures.

Asadi et al., (2023) [17] investigated reinforced concrete (RC) beams strengthened with basalt fibre-reinforced polymer (BFRP) fabrics under two-point loading. The results showed that the flexural capacity of the wrapped RC beams increased in percentage varied from 9.4 to 56%, with a maximum increase of 46.6%. The ductility increased by 84%, while a percentage decline in ductility varied from 5 to 89% compared to unstrengthened beams. Failure modes included FRP rupture, concrete crushing, debonding, and delamination. Over-reinforced beams showed sudden compressive failure, while improved crack distribution with reduced crack width and length was observed due to better stress redistribution.

Liu et al., (2023) [18] evaluated the anchoring performance of prestressed basalt fibre-reinforced polymer (BFRP) laminates using wedge anchorages through 15 FRP laminate–anchorage assemblies. The results showed that the anchorage efficiency of CFRP laminate–anchorage assembly is higher than that of BFRP, and traditional CFRP anchorages easily damage BFRP laminates due to their lower elastic modulus and transverse shear strength. Anchorage with a retracted stressing end wedge achieved higher normal stress and anchoring capacity. The sandpaper mat improved friction and reduced stress concentration. Increased presetting load improved ultimate load and stiffness but intensified stress concentration at the anchorage end.

Yehia et al., (2023) [19] investigated hybrid reinforced concrete beams with openings strengthened using internal steel/BFRP bars and external BFRP sheets. The results showed that unstrengthened opened beams lost 75% of load capacity compared to solid beams. Strengthening with internal steel and BFRP bars increased capacity by 62% and 60%, respectively, while external BFRP sheets enhanced it by 76%. A combined strengthening approach significantly improved performance, increasing load capacity by 137% and energy absorption by 191%. Crack propagation was effectively controlled, and numerical analysis showed good agreement with experimental results, confirming the efficiency of hybrid and combined BFRP strengthening techniques for beams with openings.

Mamdouh et al., (2023) [20] evaluated the behaviour of reinforced concrete deep beams with openings strengthened using BFRP sheets through experimental and analytical studies. The results showed that openings reduced beam strength by 32.4%–34%, while BFRP strengthening improved strength by 0% to 12.1% depending on opening type. Horizontal rectangular openings performed best, achieving 78.4% of original capacity. BFRP had limited effect on vertical openings, possibly due to insufficient layers. Strengthening increased stiffness and energy absorption capacity by 19% to 58.6%. Analytical predictions using ACI and nonlinear models showed good agreement with experimental results, confirming the effectiveness of BFRP for enhancing deep beam performance with openings.

Deven et al., (2023) [21] examined the effectiveness of externally bonded FRP composites, particularly basalt fiber fabrics, for strengthening and retrofitting reinforced concrete (RC) beams. The study highlighted that FRP techniques can restore or enhance load-carrying capacity without increasing section size. Comparative analysis of different FRP materials showed that basalt fiber offers performance comparable to carbon fiber while being more economical and easier to produce. Although carbon fiber has slightly higher tensile strength, basalt fiber demonstrates superior resistance to chemical attack, fire, and weathering. The findings suggest that basalt fiber is a cost-effective and durable alternative for strengthening and retrofitting applications in structural engineering.

Kar et al. (2024) [22] conducted an experimental investigation on shear-deficient reinforced concrete (RC) T-beams improved through the use of BFRP U-shaped wraps bonded externally, incorporating six different end-anchorage configurations. The findings showed a considerable enhancement in load-carrying capacity, ranging between 18% and 88%. In addition, the efficiency of the BFRP U-jackets increased by

12% to 44%, while energy absorption improved significantly, varying from 58% to 180%. Among the configurations evaluated, the anchorage arrangement located at the web–flange interface delivered the most favorable results in preventing premature debonding. The study determined that incorporating end-anchorage systems is crucial for enhancing the role of strengthening methods in improving the shear strength of RC beam elements, thereby establishing their applicability in structural rehabilitation.

Kariyawasam Don et al. (2024) [23] investigated the mechanical and fracture characteristics of Basalt Fibre-Reinforced Polymer (BFRP) laminates produced using environmentally friendly bio-based resins. Two types of bio-resins, AMPRO™ BIO (40% bio-content) and Change Climate (77% bio-content), were evaluated and compared with a conventional epoxy system, WEST SYSTEM®. The experimental program included tests to determine tensile strength, shear behavior, and fracture properties of the laminates.

The results indicated that tensile strength improved by 6% and 17% for AMPRO™ BIO and Change Climate resins, respectively, while only minor changes were observed in tensile modulus. In terms of shear performance, Change Climate showed a slight reduction in strength but an increase in modulus, whereas AMPRO™ BIO exhibited notable decreases in both parameters. For fracture behavior, Mode I results showed reductions for both resins, more significant in AMPRO™ BIO, while Mode II results revealed improvement for AMPRO™ BIO and a decrease for Change Climate. Overall, the study suggests that bio-based resins, particularly Change Climate, have strong potential as sustainable alternatives to traditional epoxy, although further investigation is needed regarding curing conditions and combined fracture modes.

Chang et al., (2024) [24] investigated the damage process and ductility behavior of reinforced concrete (RC) beams repaired with basalt fibre-reinforced polymer (BFRP) sheets using digital image correlation (DIC) and acoustic emission (AE) techniques. The results showed that tensile cracks predominated, while shear cracks increased from 1–2% in control beams to 7% after BFRP strengthening. BFRP sheets hindered crack widening and increased the number of fine cracks, improving durability. Crack development also promoted interfacial debonding at steel–concrete and BFRP–concrete interfaces. The combined effect of crack propagation and debonding contributed to achieving improved ductile flexural behavior.

Changchun et al., (2024) [25] evaluated the flexural behavior of reinforced concrete (RC) beams strengthened with BFRP sheets using MWCNT-modified epoxy under four-point bending. The results showed that yielding load, ultimate load, and ultimate deflection increased by 7.4%, 8.3%, and 18.2%, respectively, compared to pure epoxy. Post-yield stiffness, energy absorption, and ductility improved by 22.6%, 29.1%, and 14.3%. The modified epoxy effectively delayed debonding, constrained crack development, and enhanced interfacial bonding. Failure occurred due to intermediate debonding after steel yielding. SEM analysis confirmed improved energy dissipation through crack bridging and pull-out mechanisms, leading to enhanced flexural performance.

Ashika et al., (2024) [26] examined the retrofitting of reinforced concrete (RC) beams using basalt fibre-reinforced polymer (BFRP) sheets in U-wrap configuration. The results showed that compressive strength increased by 11.41% and tensile strength by 14.39%. The load-carrying capacity of BFRP-wrapped beams increased by 7.36%, while deflection decreased by 18.2% compared to the control specimen. Additionally, crack width was reduced, and durability improved, with a 43.86% reduction in charge passed in RCPT tests. These findings demonstrate that BFRP sheets significantly enhance strength, stiffness, and durability, making them effective for retrofitting damaged RC beams.

Jaber et al., (2025) [27] investigated the flexural behaviour of continuous reinforced concrete (RC) beams strengthened and rehabilitated using near-surface mounted (NSM) BFRP ropes. The results showed that flexural strength increased by 18% to 44%, while ductility improved by 9–11% in strengthened beams and 13–20% in rehabilitated beams. Optimized configurations achieved load enhancements of 31% to 65% and 21% to 58%. Experimental results closely matched finite element predictions with errors between 0.125% and 7.3%, and ACI 440.2R-08 provisions were found to be conservative. Overall, NSM-BFRP ropes effectively enhanced load-carrying capacity, ductility, and structural performance without debonding issues.

Aswad et al., (2025) [28] investigated the flexural behaviour of steel and BFRP reinforced concrete (RC) beams exposed to elevated temperatures ranging from 200°C to 700°C. The results showed that load-carrying capacity decreased for all beams, with reductions of up to 35.5% for steel RC beams at 400°C and 66.1% for BFRP RC beams at 700°C compared to room temperature conditions. Steel RC beams exhibited 5.7% to 60.5% higher load capacity than BFRP beams. Failure modes differed, with steel beams showing flexural-shear failure and BFRP beams failing by concrete crushing, indicating better high-temperature performance of steel reinforcement.

Kumari et al., (2026) [29] conducted an analytical investigation on the use of BFRP composites for enhancing the shear capacity of reinforced concrete (RC) beams using different wrapping techniques. The results showed significant improvement in shear strength, with increases of 29.28%, 46.4%, 52.88%, 53.59%, and 39.91% for various configurations compared to control beams. Side wrapping and U-strip wrapping were found to be the most effective techniques. Additionally, BFRP strengthening improved flexural stiffness and reduced displacement. Analytical results closely matched experimental data, confirming model reliability. Machine learning models, particularly random forest, demonstrated high prediction accuracy, highlighting the importance of configuration, thickness, and strength in shear performance.

Abdel et al., (2025) [30] investigated the effectiveness of BFRP sheets and ropes in strengthening and retrofitting two-span reinforced concrete (RC) beams. The results showed that externally strengthened beams achieved shear capacity increases of 17% to 37.4%, while retrofitted (preloaded) beams showed improvements of 5.7% to 19.4%. Strengthening without prior damage yielded better performance due to improved bonding conditions. All specimens failed in brittle shear near critical regions, with no debonding observed. The study also confirmed strong agreement between experimental, finite element, and ACI 440.2R-08 predictions, with deviations limited to 0.21%–5.6%, demonstrating the reliability of analytical models for BFRP-strengthened beams.

A. Summary of Literature Review

Applying Basalt Fiber Reinforced Polymer to RC beams leads to better performance in both flexural and shear. Its use can increase load-carrying capacity by nearly 40-45% and improve stiffness by about 20-25%. Moreover, beams strengthened with BFRP exhibit better fatigue resistance, higher ductility, and increased energy absorption capability. The incorporation of anchorage systems further improves performance by reducing premature debonding and increasing the overall efficiency of strengthening. In general, earlier studies indicate that integrating BFRP strengthening with appropriate anchorage methods and proper installation methods leads to significant improvements in strength, stiffness, ductility, and fatigue behaviour of structural members.

B. Research Gap

From the literature review, the following observations were made:

1. Most existing studies on BFRP laminate–strengthened RC beams primarily emphasize flexural strength enhancement, while the specific influence of anchorage systems on improving laminate efficiency has not been systematically addressed.
2. Premature debonding is widely identified as the dominant failure mode in BFRP-retrofitted beams; however, detailed experimental investigations on the effectiveness of anchorage systems in mitigating this issue are still limited.
3. In many studies, anchored and unanchored BFRP systems are evaluated separately, with very few direct comparative investigations conducted under identical geometric configurations, material properties, and loading conditions.

V. CONCLUSION

The review indicates that Basalt Fiber Reinforced Polymer (BFRP) is a promising material for strengthening reinforced concrete (RC) beams, as it improves bending performance and load-carrying ability. However, the effectiveness of externally bonded BFRP laminates is often reduced due to early debonding, which prevents full use of their tensile strength. Studies reviewed in this work show that adding anchorage systems improves bonding, ensures better stress transfer, and increases the ultimate capacity of beams. These systems also help delay debonding, leading to higher ductility and more stable modes of failure, whereas beams without anchorage tend to fail prematurely due to early separation.

In addition, beams strengthened with BFRP demonstrate better stiffness, resistance to repeated loading, and energy absorption capacity, making them suitable for structures under cyclic or dynamic loads. The overall performance depends on several factors, including surface condition, laminate arrangement, type of anchorage, and quality of installation. Well-designed anchorage systems allow improved strain utilization and help distribute stresses more evenly along the bonded surface. Both experimental and analytical studies suggest that proper anchorage design can change the failure pattern from brittle debonding to a more ductile and desirable response.

Overall, the combined use of BFRP laminates with effective anchorage systems and proper application techniques is essential to achieve reliable performance, improved durability, and extended service life of RC beams.

REFERENCES

[1] A. MONIER, X. ZHE, H. HUANG, and W. ZHISHEN, “External Flexural Strengthening of Rc Beams Using Bfrp Grids and Pcm,” J. Japan Soc. Civ. Eng. Ser. A2 (Applied Mech., vol. 73, no. 2, p. I_417-I_427, 2017, doi: 10.2208/jscejam.73.i_417.

[2] S. Ibrahim, A. A. Kunju, C. Aided, S. Engineering, and P. O. Mulavoor, “Strengthening of Partially Damaged Deficient Rc Beam With Externally Bonded Bfrp Composites Using Fea,” no. May, pp. 6236–6241, 2019.

[3] J. D. S. Rajvi T. Desai1, Dr.Priti Patel2, Meha D. Naik3, “Experimental Study on Behaviour of Basalt Fibers Reinforced Concrete Beam,” Int. J. Eng. J. Eng. Sci. Invent., vol. Volume 8, no. Issue 11, p. 6, 2019.

[4] H. Surwase, G. N. Narule, and S. B. Walke, “Behavior of RC T-Beam Strengthen Using Basalt Fiber Reinforced Polymer (FRP) Sheet,” Int. Res. J. Eng. Technol., vol. 6, no. 6, pp. 3525–3529, 2019, [Online]. Available: www.irjet.net

[5] H. M. Diab and A. M. Sayed, “An Anchorage Technique for Shear Strengthening of RC T-Beams Using NSM-BFRP Bars and BFRP Sheet,” Int. J. Concr. Struct. Mater., vol. 14, no. 1, 2020, doi: 10.1186/s40069-020-00424-x.

[6] Y. Wang, W. Zhu, X. Zhang, G. Cai, and B. Wan, “Influence of thickness on water absorption and tensile strength of BFRP laminates in water or alkaline solution and a thickness-dependent accelerated ageing method for BFRP laminates,” Appl. Sci., vol. 10, no. 10, 2020, doi: 10.3390/app10103618.

[7] H. Alkhraisha, H. Mhanna, N. Tello, and F. Abed, “Serviceability and flexural behavior of concrete beams reinforced with basalt fiber-reinforced polymer (BFRP) bars exposed to harsh conditions,” Polymers (Basel)., vol. 12, no. 9, 2020, doi: 10.3390/POLYM12092110.

[8] M. Panahi, S. A. Zareei, and A. Izadi, “Flexural strengthening of reinforced concrete beams through externally bonded FRP sheets and near surface mounted FRP bars,” Case Stud. Constr. Mater., vol. 15, p. e00601, 2021, doi: 10.1016/j.cscm.2021.e00601.

[9] G. Nikhil, K. Hemalatha, V. Mallikarjuna Reddy, and V. Swamy Nadh, “Flexural behaviour of hybrid fiber reinforced concrete beam using BFRP bars,” E3S Web Conf., vol. 309, pp. 1–9, 2021, doi: 10.1051/e3sconf/202130901179.

[10] B. Chhorn and S. Lee, “Experimental Study of the Long-term Performance of BFRP Composite Laminates under Flexural Fatigue Test,” pp. 0–30, 2022.

[11] S. Kadhim and M. Özakça, “Flexural performance of RC beams externally strengthened with a single-layer of basalt fiber reinforced polymer sheets,” Compos. Adv. Mater., vol. 31, pp. 1–17, 2022, doi: 10.1177/26349833221102471.

[12] H. Zhu, Z. Li, Q. Chen, S. Cheng, C. Li, and X. Zhou, “A New Analytical Model for Deflection of Concrete Beams Reinforced by BFRP Bars and Steel Fibres under Cyclic Loading,” Polymers (Basel)., vol. 14, no. 9, 2022, doi: 10.3390/polym14091797.

[13] P. Manibalan, S. Kesaven, G. Abirami, and R.

Baskar, "Fatigue response of RC beam strengthened by BFRP laminate," Case Stud. Constr. Mater., vol. 18, no. August 2022, p. e01707, 2023, doi: 10.1016/j.cscm.2022.e01707.

[14] H. H. A. Ali Saribiyik, Wael Al-dhabir, "Experimental and FE studies on the bonding performance of basalt FRP bonded to notched concrete beams and improving with anchorage," Elsevier, p. 14, 2023.

[15] J. A. Hawileh, Rami A.;Assad, Maha;Abdalla, "Effect of increasing the number of anchors on the flexural performance of FRP-strengthened RC beams," 2023, [Online]. Available: http://hdl.handle.net/11073/16641

[16] F. B. and J. P. Agnieszka Wdowiak-Postulak, "An Experimental and Numerical Analysis of Glued Laminated Beams Strengthened by Pre-Stressed Basalt Fibre-Reinforced Polymer Bars." 2023.

[17] A. K. Al-Asadi, S. K. Alrebeh, and W. K. Hadi, "Experimental investigation of RC beams strengthened with externally bonded BFRP composites," Open Eng., vol. 14, no. 1, 2024, doi: 10.1515/eng-2022-0548.

[18] C. Liu et al., "Experimental Study on Wedge Anchorage Performance of Prestressed BFRP Laminates for Flexural Strengthening of Reinforced Concrete Components," J. Compos. Constr., vol. 27, no. 5, pp. 1–16, 2023, doi: 10.1061/jccof2.cceng-4247.

[19] S. Yehia, B. Faihan, and A. M. A. Ibrahim, "Strength of Hybrid Steel-BFRP Reinforced Concrete Beams with Openings in the D-Region Strengthened Internally and Externally," Buildings, vol. 13, no. 10, 2023, doi: 10.3390/buildings13102522.

[20] H. Mamdouh, H. A. Awad, and M. A. Osman, "Effect of BFRP Sheets on Strengthening Deep Beams with Openings," Eng. Res. J., vol. 178, no. 0, pp. 304–324, 2023, doi: 10.21608/erj.2023.302342.

[21] T. D. Sata, N. Patel, and P. Karad, "a Behavioral Study of Basalt Fibre," vol. 11, no. 3, pp. 457–461, 2023.

[22] S. Kar and K. C. Biswal, "End-Anchored Externally Bonded BFRP Composites for Shear Strengthening of RC T-Beams," Iran. J. Sci. Technol. - Trans. Civ. Eng., 2025, doi: 10.1007/s40996-025-01853-y.

[23] D. K. Don, J. Reiner, M. Jennings, and M. Subhani, "Basalt Fibre-Reinforced Polymer Laminates with Eco-Friendly Bio Resin: A Comparative Study of Mechanical and Fracture Properties," Polymers (Basel)., vol. 16, no. 14, 2024, doi: 10.3390/polym16142056.

[24] J. Chang, Y. Yao, K. Liu, Y. Wang, M. Yan, and Y. Bao, "Damage assessment of concrete beams repaired with basalt fiber-reinforced polymer sheets through digital image correlation and acoustic emission," Case Stud. Constr. Mater., vol. 20, no. January, p. e03044, 2024, doi: 10.1016/j.cscm.2024.e03044.

[25] C. Shi, S. Jin, C. Wang, and Y. Yang, "Enhancing Flexural Behavior of Reinforced Concrete Beams Strengthened with Basalt Fiber-Reinforced Polymer Sheets Using Carbon Nanotube-Modified Epoxy," Materials (Basel)., vol. 17, no. 13, 2024, doi: 10.3390/ma17133250.

[26] A. M. Ashika and S. M. Kavitha, "Mechanical behavior of Reinforced Concrete Beams retrofitted by Basalt Fabric," vol. 11, no. 2, pp. 2217–2221, 2024.

[27] M. Abdel-Jaber, R. Al-Nsour, and A. Ashteyat, "Analyzing Flexural Integrity Enhancement in Continuous Reinforced Concrete Beams Using NSM-BFRP Ropes: Experimental and Numerical Approach," CivilEng, vol. 6, no. 4, pp. 1–29, 2025, doi: 10.3390/civileng6040058.

[28] N. Ghazal Aswad, M. Al Dawood, F. Abed, and A. El Refai, "Experimental study of BFRP-RC beams exposed to elevated temperatures," Mater. Res. Proc., vol. 48, pp. 86–92, 2025, doi: 10.21741/9781644903414-10.

[29] M. K. P. Kumari, B. M. Kiran, M. B. Srinivasa, C. L. M. Kumar, A. Ranjith, and G. Acharya, "Machine Learning Approaches for the Performance Evaluation of Shear Strengthened Reinforced Concrete Beams using BFRP Composites with Different Wrapping Methods," Int. J. Eng. Trans. C Asp., vol. 39, no. 9, pp. 2161–2176, 2026, doi: 10.5829/ije.2026.39.09c.08.

[30] M. Abdel-Jaber, R. AlKhawaldeh, R. Al-Nsour, N. Shatarat, and A. Ashteyat, "Shear strengthening and rehabilitation of high-strength continuous RC beams with BFRP: A

combined experimental and numerical study," Hybrid Adv., vol. 12, no. October 2025, p. 100592, 2026, doi: 10.1016/j.hybadv.2025.100592.