Review On Flexural Strengthening of RC Beam Using Externally Bonded BFRP Laminates

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***Abstract*—Basalt fiber–reinforced polymer (BFRP) composites have emerged as a promising alternative to traditional carbon and glass fiber systems for strengthening and rehabilitating reinforced concrete (RC) structures. Their advantages include higher fracture strain, lower elastic modulus, reduced prestress loss, and improved cost-effectiveness, alongside notable sustainability benefits. Recent experimental, numerical, and analytical investigations have demonstrated the role of anchorage design, laminate configuration, and hybrid strengthening techniques in enhancing flexural capacity, ductility, and crack resistance of RC members. Studies on fatigue behaviour, hygrothermal ageing, and strain-rate effects further reveal the influence of environmental and loading conditions on long-term performance and durability, with laminate thickness and bond optimization proving critical. Full-scale evaluations confirm BFRP's effectiveness in restoring structural capacity, while review-based insights emphasize its mechanical competitiveness and ecological advantages compared to CFRP and GFRP. Despite these promising findings, challenges remain regarding standardization of design guidelines, long-term durability under aggressive environments, and optimization of anchorage systems. This review brings together current knowledge and highlights potential avenues for future research for expanding the application of BFRP composites in structural engineering practice.**

***Index Terms*—BFRP Laminate, Flexural Strengthening, External Bonding, Anchorage systems, Fatigue behaviour, and Load carrying capacity.**

I. INTRODUCTION

Reinforced concrete (RC) structures form the backbone of modern infrastructure, supporting residential, commercial, and industrial development worldwide. Despite their widespread use and versatility, RC members are vulnerable to functional and structural deterioration caused by factors such as overloading, reinforcement corrosion, cracking, deformation, environmental exposure, and long-term ageing effects. These challenges often compromise the serviceability, durability, and safety of structures, necessitating effective strengthening and rehabilitation strategies.

In recent decades, fiber-reinforced polymer (FRP) Composites have emerged as a focal point of research as a practical solution for enhancing the structural performance of RC members. Among these, basalt fiber–reinforced polymer (BFRP) laminates have emerged as a promising alternative to conventional carbon and glass fiber systems due to their unique combination of mechanical, durability, and sustainability advantages. BFRP composites, produced by embedding basalt fibers in a polymeric matrix, exhibit high tensile strength, lightweight characteristics, corrosion resistance, and long-term stability. Compared to steel reinforcement, BFRP is stronger in tension yet considerably lighter, while being immune to corrosion in aggressive environments. Moreover, as basalt fibers are fabricated from naturally occurring volcanic rock, they offer a more eco-friendly and cost-effective option compared to synthetic fiber counterparts.

One of the most prevalent techniques for applying BFRP in structural strengthening is external bonding, in which laminates or fabrics are adhesively attached to the tension zone of RC elements. This technique is favored for its ease of installation, high strength-to-weight ratio, and ability to significantly enhance flexural performance and load-carrying capacity. Given these attributes, BFRP systems have attracted rising interest for diverse applications in civil engineering as well as in aerospace, automotive, and marine industries, where lightweight, durable, and sustainable materials are in demand.

The growing body of research demonstrates the potential of BFRP composites as a durable and sustainable material for RC strengthening. However, further investigation is needed to address challenges related to bond behavior, anchorage efficiency, long-term durability, and design standardization. This paper provides a broad assessment of the present state of research on BFRP applications in structural engineering, highlighting experimental findings, analytical studies, and practical advancements, while Pointing to areas requiring additional exploration and development.

II. LITERATURE REVIEW

Strengthening of reinforced concrete (RC) beams using fiber-reinforced polymer (FRP) composites has been extensively practiced, supported by significant research, design codes, and practical applications worldwide. Various strengthening techniques have been recommended, with FRP consistently demonstrating superior performance over conventional techniques, though cost and application challenges may arise in some cases. FRP laminates can be applied internally or externally, with the externally bonded (EB) method being the most widely adopted because of its simplicity and effectiveness.

Basalt fiber–reinforced polymer (BFRP) has emerged as a preferred option because of its high tensile strength, excellent corrosion resistance, and durability under harsh environments. Its lightweight and easy handling make it suitable for retrofitting applications, while its cost-effectiveness compared to carbon fiber composites further enhances its appeal. BFRP can be applied through EB or near-surface mounted (NSM) techniques, both offering notable structural improvements. The following section summarizes key studies that highlight its effectiveness and relevance in strengthening RC members.

Devmith Kariyawasam Don, Johannes Reiner , Matt Jennings and Mahbube Subhani (2024) [1] :- This study examined the mechanical performance of basalt fiber–reinforced polymer (BFRP) laminates manufactured with two bio-resins (AMPRO™ BIO and Change Climate) in comparison with a conventional epoxy resin (WEST SYSTEM®). Mechanical tests evaluated tensile modulus, tensile strength, fracture toughness, and shear properties. Results showed that BFRP laminates with bio-resins demonstrated comparable or superior performance to conventional resin systems, with tensile strength improvements of 6–17%. These results point to the viability of bio-resin-based BFRP composites as sustainable alternatives to conventional FRPs, Mitigating environmental impact while retaining high mechanical efficiency for engineering applications.

Maha Assad, Rami A. Hawileh, Jamal A. Abdalla (2024)[2]:-In this study the anchorage of CFRP laminates with CFRP splay anchors positively affected the flexural capacity of the specimens. It increases load carrying capacity in the range of 60–104 % compared to a control un- strengthened specimen and 14–28 % compared to unanchored strengthened specimen, respectively. All strengthened specimens failed in flexure by de-bonding of the CFRP laminates. However, anchorage mitigated the debonding failure and enhanced the strain utilization. Specimen anchored with 20 mm diameter anchors showed that highest increase in the load carrying capacity but the lowest strain in the CFRP laminates among other specimens. Increasing the anchorage numbers along the CFRP laminate shows a positive effect on controlling the brittle failure of strengthened beams and increase in the utilization of FRP strength.

Changyuan Liu, Xin Wang, Xinquan Chang (2023)[3]:- This study investigated the anchoring effect of wedge anchorages on prestressed basalt fiber–reinforced polymer (BFRP) laminates. Compared with traditional carbon fiber–reinforced polymer (CFRP) laminates, BFRP laminates have a larger ultimate fracture strain, lower elastic modulus, and smaller prestress loss, making them cost-effective prestressed materials. Based on analysis the design advice proposed by this study are Anchorage types with larger anchoring lengths and smaller slope angles are suggested for BFRP laminates to lower the normal compressive stress and The sandpaper mat improved the anchorage performance, and a rougher mat had a more significant enhancing effect.

P. Manibalan a, S. Kesavan b, G. Abirami c, R. Baskar (2023)[4]:- This research investigates efficiency of externally bonded BFRP laminates in Reinforced concrete beam subjected to repeated loading. BFRP is externally bonded at the tension/bottom face of beam to enhance its fatigue resistance. The load and

deflection relationship, Crack pattern, stiffness and energy dissipation capacity of RC beams externally reinforced with BFRP laminates are experimentally investigated and validated using ANSYS software stimulated results. The computational results are supported by experimental verification which are correlated with negligible deviation. BFRP strengthened RC beam substantially enhances the stiffness in initial, cracking, and post -yielding stages compared to control concrete beam. Thus, BFRP strengthening improves the performance of RC structures when suffered from sudden loss of stiffness under impact load. BFRP strengthening delays the formation of cracks and improves the ductile failure of reinforced concrete beam. Thus, increases the energy dissipation capacity in pre-crack and post -crack stages.

Ali K. Al-Asadi, Salih K. Alrebeh and Waleed Kh. Hadi (2022)[5] :- This study investigated the flexural performance of reinforced concrete (RC) beams strengthened by basalt fiber-reinforced polymer (BFRP) fabrics. Eight beams were tested, including one control specimen and seven beams wrapped in different lay-up configurations, under two-point loading. The results highlighted improvements in flexural strength and ductility, with increases of 46.6% and 84% respectively, compared to the unstrengthened beam. Load–deflection behavior, cracking, delamination, and ultimate failure modes were carefully examined, showing that strengthened beams generally performed better, though failures were associated with BFRP rupture and concrete crushing. Overall, the study confirms that BFRP wrapping can effectively enhance the flexural performance of RC beams.

R. Madotto a, N.C. Van Engelen b, et al., (2022)[6]:- This paper presents experimental research done to examine the effectiveness of BFRP for strengthening of RC beams. Seven concrete beams used as specimens were tested utilizing a 2-point loading scheme. The properties of unidirectional BFRP fabric used were exploited in different ways to produce shear and flexural strengthening systems. The best results in terms of load and ductility increase were obtained by applying four overlapped layers of BFRP wrapped around the mid-span and the BFRP was laid vertically. In this way, maximum load obtained was 20% more than the one obtained for control beam. The effectiveness of the BFRP reinforcement is strongly influenced by orientation of the layers, and their contribution is greatest when the fibers work in tension.

Sara Kadhim and Mustafa Ozakça(2021)[7]:- In this previous experimental study, eight beams which are simply supported were tested under four-point bending using an identical concrete mix. Strengthening configurations included a single BFRP layer on the soffit, partial side wrapping with vertical extensions of 25, 75, and 105 mm, and U-strip reinforcement with or without an additional bottom layer of BFRP sheet. The results indicated that side wrapping reduced ductility compared with the reference specimen, by up to 33% for partial wrapping and 45% for full wrapping. However, toughness improved in all strengthened beams, with increases ranging from 8% to 78%. It was further observed that extending the BFRP layer along the beam sides contributed to a significant enhancement in load-carrying capacity.

Minoo Panah, Seyed Alireza Zareei, Ardavan Izadi (2021)[8]:- In this study, The flexural strengthening performance of reinforced concrete (RC) beams using FRP composites was analyzed through numerical simulations in ABAQUS 6.11, considering near-surface mounted (NSM), externally bonded (EBR), and combined EBR–NSM techniques. The combined application of EBR and NSM methods can effectively mitigate the individual limitations of each approach. Compared to the control beams, RC beams strengthened with NSM FRP rods exhibited a substantial increase in both flexural capacity and stiffness, while the mid-span deflections of strengthened beams at failure mainly decreased compared to the un-strengthened beam. Load-carrying capacity of reinforced concrete(RC) beams strengthened with EB FRP sheets increases with increase in width of FRP sheets. The flexural strength of strengthened beams increased as the width of the FRP sheet increased, which was arising from the better anchoring effect of NSM FRP rod and EBR FRP sheet. FRP sheet width of 20 mm and 1Φ12 mm as NSM FRP rods, ultimate bending moments of beams increased 6, 15, 17, 19, and 24 % for beams with b = 40mm, 80mm, 100mm, 120mm, 150 mm, respectively.

Yanlei Wang, Wanxin Zhu; et al, (2020) [9]:- A study on the durability of BFRP laminates examined the influence of specimen thickness (1, 2, and 4 mm) on water absorption and tensile performance under hygrothermal ageing. Laminates fabricated by the wet lay-up method were immersed in deionized water and alkaline solution at 60 °C for up to 180 days. The results showed a noticeable reduction in tensile properties after ageing, particularly in alkaline solution. Thickness was reported to have a strong effect: thinner specimens exhibited higher water absorption and greater strength loss due to their larger exposed surface-to-volume ratio, whereas thicker laminates demonstrated better tensile strength retention over time.

Zhong-Xian Li, Xuejie Zhang, Yanchao Shi (2020) [10]:- Another investigation focused on the strain-rate sensitivity of unidirectional BFRP composites, with tensile tests conducted covering a wide variety strain rates (0.00006 s^{-1} to 260 s^{-1}). Quasi-static and low-speed tests were executed with the help of a universal testing machine, while high-speed tests were executed with a servo-hydraulic system (INSTRON VHS 160/100-20). The findings indicated that the epoxy resin type had little effect on tensile properties, as its contribution to strength was negligible compared with the FRP fibers. At higher strain rates, number of diagonal cracks were observed due to limited time for crack development along weaker planes, leading to a change in failure mode. This altered cracking behaviour was considered responsible for the improvement in tensile strength under dynamic loading.

Elisabetta Monaldoa, Francesca Nerillia, Giuseppe Vairo (2019) [11]:- Basalt fibers provide an alternative for creating composite materials that are competitive with those made using conventional glass or carbon fibers. The final properties of these composites depend on factors such as fiber treatment, fiber arrangement, and the type of matrix, whether polymeric or cementitious. Basalt-based composites have been applied in the strengthening and retrofitting of existing concrete and masonry structures, using either basalt fiber-reinforced polymers (BFRP) or basalt fiber-reinforced cementitious matrices (BFRCM). In terms of flexural reinforcement, the mechanical performance of BFRP is typically little lower than that of GFRP and CFRP when considering improvements in yield and ultimate strength.

Jason Duic; et al., (2018) [12]:- A study involving seven full-scale RC beam specimens investigated the potential of basalt fiber–reinforced polymer (BFRP) composites as a sustainable material for flexural strengthening and rehabilitation. The key parameters considered were flexural reinforcement ratio, degree of corrosion, number of BFRP layers, and the use of cross-strapping. The results demonstrated that externally bonded BFRP composites can substantially improve beam performance, provided that premature debonding is prevented through an appropriate cross-strapping scheme. The use of BFRP was effective in restoring the service, yield, and ultimate load capacities of corroded beams to levels comparable with uncorroded specimens. Strengthened beams exhibited about a 25% increase in load-carrying capacity with just three layers of BFRP, along with a notable reduction in crack widths.

Ahmed Monier, Xu Zhe, et. al,. (2017) [13] :- A study proposed the use of FRP grids bonded with polymer cement mortar (PCM) as a method for strengthening RC structures, Particular attention is given to basalt FRP (BFRP) grids, evaluating their effectiveness in improving the flexural capacity of RC beams was evaluated. To investigate bond characteristics between BFRP grids and concrete, double-shear tests were performed, while the flexural behaviour of externally strengthened beams was assessed using four-point bending tests. The experimental findings indicate that ultimate load of beams strengthened with BFRP grids increased by 47.60–63.65% compared with the control specimen. Based on earlier findings that recommended a bond length of 250 mm for BFRP grids bonded with epoxy, this study adopted a bond length of 300 mm to achieve complete composite action between the grids and concrete surface.

Chen W, Pham TM, Sichembe H, Chen L, Hao H (2017) [14] :- Carbon FRP (CFRP) and Glass FRP (GFRP) composites have been widely researched for strengthening reinforced concrete (RC) and masonry structures, and many studies confirm that FRP systems can significantly improve load-carrying capacity. Basalt FRP (BFRP), on the other hand, is a relatively newer material that shows great potential due to its

lower cost, good mechanical properties, and excellent corrosion resistance. However, research on the use of BFRP for externally strengthening RC beams is still quite limited. This study focuses on experimentally examining how effective BFRP is in improving the flexural performance of RC beams using three-point bending tests. The structural behavior and failure patterns of both unstrengthened and BFRP-strengthened beams were carefully observed. Different wrapping techniques, U-jacket anchorage, and the role of epoxy adhesives were also analyzed to understand their influence on beam capacity. Additionally, formulas developed for predicting flexural behavior in CFRP- and GFRP-strengthened beams were assessed for their suitability in BFRP applications.

R. Kishore, N. Zia Nasiry and A. Muslim Rujhan (2016) [15] :- An experimental investigation was carried out to assess the impact of external wrapping with carbon fiber–reinforced polymer (CFRP) laminates on the load-carrying capacity of reinforced concrete beams. The primary parameters considered were the internal reinforcement ratio and the position of strengthening. A total of eight beams were tested under two-point loading and classified into two groups: beams deficient in flexure (SF series) and beams deficient in shear (SS series). For the flexure-deficient series, CFRP wrapping resulted in a 40% improvement in load capacity, while for the shear-deficient series, CFRP strengthening led to a 45% increase.

Rami A. Hawileh, Jamal A. Abdalla a, et. al,(2016) [16].:- An experimental investigation was conducted on the mechanical behavior of basalt (B), carbon (C), and hybrid B–C composite laminates subjected to elevated thermal conditions (25–250 °C). A total of 140 coupon specimens were investigated to evaluate tensile strength and elastic modulus degradation. Results showed that both properties decreased with rising temperature, with carbon laminates exhibiting the most severe degradation—up to 90% strength loss at 250 °C. In contrast, basalt and basalt-dominant hybrids (particularly BBC and B laminates) retained superior mechanical performance under thermal exposure. Analytical models were designed to forecast the variation of tensile strength and modulus with temperature, providing useful parameters for design. The findings highlight the superior thermal resistance of basalt-based laminates and support their application, alone or in hybrid forms, for externally strengthening RC slabs and beams.

Douglas Tomlinson1 and Amir Fam (2015) [17]:- The flexural and shear behavior of RC beams reinforced with basalt fiber–reinforced polymer (BFRP) rebars and stirrups was investigated through four-point bending tests on nine specimens. Flexural reinforcement ratios ranged from 0.28 to 1.60 times the balanced ratio under varying shear reinforcement conditions. Ultimate and service loads increased with reinforcement ratio regardless of stirrup type. Beams without stirrups failed in shear at about 55–58% of flexural capacity, while those with BFRP stirrups failed by rupture at 90–96%, and beams with steel stirrups failed in flexure. Standard design provisions predicted flexural capacity accurately but were inconsistent for shear-critical beams, whereas the updated CF theory (compression field theory) provided reliable shear predictions and service load estimates.

Alaa Morsy A, El Tony Mahmoud (2013) [18] :- An experimental study explored an alternative technique for attaching FRP laminates to RC beams using steel rivets instead of relying solely on epoxy bonding. Five full-scale beams were cast and strengthened in flexure, with some bonded conventionally using epoxy and others fixed with 50 mm × 10 mm steel rivets. Results indicated that beams strengthened with epoxy-bonded laminates failed due to debonding, achieving about a 13% enhancement in flexural capacity in comparison with control beam. In contrast, beams strengthened by rivet-fastened FRP laminates also failed by debonding but exhibited a higher flexural capacity, with an improvement of around 19% over the un-strengthened specimen.

Jongsung Sim, Cheolwoo Park, Do Young Moon (2005) [19]**:-** A study investigated the capabilities of basalt fiber as a strengthening material for concrete structures by evaluating its durability, mechanical behaviour, and flexural strengthening performance. The basalt fibers, produced in Russia, had a tensile strength of 1000 MPa, equivalent to about 30% of carbon fiber and 60% of high-strength glass (S-glass) fiber. Flexural tests revealed that basalt fiber reinforcement enhanced both the yield and ultimate

strength of beam specimens by up to 27%, depending on the number of layers applied. The authors concluded that basalt fiber offers a promising alternative to conventional FRP systems, particularly in applications where moderate structural strengthening is required alongside high fire resistance, such as in building structures.

III. CONCLUSION

The reviewed studies highlight the growing potential of Basalt Fiber Reinforced Polymer (BFRP) as a potent and sustainable material for strengthening reinforced concrete (RC) structures. Experimental results consistently show that BFRP enhances the flexural and shear capacity of RC beams, improves ductility, and offers superior corrosion and thermal resistance compared to many conventional materials. Different strengthening schemes, including externally bonded laminates, U-jacket anchorage, and fabric wrapping, have been shown to significantly improve load-carrying capacity while altering the failure modes of beams. Moreover, BFRP and its hybrid laminates demonstrate better performance under elevated temperatures, with basalt-dominant systems retaining higher strength and stiffness. The use of bio-resins with BFRP further indicates promising avenues for eco-friendly composite systems without compromising mechanical performance. Overall, these findings establish BFRP as a cost-effective, durable, and environmentally sustainable alternative for structural strengthening, though continued research is essential to refine design models, optimize anchorage methods, and validate long-term field performance.

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