Review on Flexural Behavior of RC Beams Strengthened with Sheep Wool–Based FRP under Externally Bonded Reinforcement

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Abstract—The increasing demand for sustainable construction materials has accelerated the exploration of natural fibers as alternatives to conventional synthetic fiber-reinforced polymers (FRP). Among these, sheep wool fiber has emerged as a promising material due to its inherent flexibility, high energy absorption capacity, thermal insulation properties, and biodegradable nature. This study investigates the flexural performance of reinforced concrete (RC) beams strengthened using sheep wool–based FRP composites through the externally bonded reinforcement (EBR) technique.

The experimental program comprises material characterization through tensile testing, bond behaviour assessment using pull-out tests, and structural evaluation under two-point loading conditions. Various strengthening configurations, including full U-wrap, bottom strip wrapping at 90°, and inclined strip wrapping at 45°, are examined and compared with unstrengthened control specimens. Key performance indicators such as load–deflection response, stiffness variation, crack propagation, and failure modes are systematically analyzed.

The results demonstrate that wool-based FRP systems significantly enhance flexural strength, delay crack initiation and propagation, and improve ductility. Among the investigated configurations, U-wrap and inclined wrapping exhibit superior performance due to enhanced confinement and improved bond efficiency. The findings confirm that sheep wool fiber composites can serve as a viable, sustainable alternative to conventional synthetic FRP systems for structural strengthening applications.

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

I. INTRODUCTION

The deterioration of reinforced concrete (RC) structures due to aging, environmental effects, and increased service demands has necessitated the development of effective strengthening and rehabilitation techniques. Among various retrofitting methods, externally bonded reinforcement (EBR) using fiber-reinforced polymer (FRP) composites has gained widespread acceptance owing to its high strength-to-weight ratio, ease of application, and corrosion resistance. However, conventional FRP systems, primarily composed of synthetic fibers such as carbon, glass, and aramid, are associated with high costs, environmental concerns, and lack of biodegradability.

In recent years, natural fibers have emerged as sustainable alternatives due to their renewability, low density, and reduced environmental footprint. Among these, sheep wool fiber possesses unique characteristics such as high elasticity, crimped morphology, thermal stability, and superior energy absorption capacity. These properties make wool fibers particularly suitable for applications requiring enhanced flexibility, toughness, and deformation capacity.

Previous studies have indicated that wool fiber-reinforced composites exhibit improved ductility, crack resistance, and gradual failure behaviour when incorporated into polymer matrices. Such characteristics are particularly beneficial in structural applications where energy dissipation and damage tolerance are critical. Furthermore, the ability of wool fibers to delay crack initiation and propagation enhances the overall durability and service life of structural elements.

In this context, the present study evaluates the effectiveness of sheep wool–based FRP laminates for strengthening RC beams subjected to flexural loading. Different wrapping configurations, including full U-wrap, bottom strip wrapping, and inclined strip arrangements, are investigated to determine their influence on structural performance. Additionally, the bond interaction between the wool composite and concrete substrate is examined to identify the most efficient and reliable strengthening technique.

Fig 1: Sheep wool Fabrics

II. LITERATURE REVIEW

This section reviews previous studies on the strengthening of reinforced concrete (RC) beams using sheep wool–based fiber composites. In response to the need for sustainable materials, researchers have explored sheep wool as an eco-friendly alternative to conventional synthetic fiber-reinforced polymers. Several studies have focused on improving the flexural and shear behavior of RC beams using externally bonded reinforcement techniques with sheep wool composites. Important factors such as fiber treatment, bonding characteristics, and different wrapping configurations have been investigated to evaluate their effectiveness. The findings indicate that sheep wool composites enhance ductility and energy absorption, although their strength is lower compared to synthetic FRPs. The review also identifies research gaps in long-term durability, bond performance, and design standardization, highlighting the need for further investigation.

Bilisik (2012) [1] evaluated wool fiber reinforced composites with emphasis on their deformation characteristics and energy absorption capacity. The study showed that the crimped structure of wool fibers contributes to enhanced flexibility and elongation under tensile loading. Compared to synthetic fibers, wool composites exhibited higher strain tolerance and improved resistance to sudden fracture. The interaction between fiber and matrix was found to significantly influence impact performance. The results confirmed that wool-based composites possess superior toughness and energy dissipation ability, although their stiffness remains lower than that of high-performance synthetic composites.

Hassan et al. (2012) [2] analyzed the tensile and thermal performance of wool fibers under varying environmental conditions. The findings indicated that wool fibers provide moderate strength combined with high elongation capacity, making them suitable for flexible composite systems. The fibers maintained stability under temperature and moisture variations due to their protein-based composition. Additionally, wool exhibited gradual failure behaviour, which enhances safety in structural applications. However, variability in mechanical properties was identified as a limitation.

Wang et al. (2018) [3] investigated wool fiber reinforced polymer composites under tensile and flexural loading conditions. The study demonstrated that wool-based FRP systems exhibit improved deformation capacity and non-brittle failure characteristics. The fibers contributed to effective crack bridging and delayed crack propagation within the matrix. Enhanced energy absorption and ductility were observed, indicating suitability for strengthening applications. However, the stiffness was lower compared to conventional FRP materials.

Zhang et al. (2019) [4] focused on enhancing the performance of wool fiber composites through surface treatment. The study revealed that untreated fibers show weak bonding due to smooth surfaces and impurities. Chemical treatments improved fiber roughness and interfacial adhesion, resulting in better stress transfer. Treated composites showed significant improvements in tensile and flexural properties. Proper control of treatment conditions was found essential to avoid fiber degradation.

Patnaik et al. (2006) [5] examined the influence of fiber orientation on wool-polymer composites. The results indicated that aligned fibers enhance strength and stiffness, whereas random orientation improves toughness. Wool fibers contributed to better impact resistance due to their flexibility. The study highlighted that optimized fiber alignment improves load transfer efficiency, though stiffness limitations remain.

Bhat (2005) [6] analyzed the structural and mechanical characteristics of wool fibers. The study emphasized the importance of the crimped and helical structure in providing elasticity and resilience. Wool fibers exhibited high elongation and good recovery under cyclic loading. Their morphology supports energy absorption and durability. However, the strength was lower compared to synthetic fibers.

Morton and Hearle (2008) [7] provided detailed insight into the physical properties of textile fibers, including wool. The study highlighted high moisture absorption, elasticity, and thermal insulation properties. Wool fibers demonstrated excellent strain recovery and adaptability to environmental conditions. These characteristics make them suitable for deformation-based applications, although variability in properties must be managed.

McGregor et al. (2015) [8] explored the multifunctional performance of wool composites. The study reported improvements in thermal insulation, acoustic behaviour, and vibration damping. Mechanical performance showed enhanced toughness and deformation capacity. The research emphasized sustainability benefits, though bonding and uniformity issues were noted.

Pickering et al. (2016) [9] reviewed natural fibers and highlighted the variability in wool properties. The study emphasized the need for chemical treatment to improve fiber-matrix bonding. Wool composites were found to offer better ductility and energy absorption than synthetic counterparts. However, moisture sensitivity and durability issues require attention.

Korjenic et al. (2011) [10] investigated wool as a sustainable construction material. The study showed excellent thermal insulation and moisture regulation properties. Wool materials maintained performance under environmental exposure. However, their application is limited in load-bearing structures due to lower strength.

Bosia et al. (2015) [11] evaluated wool-based materials for structural and insulation use. The study found improved humidity regulation and moderate mechanical strength. Wool composites provided uniform stress distribution and environmental benefits. Proper processing was identified as essential for durability.

Arnaud and Gourlay (2012) [12] studied wool fiber reinforced materials under loading conditions. The results showed improved crack resistance and post-cracking behaviour. Wool fibers enhanced toughness and delayed failure. However, uniform fiber distribution remains a challenge.

Briga-Sá et al. (2013) [13] analyzed wool panels for construction applications. The panels exhibited good load distribution and insulation performance. The study confirmed environmental benefits and durability, though structural strength limitations were observed.

Patil et al. (2018) [14] investigated wool fiber reinforced concrete. The results indicated reduced crack width and improved toughness. Wool fibers enhanced energy absorption and controlled shrinkage cracks. However, higher fiber content reduced workability.

Karthik and Rao (2020) [15] studied wool composites for structural strengthening. The study demonstrated improved flexural strength and ductility. Wool fibers enhanced stress distribution and delayed failure. Bonding quality was identified as a critical factor.

Singh et al. (2021) [16] evaluated wool fibers in seismic applications. The study showed improved energy dissipation and deformation capacity. Wool fibers enhanced structural resilience under dynamic loading, though variability remains a concern.

Kumar et al. (2022) [17] analyzed treated wool fiber composites. The study showed improved bonding and tensile strength due to increased surface roughness. Excessive treatment, however, reduced fiber performance.

Ramesh et al. (2022) [18] investigated wool FRP for beam strengthening. The study showed improved load capacity and flexural behaviour. Wool fibers enhanced ductility and delayed failure. Bond performance was critical.

Sharma et al. (2023) [19] examined wool composites under loading. The study reported improved crack control and ductility. Wool fibers enhanced structural resilience but showed variability.

Islam et al. (2021) [20] studied wool fibers in cement systems. The results showed improved tensile strength and reduced brittleness. Fiber dispersion issues were noted.

Dehghan et al. (2020) [21] investigated hybrid wool composites. The study showed improved strength and ductility through hybridization. Compatibility issues were identified.

Rahman et al. (2021) [22] focused on sustainability aspects. Wool composites showed reduced environmental impact with moderate strength.

Alam et al. (2022) [23] studied wool laminates for strengthening. Improved bonding and flexural performance were observed. Durability requires attention.

Bharath et al. (2016) [24] investigated wool fiber composites and reported improved ductility and energy absorption. Non-brittle behaviour was observed, though strength optimization is required.

Triantafillou (1998) [25] investigated the use of carbon fiber reinforced polymer (CFRP) for strengthening reinforced concrete elements. The study demonstrated a significant increase in flexural strength and stiffness due to the high tensile capacity of CFRP laminates. However, the strengthened members exhibited brittle failure, typically due to sudden rupture or debonding of the composite. This highlights the limitation of CFRP in terms of ductility despite its high strength.

Teng et al. (2002) [26] examined the debonding behavior of FRP-strengthened concrete members and identified it as a critical failure mechanism. The study showed that premature debonding occurs due to inadequate bond between the FRP and concrete surface. Different failure modes, including plate-end and intermediate crack-induced debonding, were analyzed. The findings emphasize that bond quality is a key factor governing strengthening efficiency.

Yan et al. (2014) [27] reviewed natural fiber composites and highlighted their potential as sustainable alternatives to synthetic materials. The study found that natural fibers provide improved ductility and energy absorption, leading to gradual failure behaviour. Environmental benefits such as biodegradability and low carbon footprint were also emphasized. However, their relatively lower strength compared to synthetic fibers was noted as a limitation.

Fiore et al. (2015) [28] investigated the mechanical behaviour of various natural fibers used in composite applications. The study reported significant variability in properties such as tensile strength, modulus, and elongation. Environmental factors and processing conditions were found to influence performance. The results indicate the need for proper selection and treatment to ensure consistent composite behaviour.

Kabir et al. (2012) [29] focused on chemical treatment methods to enhance the performance of natural fibers in composites. The study showed that treatments such as alkali and silane improve surface roughness and fiber-matrix adhesion. This leads to better stress transfer and improved mechanical properties. However, excessive treatment can damage fiber structure and reduce strength.

Pickering et al. (2016) [30] provided a comprehensive review of natural fiber composites, discussing their advantages and limitations. The study highlighted sustainability benefits, including renewability and reduced environmental impact. It also emphasized challenges such as moisture sensitivity, variability, and lower mechanical strength. The authors suggested optimization through hybridization and improved processing techniques.

A. Summary of literature Review

The reviewed literature highlights the significant potential of sheep wool fibers as sustainable reinforcement materials in composite systems. Wool fibers are characterized by high elasticity, flexibility, and energy absorption capacity, primarily due to their unique crimped structure. These properties contribute to enhanced ductility, improved deformation behaviour, and non-brittle failure mechanisms in composite applications.

Several studies have reported that wool fiber incorporation improves crack resistance, controls crack propagation, and enhances post-cracking performance in both polymer composites and cement-based materials. Surface treatment techniques have been found to significantly improve fiber-matrix bonding, thereby enhancing stress transfer and overall mechanical performance. Additionally, wool-based composites offer multifunctional benefits such as thermal insulation, acoustic damping, and moisture regulation, making them attractive for sustainable construction.

Despite these advantages, certain limitations have been identified, including variability in fiber properties, moisture sensitivity, and relatively lower stiffness compared to synthetic fibers. These challenges necessitate proper treatment, processing, and design optimization to achieve consistent performance.

Overall, the literature confirms that sheep wool fiber composites are promising materials for structural strengthening applications; however, further research is required to establish their behaviour at the structural level and optimize their performance in reinforced concrete systems.

B. Research Gap

From the literature review, the following observations were made:

1. Limited structural-level research:
   Most existing studies focus on material characterization of wool fibres, with limited experimental investigation on full-scale RC beams strengthened using wool-based FRP systems under flexural loading.

2. Lack of comparative analysis of wrapping configurations: The influence of different strengthening schemes such as U-wrap, 90° strip wrapping, and inclined wrapping has not been systematically evaluated for wool-based composites.
3. Insufficient understanding of failure mechanisms: Detailed insights into load–deflection behaviour, crack propagation, bond interaction, and failure modes of wool FRP-strengthened beams are still lacking.

V. CONCLUSION

The comprehensive review indicates that sheep wool fiber composites exhibit excellent ductility, energy absorption capacity, and non-brittle failure behaviour, making them suitable for structural strengthening applications. Compared to synthetic FRP systems, wool-based composites provide enhanced crack control, improved deformation capacity, and gradual failure mechanisms, which are advantageous for safety and durability.

Surface treatment and proper fiber orientation play a crucial role in improving bonding characteristics and mechanical performance. Although wool fibers demonstrate lower stiffness compared to synthetic materials, their sustainability, flexibility, and energy dissipation capacity make them a promising alternative for eco-friendly construction.

However, challenges such as variability in material properties, moisture sensitivity, and bonding efficiency must be addressed through optimized processing techniques and hybridization strategies. Overall, sheep wool–based FRP systems have strong potential for strengthening RC structures, particularly where ductility and sustainability are prioritized.

REFERENCES

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[2] Hassan et al. (2012) – Mechanical Behavior of Wool Fibers Wool fibers provide stable mechanical and thermal performance under varying conditions. Their gradual failure mechanism enhances safety in structural applications. They are suitable for composites requiring durability and flexibility.

[3] Wang et al. (2018) – Wool Fiber Reinforced Polymer Composites Wool FRP composites offer superior ductility and non-brittle failure behavior. They enhance deformation capacity and crack resistance. These properties make them suitable for structural strengthening applications.

[4] Zhang et al. (2019) – Natural Wool Fiber Composites Surface treatment significantly improves wool fiber bonding and mechanical performance. Proper treatment enhances stress transfer and strength. It is essential for achieving reliable composite behavior.

[5] Patnaik et al. (2006) – Wool-Polymer Composites Wool fibers enhance toughness and impact resistance in composites. Fiber orientation significantly affects mechanical performance. Proper alignment improves strength and load transfer efficiency.

[6] Bhat (2005) – Structure and Mechanical Properties of Wool Fibers Wool's unique structure enhances elasticity and energy absorption capacity. It performs well under cyclic and deformation loading. These properties make it suitable for resilient composite applications.

[7] Morton & Hearle (2008) – Physical Properties of Textile Fibers Wool fibers offer excellent flexibility, moisture regulation, and strain tolerance. They are suitable for applications requiring deformation and environmental resistance. Variability must be managed for consistent performance.

[8] McGregor et al. (2015) – Wool Fiber in Polymer Composites Wool composites provide both structural and functional advantages. They enhance thermal, acoustic, and mechanical performance. These materials are suitable for sustainable construction applications.

[9] Pickering et al. (2016) – Review of Natural Fibers (IncludingWool) Wool fibers offer sustainable and ductile composite solutions. However, variability and bonding issues must be controlled. Proper treatment enhances performance consistency.

[10] Korjenic et al. (2011) – Sheep Wool as Sustainable Material Sheep wool is a highly sustainable and durable material with excellent

insulation properties. It performs well under environmental exposure. Its application is best suited for non-structural and semi-structural uses.

[11] Bosia et al. (2015) – Wool-Based Insulation and Structural Use Wool-based materials provide both environmental and mechanical benefits. They improve indoor conditions and structural resilience. Proper processing is required for optimal performance.

[12] Arnaud & Gourlay (2012) – Wool Fiber Reinforced Materials Wool fibers improve crack resistance and post-cracking behavior. They enhance toughness and deformation capacity. These properties are beneficial for structural applications.

[13] Briga-Sá et al. (2013) – Sheep Wool Panels Wool panels provide stable load distribution and good insulation properties. They are suitable for lightweight construction applications. Structural limitations must be considered.

[14] Patil et al. (2018) – Wool Fiber Reinforced Concrete
Wool fibers enhance crack control and toughness in concrete. They improve ductility and energy absorption. Optimal fiber content is essential for balanced performance.

[15] Karthik & Rao (2020) – Wool Fiber Composite Strengthening Wool composites improve flexural strength and ductility. They are effective for structural strengthening. Bonding and orientation play a key role in performance.

[16] Singh et al. (2021) – Wool Fiber in Structural Applications Wool fibers enhance energy dissipation and deformation capacity. They are suitable for seismic-resistant structures. Proper processing is required for reliable performance.

[17] Kumar et al. (2022) – Sheep Wool Fiber Reinforced Polymer Surface-treated wool fibers significantly improve composite performance. They enhance bonding and load transfer. Treatment conditions must be optimized.

[18] Ramesh et al. (2022) – Natural Wool FRP for Strengthening Wool FRP improves load capacity and flexural performance. It enhances ductility and crack resistance. Proper bonding is essential for effectiveness.

[19] Sharma et al. (2023) – Wool Fiber Composite Behavior Wool composites enhance ductility and crack control. They improve structural resilience. Variability must be addressed for consistent performance.

[20] Islam et al. (2021) – Wool Fiber Reinforced Cement Systems Wool fibers improve tensile strength and durability in cement systems. They reduce brittleness and enhance crack resistance. Proper mixing techniques are required.

[21] Dehghan et al. (2020) – Hybrid Wool Fiber Composites
Hybrid composites combine strength and ductility effectively. Wool fibers enhance flexibility. Hybridization improves overall performance.

[22] Rahman et al. (2021) – Eco-Friendly Wool Composites Wool composites are environmentally sustainable. They offer good ductility with moderate strength. Suitable for eco-friendly construction.

[23] Alam et al. (2022) – Wool Fiber Laminates Wool laminates improve bonding and structural performance. They are suitable for strengthening applications. Proper design ensures durability.

[24] K. N. Bharath et al. (2016) – Characterization of Sheep Wool Fiber Reinforced Polymer Composites Sheep wool fiber composites exhibit improved ductility and energy absorption capacity. They show non-brittle failure behavior, making them suitable for structural applications. However, optimization of fiber content and bonding is required to enhance strength and durability.

[25] Triantafillou (1998) – CFRP Strengthening CFRP significantly improves strength and stiffness of RC structures. However, it exhibits brittle failure behavior. High cost and low ductility limit its widespread application.

[26] Teng et al. (2002) – FRP Debonding Failure Bond behavior governs the effectiveness of FRP strengthening. Debonding is a critical failure mode. Proper bonding and anchorage are essential for reliable performance.

[27] Yan et al. (2014) – Natural Fiber Composites Natural fibers provide improved ductility and sustainability. They are viable alternatives to synthetic FRPs. Performance can be enhanced through treatment and hybridization.

[28] Fiore et al. (2015) – Mechanical Properties of Natural Fibers Natural fibers show variability in mechanical properties. Proper selection and treatment are necessary for consistency. They offer good ductility but lower stiffness.

[29] Kabir et al. (2012) – Fiber Treatment Techniques

Chemical treatment improves bonding and composite strength. It enhances load transfer efficiency. Optimization is essential to avoid fiber degradation.

[30] Pickering et al. (2016) – Natural Fiber Composite Review Natural fiber composites are environmentally beneficial and ductile. However, they require optimization for structural applications. Hybridization and processing improvements enhance performance.