ISSN (e): 2250 – 3005 || Volume, 15 || Issue, 4|| April – 2025 ||
International Journal of Computational Engineering Research (IJCER)

Revolutionizing Concrete Structures: Enhancing Durability & Longevity With High-Strength Fiber Composite (HSFC)

Raja Sah[1], Durgesh Nandan Verma[2]
Department of Civil Engineering, Dr. KN Modi University, Newai, Rajasthan (India)

Abstract
Many existing structures worldwide are no longer sufficient to meet modern load requirements due to factors such as increased loads, corrosion from de-icing salts, changes in function, initial design deficiencies, and stricter regulations. However, completely replacing these compromised structures is often impractical and expensive. A more feasible approach is strengthening them while they remain in use.
In recent years, High-Strength Fiber Composite (HSFC) or adhesively bonded fiber materials have gained recognition as effective solutions for improving the durability and performance of concrete structures. Compared to traditional strengthening methods, High-Strength Fiber Composite (HSFC) provides several advantages, including superior strength, stiffness, corrosion resistance, ease of installation, repairability, longevity, and cost-effectiveness. Among these, Glass Fiber Reinforced Polymers (GFRP) are particularly beneficial for reinforcing the external surfaces of RCC structures due to their lightweight yet high-strength properties and environmentally friendly composition. Glass Fiber Reinforced Polymers (GFRP) sheets are widely used to strengthen reinforced concrete beams and columns, with studies analyzing their impact on structural performance.
Similarly, evaluations of reinforced cement concrete (RCC) columns strengthened with GFRP sheets using the Universal Testing Machine (UTM) have assessed improvements in axial compressive strength. The incorporation of GFRP in RCC elements has been found to enhance both flexibility and compressive strength. Additionally, studies focusing on improving the axial load-bearing capacity of RCC columns through GFRP reinforcement have contributed to a deeper understanding of its structural benefits. Research findings indicate that GFRP wrapping significantly enhances the load-carrying capacity and stiffness of RCC beams and columns.
Keywords: *Concrete beams, axial compression, High-Strength Fiber Composite (HSFC), glass-fiber-reinforced polymers (GFRP), reinforced cement concrete (RCC), and universal testing machines (UTM).*

Date of Submission: 05-04-2025 Date of acceptance: 15-04-2025

I. Introduction

The building business uses concrete more than any other building material. Numerous buildings around us are made of concrete, but this material has some major issues that make it unsuitable for use, including a low ability to withstand tension, absorb energy, and bend. As modern technology improved, builders were able to use steel to strengthen concrete, with or without pre-stress, to make up for the fact that concrete is weak in tension. The term "ductility" refers to a material or structural member's ability to handle big bendable deformations without breaking [1]. A structure should be able to bend a lot at or near its highest load carrying capacity in the worst case scenario of being loaded so much that it breaks. This will indicate failure ahead of time, stop the whole thing from falling apart, and could even save lives. Statically uncertain concrete structures need members that are flexible at the key sections so that moments can be redistributed [2]. Inserting fibers into concrete can improve its ductility and ability to absorb energy.

Structures may not be strong enough because they don't have enough support, they bend too much, the concrete isn't good enough, the reinforcement is rusting, or the structure can't hold enough weight. Sometimes, fixing and strengthening things are needed to make up for mistakes made by people when they were creating or building something. To meet the growing need for load carrying capacity and/or meeting certain serviceability standards, different strengthening techniques have been created for these uses. Some of the most common ways to make concrete buildings stronger are:

- Putting in extra supports to make the spread of flexural members shorter
- Adding fortification by removing and recasting concrete later on
- Adding more internal or external pre-stressing
- Attaching steel plates to the outside of the structure
- Use of high-tech hybrid materials

1.1 Fibers

The majority of the variations to the properties of composites come from the fibres that are utilised, such as aramid, glass, and carbon. Composites are often named after the fibers that hold them together. GFRP stands for "glass fibre reinforced polymer," whereas CFRP stands for "carbon fibre reinforced polymer." Different fibers are best used for different things because they have different qualities. High-Strength Fiber Composite (HSFC) systems are becoming a more popular choice instead of steel reinforcement for reinforced concrete buildings liprecast concrete pipes, beams, columns, and other components, as well as pre- and post-tensioned bridges. Some things that FRP does better than steel support are that it doesn't rust. FRP reinforcement has also been used to help masonry buildings. More and more, structural engineers in both the public and private sectors are calling for them to be used as original reinforcement and to make buildings stronger.

1.2 High-Strength Fiber Composite (HSFC):

A fibre or other material that is long and thick enough to clearly serve as reinforcing in one or more directions is used to reinforce a thermoset or thermoplastic matrix in a kind of plastic known as fibre reinforced polymer composite. FRP composites are not interchangeable with standard building materials such as aluminum or steel [3]. They have properties that change with the direction of the applied load, which is different from steel or aluminum, which has properties that stay the same in all directions, no matter what the applied load is. Because of this, FRP composites have directional properties, indicating that the finest mechanical attributes are in the direction of where the fibers are placed [4].

FRP has only been used for structural support in the building sector for a number of years. It is usually used with other building materials like wood, steel, and concrete. Their many great qualities include a high stiffness-to-weight ratio and a high strength-to-weight ratio. They are also very strong under stress, don't rust, can be designed in many ways, and are easy to use [5]. Several experts have looked into how Concrete beams can have FRP sheets or plates affixed to them. The effectiveness of using adhesively bonded fibre reinforced polymers to reinforce various concrete building components, such as walls, slabs, columns, and beams, has been demonstrated. More and more, FRP materials are being used to reinforce the outside of existing concrete buildings because they don't corrode, aren't magnetic, and can't be damaged by many chemicals.

There are different ways that the fibers can be arranged to improve the mechanical qualities of the composite, depending on the use. There is a vast array of shapes and strengths available for fabrics. Most fabrics are either unidirectional, which means that all of the fibers are aligned in one direction, or biaxial, which means that the fibers are put in two different directions [6]. These days, the cloth is usually less than 2 mm thick, and adding the resin matrix doesn't make it any thicker. Two or more layers of cloth can be used to increase strength, depending on what is needed.

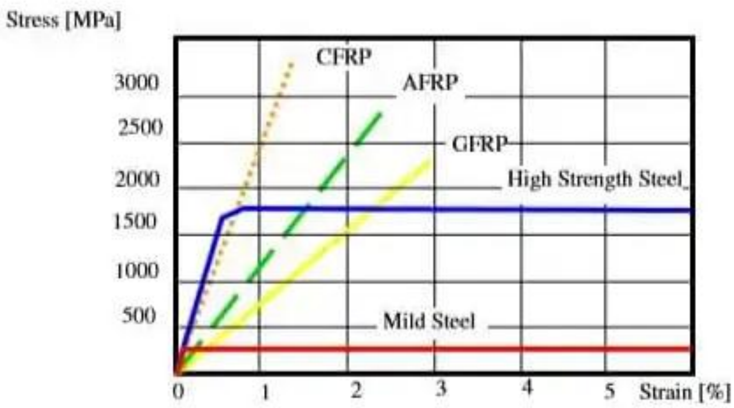

Fig 1.1 Properties of Different Types of FRP Compared with Steel

1.2.1 Advantages and limitations of HSFC (High-Strength Fiber Composite):

High-Strength Fiber Composite (HSFC) has a huge amount of potential and clear benefits over traditional building materials and methods for repairing RC structures. FRP is being used more and more to improve reinforced concrete buildings because it has many great qualities, including being light, resistant to rust, having a very high strength-to-weight ratio, being easy to work with, and being quick and easy to install, which means less work for the workers. But it's not used very often because the materials are very expensive, many countries, like India, don't have design codes for FRP, and people don't know about or don't want to accept the reports, guidelines, and technical books that are already used around the world. Here are some of the best things about HSFC:

- Variable and high tensile strength
- Adjustable properties
- High dynamic strength and Young's modulus
- Exceptional resistance to corrosion
- Lightweight
- Neutral magnetic and electric properties
- High tensile strength relative to weight
- Excellent resistance to corrosion
- Compatible thermal properties with common construction materials like concrete
- Remarkable fatigue resistance
- Rapid construction process
- Adaptable for use on non-flat surfaces
- Odorless, crucial for occupied structures
- Economical option

Limitations of HSFC:

- Quickly plastic behavior and low ductility value;
- High cost;
- Vulnerability to local unevenness

1.3 High Strength Fibers in Composites:

Composites are what Fiber Reinforced Polymers are also known as. This word's root is componere, a Latin verb that means "to put together." It is called a composite when it is made up of two or more different parts that have a clear phase between them.

Besides sports gear, composites are used in airplanes and spacecraft. Besides being used in the building industry, they are seen as new by people in the building industry. It is called a composite when the fiber and the binder are mixed together to make a new material. The combination can be uni-directional, bi-directional, or multi-directional depending on the direction of the fibers in it. Several methods can be used to create composite materials, including by hand layup, pultrusion, filament wrapping, and molding. How strong a composite material is depending on how many fibers are in it and which way they are arranged. The mechanical qualities will also be changed by the volume or size of the composite. The fiber content by volume (VF) (the proportion of fibre volume to composite volume) is usually between 30 and 60%, but this can change based on the materials used, the way they are made, and the properties that are wanted. Fig 1.2 and fig 1.3 describes, Different orientation of Fibers in the Composite.

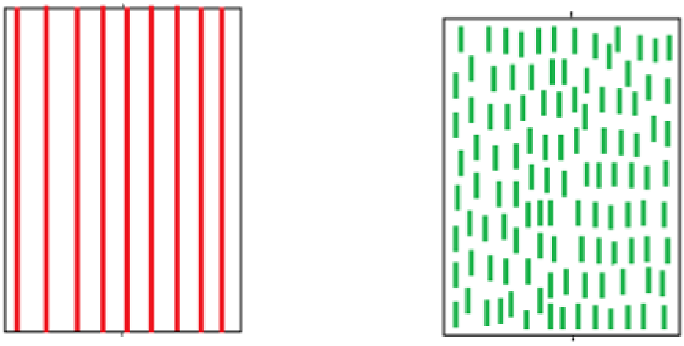

Fig 1.2 (a): Continues and Aligned Fibers
(b): Discontinues and Aligned Fibers

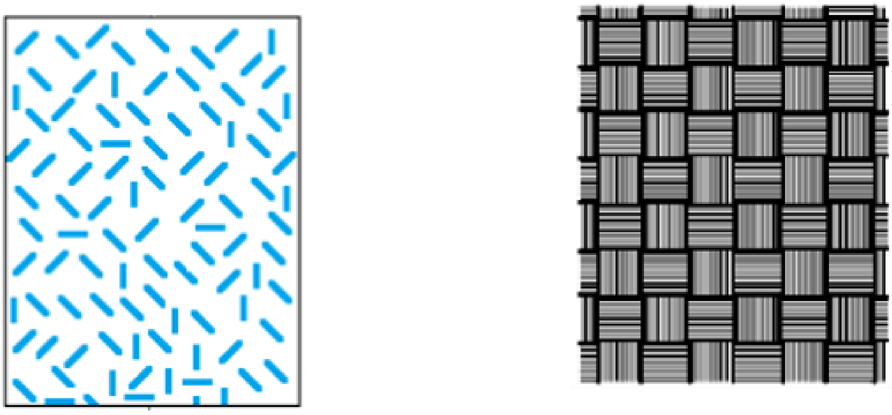

Fig 1.3 (a) Discontinues and Randomly Fiber
(b) Fabric Fiber

Properties of composite materials:
- **Lightweight:** Possesses low weight relative to strength.
- **High Strength-to-weight ratio:** Exhibits exceptional strength in proportion to weight.
- **Corrosion resistance:** Resists corrosion, ensuring longevity in diverse environments.
- **Weather resistance:** Endures exposure to various weather conditions without deterioration.
- **Dimensional stability:** Maintains consistent shape and size under different conditions.
- **Low thermal conductivity and low thermal expansion:** Shows minimal heat transfer and expansion.
- **Radar transparency:** Transparent to radar signals, suitable for specific applications.
- **Non-magnetic:** Lacks magnetic properties, enhancing versatility.
- **High impact strength:** Demonstrates resilience against impact and physical stress.
- **High dielectric strength (insulator):** Provides effective electrical insulation.
- **Low maintenance:** Requires minimal upkeep for sustained performance.
- **Long-term durability:** Ensures enduring performance and reliability over time.
- **Small to large part geometry possible:** Adaptable for fabrication into various sizes and shapes.
- **Tailored surface finish:** Allows customization of surface appearance and texture.
- **Radar transparency:** Allows penetration of radar signals without interference.

Benefits of using fiber reinforced plastic composites:
- Accelerated construction process
- Dependability of pre-engineered systems
- Improved resilience and fatigue resistance
- Innovative and streamlined installation methods
- Prolonged lifespan of structures
- Environmentally sustainable

1.4 Fiber Reinforced Concrete:

High-Strength Fiber Composite (HSFC) is a hybrid material made of the right amount of fiber mixed into concrete or cement mortar that are equally and sporadically distributed. FRC can have different kinds of fibers added to it, such as steel, carbon, glass, galvanized iron, polymer, asbestos, plastic, and more [7]. It is now well known that one of the most important things about FRC is that it is very good at stopping cracks from spreading. Because they can stop cracks from spreading, fiber composites have higher tensile and extensibility strengths, both at the first crack and at the final crack. The fibers can also hold the matrix together even after it has cracked a lot.

All of these things work together to give the fiber mixture a strong ability to bend after cracking, which is not normally seen in concrete. Changing concrete from a rigid to a ductile material would make the fiber composite much better at absorbing energy and withstanding repeated shock or impact loading. These better qualities can be used to build floors at airports and on highways, buildings that can withstand earthquakes and blasts, mine and Turmel linings, and more.

1.5 Significance of the study

The study's relevance stems from its potential to apply High-Strength Fiber Composite (HSFC) to concrete structures, so revolutionizing their longevity and durability. By examining how well High-Strength Fiber Composite (HSFC) strengthens concrete components, the study aims to address critical issues such as structural deterioration, load capacity, and resistance to environmental factors. The findings have broader implications for the construction industry, offering innovative solutions for enhancing the performance and longevity of infrastructure while minimizing maintenance and repair costs. Additionally, the study contributes to advancing sustainable construction practices by promoting materials that reduce reliance on traditional reinforcement methods prone to corrosion and degradation.

II. Objectives of the study:

1. Investigate the Effectiveness of FRP Sheets in Strengthening Concrete Structural Components.
2. Conduct Load Tests on FRP-Wrapped RCC Beams.
3. Compare Ultimate Load Carrying Capacity and Deflection of FRP-Wrapped Beams.
4. Conduct Axial Compressive Tests on RCC Columns Strengthened with FRP.
5. Enhance Axial Compressive Strength of RCC Columns with FRP.
6. Evaluate Percentage Increment of Compressive Strength in FRP-Wrapped RCC Columns.

1.12 Limitations of the study:

The following are the study's limitations on the use of fiber-reinforced plastic (FRP) in concrete structures:

Experimental Constraints:

Findings based on lab experiments may not fully represent real-world conditions.

Field testing needed for validation in diverse environments and structures.

Singular Focus: Primarily examines mechanical properties, neglecting long-term effects and environmental interactions.

Limited Scope of Materials: Focuses on specific HSFC types, potentially overlooking variations in behavior with different composites.

Short-Term Analysis: Study's duration may not capture long-term durability and aging effects of FRP-strengthened structures.

Cost Considerations: Economic feasibility and lifecycle costs compared to traditional materials not fully explored.

Geographical Variability: Findings influenced by local conditions, limiting generalizability to other regions.

Regulatory Compliance: Doesn't address compliance with building codes and standards, crucial for safety and integrity.

III. Literature Review:

For retrofitting the building, different materials are available, such as FRP, steel, concrete, and more. However, FRP is being used more and more. This is because FRP materials are better in many ways than steel and other materials. They are made up of FRP laminates that are easy to stick to concrete surfaces, don't weigh too much, have a high strength-to-weight ratio, and don't rust. A lot of research and experiments have been done on different Fiber reinforced plastic strips by different writers.

Harle et al. (2024) listed the studies that have been done on the performance and longevity of fiber-based materials and fiber-reinforced polymer (FRP) composites. The research showed that many environmental factors, such as humidity, can have a big effect on the mechanical and physical properties of fiber-reinforced polymer (FRP) materials.

Azad et al. (2024) emphasized the possible uses of fiber-reinforced polymer (FRP) materials in fixing up concrete buildings because they are stronger for their weight and don't rust. Over time, concerns were made about the long-term durability of structures that were fixed using fiber reinforced polymer.

Xing et al. (2024) assessed the FRP-reinforced concrete bars and beams' initial mechanical characteristics.

Kanagaraj et al. (2024) tried to find out if synthetic fiber-reinforced polymer (SFRP) stirrups could be attached to reinforced concrete beams. The study's main objectives were to assess their environmental impact and structural efficacy.

IV. Research Materials & Methodology

4.1 Materials used for RCC Beam

Water acts as a medium for the hydration process, facilitating the hardening of the concrete mixture. Steel reinforcement, often in the form of bars or meshes, provides tensile strength to the structure, compensating for concrete's weakness in tension. Furthermore, the beam's strength, stiffness, or resistance to corrosion may be improved by adding composite materials, such as (HSFC). Together, these materials form a cohesive and durable RCC beam capable of withstanding various loads and environmental conditions.

4.1.1 Cement:

Portland cement is the type of building cement that is used the most. a bluish-gray powder produced by finely grinding clinker, which is created by rapidly heating a tightly-knit mixture of argillaceous and calcareous rocks. The primary colorant of cement is iron oxide. The color would be white if there were no defects, but you can't determine the quality of something by looking at its color or specific gravity alone. For the investigation, Portland Pozzolana Cement, or PPC, was utilized. As per IS 10262 - 1982, Portland Pozzolana Cement should be used for the design mix. It takes 4.5% of the cement to make it fine. It weighs 3.10 times as much as water.

4.1.2 Aggregates:

The most important parts of concrete are the aggregates. They give the concrete shape and keep it from shrinking. Good gradation of materials is one of the most important things for making concrete that can be worked with. About 55% of the volume of mortar is made up of aggregate, and 85% of the volume of mass concrete is made up of aggregate. The largest piece of aggregate in mortar is 4.75 mm, and the biggest piece of aggregate in concrete is 150 mm. IS 383 - 1970 sets the rules for how coarse and small aggregates must be used.

4.1.3 Coarse Aggregate:

Granite is an igneous rock with big grains that has a smooth texture and is mostly made up of quartz and feldspar, with small amounts of mica and other minerals. Granite is very dense and hard, and a fine shine brings out the beauty of the crystals in it.

Granite lasts a very long time and doesn't soak up water like sandstone and limestone do. The following are the requirements for large aggregates:

Size of coarse aggregate: 20 mm
Specific gravity of coarse aggregate: 2.6
Water absorption: 0.5 %

4.1.4 Fine Aggregate:

A lot of the earth's surface is made up of sand, which is generally made up of quartz and other siliceous materials. Most of the time, silica sands that are above 98% clean are the most useful for business.

For the tests, fine aggregate from a river that didn't have any organic impurities in it was used. The fine stuff has a specific gravity of 2.6 and can pass through a 4.75 mm sieve. Based on the Indian Standard, the fine gravel fell in the grading zone III.

It is used aggregate that can pass through a 4.75-inch sieve. Fine aggregate is mixed into concrete to make it easier to work with and make the combination more even.

Specific gravity of fine aggregate: 2.6
Water absorption: 1 %
Free surface moisture: 2 %

4.1.5 Water: As an active ingredient in the chemical process with cement, water is an important part of concrete. Cement concrete is strong because of the binding action of the cement getting hydrated. The amount of water should be lowered to the level needed for the chemical reaction of unhydrated cement, since too much water would only create unwanted holes or capillaries in the hardened cement paste in concrete.

4.1.6 Iron and steel: To make the bars stronger along their length, 12 mm bars with a high yield strength were used. They were made from bars of mild steel that were 8 mm in diameter. To find out the yield strength of the steel reinforcement used in this study, three samples of each bar were put through the usual tensile test. For testing Fe 500 grade steel, a UTM (Universal Testing Machine) was utilized. For steel bars having a diameter of 12 mm, the yield stress, ultimate stress, elongation, and area decrease were determined.

For the tests, steel rebars with a 12 mm diameter were used to strengthen the length of the structure, and steel rebars with an 8 mm diameter round shape were used to reinforce the width. As you can see in Table 2.1, steel bars have certain qualities.

Table 2.1: Material Properties of steel bar

Diameter of the Bar (mm)	Yield Stress (MPa)	Ultimate Stress (MPa)	Young's Modulus (MPa)	Elongation (%)	Percentage Reduction in Area
12	540	720	2*10 5	16.68	59.21

4.1.7 Composite Material: GP resin was used as an adhesive in this project, and glass fiber reinforced polymer (GFRP) mat was used for gluing on the outside.

4.1.7.1 Glass Fiber Reinforced Polymer (GFRP): Characteristics of GFRP as follows:
The Glass Fiber Reinforced Polymer (GFRP) boasts several desirable characteristics. Firstly, it offers uniform fiber distribution throughout its structure, ensuring consistent performance. Additionally, its surface is smooth, providing a sleek appearance and feel. The material exhibits a soft and pliable texture, enhancing its flexibility and adaptability for various applications. Since GFRP doesn't have a lot of glue or strainer in it, resin can be infused quickly. This makes manufacturing processes more efficient. Moreover, it demonstrates good mould obedience, conforming well to desired shapes and configurations. Specifications of GFRP include a weight of 30 g/m2, a binder content of 7%, and a resin wet-out time of 10 seconds. Its tensile strength measures at 20 N/5 cm, with a maximum moisture content of 2%. GFRP is available in a width of 1 meter, and its color fastness to light is rated as very good to excellent, as tested by BTRA.

Figure 2.1: Fiber Glass

V. RESULT ANALYSIS

5.1 Results for RCC Beam: The control beam, the single-layered GFRP wrapped beam (S-1), and the double-layered GFRP wrapped beam (S-2) have maximum bend and load values displayed in Table 5.1. The average cracking load and average ultimate load for the control beam, reinforced beams S-1 and S-2 can be seen in Table 5.2.

Table 5.1: Peak deflection and Load for RCC beam

Specimen	Peak Deflection (mm)	Load (kN)
CB-1	6.4	54.8
CB-2	8.0	52.5
CB-3	10.5	41.0
S-1a	6.0	64.0
S-1b	7.8	63.0
S-1c	7.4	71.5

S-2a	5.9	56.0
S-2b	5.5	67.0
S-2c	6.2	72.3

Table 5.2: Cracking Load and Ultimate Load

Specimen	Average Cracking Load (kN)	Average Ultimate Load (kN)
Control Beam (CB)	18.10	55.00
Strengthened Beam (S1)	19.00	65.20
Strengthened Beam (S2)	20.00	70.10

VI. CONCLUSION AND DISCUSSION

6.1 Summary of RCC Beam

Experiments were conducted to examine the bending behavior of reinforced concrete beams (RC beams) enhanced with glass fiber reinforced polymer (GFRP) mats. Beams of externally reinforced concrete with GFRP mats were tested to failure using a symmetrical two-point concentrated loading technique. They tried three sets of beams. There were three sets of three beams: control beams, single-layered GFRP (S1) beams, and double-layered GFRP (S2) beams.

Experimental information was gathered on the load, deflection, and failure causes of each beam. The number of GFRP layers and their orientation are studied to see how they affect the beams' final load carrying capacity and how they failure.

The experimental procedure involved several steps:

1. Casting of three beams designated as CB, S-1, and S-2.
2. Strengthening of beams S-1 and S-2 with GFRP mat using different layouts.
3. Testing of all three specimens under four-point loading using a loading frame.
4. Comparative analysis conducted between the control beam (CB) and beams (S-1 & S-2) reinforced with GFRP mat.
5. Presentation of graphical representations depicting the comparative study outcomes.
6. Calculation of the percentage increase in cracking load and ultimate load for each specimen.

6.2 Conclusions of RCC Beam:

The final load carrying capacity goes up when the beam is strengthened up to its neutral axis. However, the cracks that appeared at higher loads could not be seen. It doesn't give as much of a signal as beams that are strengthened only at the soffit because the first cracks are harder to see. By making the beam stronger up to its neutral axis, the maximum load that it could hold was increased. The first cracks in the S1 and S2 strengthened beams showed up when they were under more stress than the control beam. After the beam was strengthened, the first cracks showed up in its bending zone. As the load increased, the cracks got bigger towards the neutral axis. The last failure is a bending failure, which means that the GFRP made the beam stronger in shear.

The results of the experiment clearly indicate the following conclusions:

1. The graphs suggest a stiffness augmentation in the beams due to GFRP mat bonding in comparison to the control beam.
2. The wrapping procedure significantly improves strength.
3. Retrofitting for shear could notably enhance ductility due to additional confinement effects.
4. Cracks got bigger when the last load was 75.50 kN for S-1 and 80.00 kN for S-2.
5. It was found that S-1 and S-2's mid-span deflections were 26.59% and 32.45% less when the service load was 65.20 kN (CB).
6. In comparison to the concrete control beam (CB), the maximum load is 15.44% higher on beams enhanced with a single layer of GFRP mat (S-1) and 23.6% higher on beams strengthened with two layers of GFRP mat (S-2).
7. Previous research (Syed Ibrahim et al. 2015) found that the largest mid-span bending for a single-layer GFRP laminated beam was 15.4% and for a double-layer beam it was 27.5%.
8. Compared to the earlier study, the mid-span bending increased by 42% for beams strengthened with single-layer GFRP mat S-1 and by 15% for beams strengthened with double-layer GFRP mat S-2.

6.3 Conclusions of RCC Column

Some important conclusions have been drawn from the study's analysis of the experimental data. The compressive loading test results for the posts show that wrapping them in GFRP makes them stronger so they can hold more weight. Giving the beams more strength by delaying the breaking of the concrete and reinforcement was one of the most important benefits of the GFRP wrapping. It made the column more flexible. The supports could handle more weight and work better when there were more GFRP layers.

It turned out that putting GFRP mats around columns with a lot of eccentricity (a lot of bending moment) made them more load- and bend-resistant than control columns. Another thing that this study found was that uneven loading makes the beams less able to hold weight and work well. The last thing that was shown was that wrapping RCC beams in GFRP made them work better. It is recommended to use at least two pieces of wrapping to get good results.

References

[1]. Ding, Z., & Elkady, A. (2023). Accuracy assessment of predictive models for semirigid extended end-plate connections. *ce/papers*, *6*(3-4), 1263-1268.

[2]. Lee, M., Mata Falcón, J., & Kaufmann, W. Extending the design space of concrete structures using stay-in-place flexible formworks with integrated textile reinforcement.

[3]. Rajulwar, V. V., Shyrokykh, T., Stirling, R., Jarnerud, T., Korobeinikov, Y., Bose, S., ... & Sridhar, S. (2023). Steel, Aluminum, and FRP-Composites: The Race to Zero Carbon Emissions. *Energies*, *16*(19), 6904.

[4]. 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.

[5]. Karim, M. A., Abdullah, M. Z., Deifalla, A. F., Azab, M., & Waqar, A. (2023). An assessment of the processing parameters and application of fibre-reinforced polymers (FRPs) in the petroleum and natural gas industries: A review. *Results in Engineering*, 101091.

[6]. Kahavita, K. D. H. N., McCarthy, E. D., Zhang, M., Brádaigh, C. Ó., & Harrison, P. (2023). Characterising the shear resistance of a unidirectional non-crimp glass fabric using modified picture frame and uniaxial bias extension test methods. *International Journal of Material Forming*, *16*(5), 49.

[7]. Khan, M. I., & Khan, A. (2023). Flexural Behaviour of FRC Beams Wrapped With FRP. *Indian Journal of Structure Engineering (IJSE)*, *3*(2), 12-18.

[8]. Kim, J. H. J., Park, C. G., Lee, S. W., Lee, S. W., & Won, J. P. (2008). Effects of the geometry of recycled PET fiber reinforcement on shrinkage cracking of cement-based composites. *Composites Part B: Engineering*, *39*(3), 442-450.

[9]. Abdel-Rahman, A. G., Mirza, F. A., & Salah, A. A. (2019). An overview of fibre reinforced concrete, FRC and fibres properties and current applications. *International Journal of Science and Research (IJSR)*, *8*(10), 504-515.

[10]. Monette, L., Anderson, M. P., & Grest, G. S. (1994). Effect of volume fraction and morphology of reinforcing phases in composites. *Journal of applied physics*, *75*(2), 1155-1170.

[11]. Niroumand, H., Kassim, K. A., & Yah, C. S. (2011). SOIL IMPROVEMENT BY REINFORCED STONE COLUMNS BASED ON EXPERIMENTS WORKS. *Electronic Journal of Environmental, Agricultural & Food Chemistry*, *10*(7).

[12]. Scaffaro, R., Di Bartolo, A., & Dintcheva, N. T. (2021). Matrix and filler recycling of carbon and glass fiber-reinforced polymer composites: A review. *Polymers*, *13*(21), 3817.

[13]. Bhatt, A. T., Gohil, P. P., & Chaudhary, V. (2018, March). Primary manufacturing processes for fiber reinforced composites: History, development & future research trends. In *IOP conference series: materials science and engineering* (Vol. 330, p. 012107). IOP Publishing.

[14]. Dhimole, V. K., Serrao, P., & Cho, C. (2021). Review and suggestion of failure theories in voids scenario for VARTM processed composite materials. *Polymers*, *13*(6), 969.

[15]. Rajpurohit, A. (2014). Fiber Reinforced Composites: Advances in Manufacturing Techniques. *FRP Today*, *14*(04), 22.

[16]. Buck, L. (1997). *Furniture Design with Composite Materials* (Doctoral dissertation, Buckinghamshire New University).

[17]. Hadi, M. N., & Youssef, J. (2016). Experimental investigation of GFRP-reinforced and GFRP-encased square concrete specimens under axial and eccentric load, and four-point bending test. *Journal of Composites for Construction*, *20*(5), 04016020.

[18]. Dash, N. (2009). *Strengthening of reinforced concrete beams using glass fiber reinforced polymer composites* (Doctoral dissertation).

[19]. Harle, S. M. (2024, February). Durability and long-term performance of fiber reinforced polymer (FRP) composites: A review. In *Structures* (Vol. 60, p. 105881). Elsevier.

[20]. Azad, H. M., Diganto, M. H., Rahman, M. Z., & Zhu, D. (2024). Durability problems of concrete structures rehabilitated with fiber-reinforced polymer. In *Eco-Efficient Repair and Rehabilitation of Concrete Infrastructures* (pp. 217-248). Woodhead Publishing.

[21]. Xing, L., Sun, S., Mei, K., Guo, Y., & Yang, Z. (2024). Research progress on short-term mechanical properties of FRP bars and FRP-reinforced concrete beams. *Journal of Traffic and Transportation Engineering (English Edition)*.