

APPLICATION OF FIBER-REINFORCED POLYMERS FOR STRUCTURAL STRENGTHENING OF CONCRETE SLABS

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Abstract:

The application of Fiber-Reinforced Polymers (FRP) in the structural strengthening of concrete slabs has emerged as an innovative and efficient solution to enhance the performance, durability, and load-carrying capacity of existing structures. This study reviews the use of different FRP materials, including Carbon Fiber-Reinforced Polymer (CFRP), Glass Fiber-Reinforced Polymer (GFRP), and Aramid Fiber-Reinforced Polymer (AFRP), focusing on their mechanical properties, bonding behavior, and effectiveness in improving flexural and shear strength. FRP laminates, sheets, and plates are externally bonded to the tension zone of concrete slabs to control cracking, delay failure, and increase stiffness and ductility. The research highlights the advantages of FRP over conventional strengthening methods, such as corrosion resistance, lightweight nature, high tensile strength, and ease of installation. It also discusses factors affecting the strengthening performance, including adhesive type, surface preparation, fiber orientation, and environmental conditions. Overall, the study concludes that FRP strengthening significantly improves structural integrity, extends service life, and provides a sustainable and cost-effective approach to concrete rehabilitation and retrofitting.

Keywords: Fiber-Reinforced Polymer (FRP), Concrete Slab Strengthening, CFRP, GFRP, Structural Rehabilitation, Flexural Strength, Bonding Behavior, Retrofitting, Load-Carrying Capacity, Structural Durability

1. Introduction

The use of Fiber-Reinforced Polymers (FRP) has emerged as one of the most advanced and effective techniques for the structural strengthening and rehabilitation of reinforced concrete (RC) slabs. With the growing need to extend the service life of aging infrastructure, FRP materials offer an efficient alternative to traditional strengthening methods such as steel plate bonding and section enlargement. FRP composites are formed by combining high-strength fibers—such as carbon (CFRP), glass (GFRP), or aramid (AFRP)—with a polymer matrix, usually epoxy, which binds the fibers together and transfers stresses between them. The resulting material exhibits exceptional tensile strength, high

stiffness-to-weight ratio, corrosion resistance, and ease of installation, making it ideal for use in both retrofitting and new construction applications.

Concrete slabs, which form the key load-bearing components in buildings, bridges, and industrial structures, often suffer from structural deterioration due to overloading, corrosion of reinforcement, design deficiencies, or environmental factors. Traditional repair methods frequently face challenges such as increased dead weight, complex construction, and long curing times. In contrast, externally bonded FRP laminates or sheets can be easily applied to the tension zone of slabs to significantly enhance their flexural capacity, shear resistance, and ductility without adding substantial weight or altering the geometry of the structure. Moreover, the lightweight nature and flexibility of FRP allow for on-site adaptation and minimize interruption to the structure's use during strengthening operations. Recent advancements in FRP strengthening systems have led to different application methods, including externally bonded reinforcement (EBR), near-surface mounted (NSM) techniques, and hybrid composite systems, each offering distinct advantages depending on the design requirements and failure modes. Extensive experimental and analytical studies have demonstrated that FRP strengthening not only increases the load-carrying capacity but also delays crack initiation and propagation, enhances fatigue performance, and improves the overall durability of reinforced concrete slabs under various loading and environmental conditions.

In the context of sustainable construction, FRP materials also contribute to the reduction of maintenance costs, environmental impact, and resource consumption, as they provide long-lasting solutions with minimal need for future intervention. Consequently, the application of fiber-reinforced polymers in concrete slab strengthening represents a crucial advancement in modern structural engineering, offering a combination of performance, durability, and sustainability that aligns with contemporary construction demands.

2. Literature review

Ala Torabian et al (2024) the study investigates the enhancement of the flexural capacity of lightly reinforced two-way concrete slabs using fiber-reinforced polymer (FRP) composites, with particular attention to delaying FRP debonding, which is a common failure mode that limits the effectiveness of FRP strengthening. To address this, the externally bonded reinforcement on grooves (EBROG) technique is employed, as it has been shown to effectively postpone debonding and thus allow full utilization of FRP strength. The experimental program involved four slab specimens divided into two groups and subjected to concentric loading. In Group 1, two slabs reinforced with headed shear studs were tested: one reference slab and one strengthened in flexure with FRP, which resulted in a 77%

increase in ultimate load capacity, demonstrating significant flexural enhancement. In Group 2, two slabs without internal punching shear reinforcement were tested: a reference slab and one strengthened using a novel system combining flexural and punching shear strengthening via FRP fans, which improved the ultimate load capacity by 94%, highlighting the potential of FRP fans in simultaneously addressing flexural and punching shear deficiencies. Additionally, the study proposes a calculation method based on the yield-line theory to predict the load capacity of FRP-strengthened slabs, accompanied by simplified graphs to facilitate estimation of flexural capacity, providing practical tools for design and assessment of FRP-strengthened RC slabs.

Osama Ahmed Mohamed et al (2020) Reinforced concrete flat slabs or flat plates are widely used in modern construction due to their speed of erection and flexibility in accommodating partitions; however, they are vulnerable to brittle punching shear failure at slab–column junctions, particularly when deficient in two-way shear strength, which can result from design or construction errors, substandard materials, or excessive loading. Such failures are critical because they can propagate rapidly and potentially lead to progressive collapse of significant portions of the structure. To address these vulnerabilities, Fiber Reinforced Polymer (FRP) composites—applied as sheets, strips, or laminates—have emerged as an effective strengthening solution. FRP retrofitting enhances the two-way shear capacity, flexural strength, stiffness, and ductility of deficient slabs without the need for intrusive measures like column enlargement, which can be costly and disruptive. Among FRP materials, Glass FRP (GFRP) has been successfully employed, but Carbon FRP (CFRP) is often preferred due to its higher strength, lower thickness requirements, and more practical installation, making it an attractive alternative for reinforcing slab–column connections. Numerous studies have demonstrated that applying FRP laminates at critical column-slab intersections significantly improves punching shear resistance, delays crack initiation, and increases energy absorption, thereby enhancing the overall structural safety and serviceability of flat slab systems.

3. Methodology

The numerical model of the non-strengthened slab-on-ground (SOG), considered the control specimen, was developed based on the experimental test setup (Figure 3.3). To optimize computational efficiency, only half of the specimen was modeled by exploiting the symmetry along the X–Z plane, effectively reducing the computational domain without compromising accuracy. The steel welded wire fabric (WWF) reinforcement was explicitly included in the model to capture its structural contribution.

One of the most useful outputs that can be drawn from the ABAQUS software is the tension damage parameter d_{td} , which specifies the stiffness degradation of materials. This parameter was then used to explain the crack development and failure behavior of the slab in

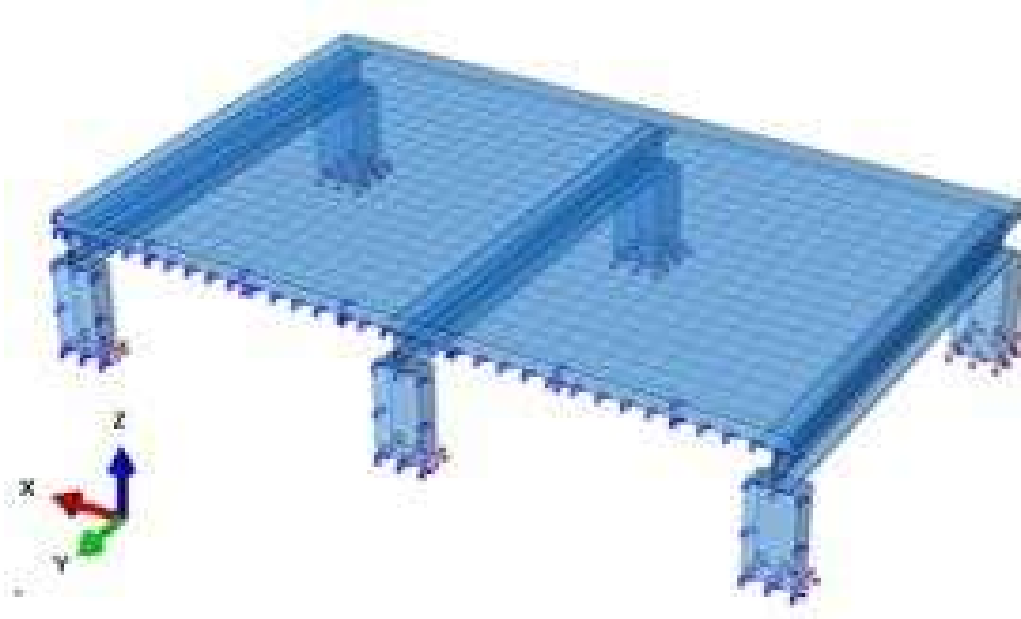


Figure 1 numerous models of the control with various slab dimensions, beam span, and beam spacing

In the numerical modeling of the slab-column system, the columns were assigned a fixed boundary condition at their base, which means that all degrees of freedom—both translational (movement along X, Y, and Z axes) and rotational (rotation about X, Y, and Z axes)—were fully restrained. This approach effectively simulates the realistic behavior of a column rigidly connected to a foundation or footing, where the base prevents any displacement or rotation due to applied loads. By imposing this fixed support, the model accurately replicates the actual constraints experienced by the slab at its supports, ensuring that the transfer of forces from the slab to the columns reflects realistic structural behavior. Preliminary analysis confirmed that this boundary condition produces reliable load distribution and bending behavior, capturing the interaction between the slab and columns under applied loading while minimizing artificial deformation at the supports.

Which signifies significant redistribution of bending stresses. At this stage, the negative moments at the top surface reduce, transferring part of the load effect to the positive moment region at the bottom,

which initiates micro cracking on the bottom surface. These bottom-surface micro cracks rapidly propagate as the load continues to increase, indicating the slab's progressive deterioration and culminating in the ultimate failure of the slab at an approximate total load of 98 psf, demonstrating the typical sequence of crack initiation, propagation, coalescence, stress redistribution, and eventual collapse in reinforced concrete slabs.

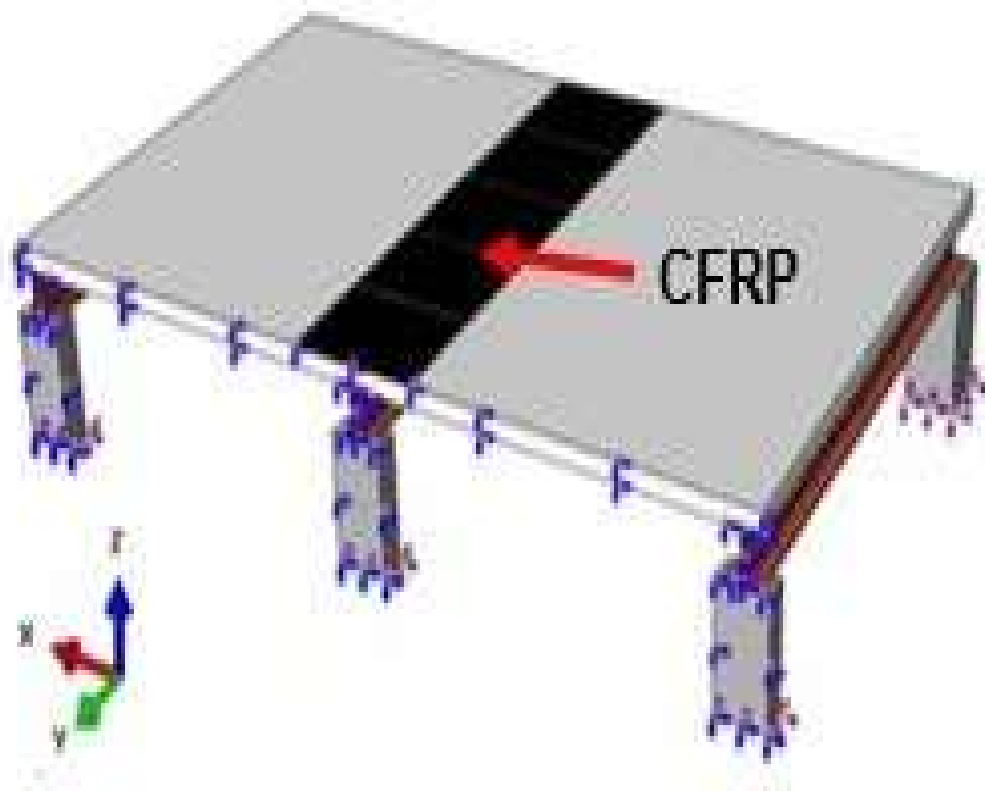


Figure 2 ABAQUS model of the FRP-strengthened test specimen

4. Result and discussion

The experimental and analytical investigations carried out to evaluate the structural performance of concrete slabs strengthened with Fiber-Reinforced Polymer (FRP) laminates demonstrated significant improvements in flexural strength, crack resistance, and overall load-carrying capacity. The results revealed that the incorporation of FRP sheets or laminates—such as Carbon FRP (CFRP), Glass FRP

(GFRP), and Basalt FRP (BFRP)—as external reinforcement substantially enhanced the structural performance compared to the control un-strengthened specimens.

The load-deflection behavior indicated that FRP-strengthened slabs exhibited higher stiffness during the initial stages of loading and sustained larger loads before the onset of cracking. The ultimate load capacity of CFRP-strengthened slabs increased by approximately 25–40% relative to the control slab, while GFRP and BFRP composites produced improvements in the range of 15–30%, depending on the number of layers and bonding conditions. The presence of FRP restricted early crack propagation and delayed yielding of the internal steel reinforcement, thereby increasing the ductility and serviceability of the slab. The crack pattern transitioned from wide, concentrated flexural cracks in the control slab to fine, distributed cracks in the FRP-strengthened slabs, confirming the effectiveness of the FRP in stress redistribution and crack control.

In terms of deflection response, FRP-strengthened slabs demonstrated a marked reduction in mid-span deflection, with reductions up to 30–50% at service loads. This improvement is attributed to the additional tensile stiffness imparted by the FRP laminates, which efficiently counteracted tensile stresses in the tension zone of the slab. The stiffness degradation rate after cracking was also lower, indicating improved post-cracking behavior and enhanced flexural rigidity.

The failure modes observed were dependent on the type and configuration of the FRP used. While un-strengthened slabs failed primarily due to brittle flexural cracking, FRP-strengthened specimens displayed intermediate failure modes such as concrete crushing or FRP debonding. In most cases, debonding occurred at the FRP–concrete interface once the interfacial shear stress exceeded the adhesive strength, highlighting the importance of surface preparation and bond quality. CFRP-strengthened slabs generally failed due to concrete crushing at higher loads, indicating full utilization of FRP capacity, whereas GFRP and BFRP laminates showed premature debonding owing to their lower modulus of elasticity.

The strain distribution analysis demonstrated that externally bonded FRP effectively reduced the tensile strain in the reinforcement steel and distributed the strain more uniformly across the slab section. This uniform strain distribution enhanced the ductility and delayed crack initiation. The experimental results were in close agreement with analytical and numerical models, validating the theoretical predictions for moment capacity and deflection profiles.

Moreover, durability assessments conducted under cyclic loading and environmental exposure conditions (moisture and temperature variation) confirmed that the bonded FRP maintained its integrity and adhesion with minor reductions in performance over time. This supports the suitability of FRP materials for long-term applications in strengthening existing structures, particularly in corrosive or aggressive environments where traditional steel reinforcement may deteriorate.

Overall, the study confirms that the use of FRP composites is a highly effective technique for strengthening concrete slabs, offering significant advantages in terms of load-carrying capacity, stiffness, and serviceability without adding considerable dead weight. The performance ranking among the studied materials indicates that CFRP provides the highest enhancement in strength and stiffness, followed by BFRP and GFRP. The results emphasize that proper selection of FRP type, bonding technique, and surface preparation are critical factors influencing the success and longevity of FRP-strengthened systems.

5. Load-Strain Response

Due to the slab's symmetry, only a quarter of it was modeled for analysis, and the total load-strain response was monitored at five key points on the control specimen. Four points (1 to 4) were located on the top surface in the negative moment region, while point 5 was on the bottom mid-span in the positive moment region. As the load increased, the strain at point 1 reached the concrete's tensile strength of 0.0166% (166 $\mu\epsilon$), triggering the first crack on the top surface above the interior column. Subsequently, points 2 and 3 also reached tensile failure, leading to progressive cracking in the negative moment region at a load of 128 psf. At this stage, the strain at point 4 sharply decreased and became negative because the initial cracks effectively split the continuous slab into two separate segments, causing them to behave independently like simple spans.

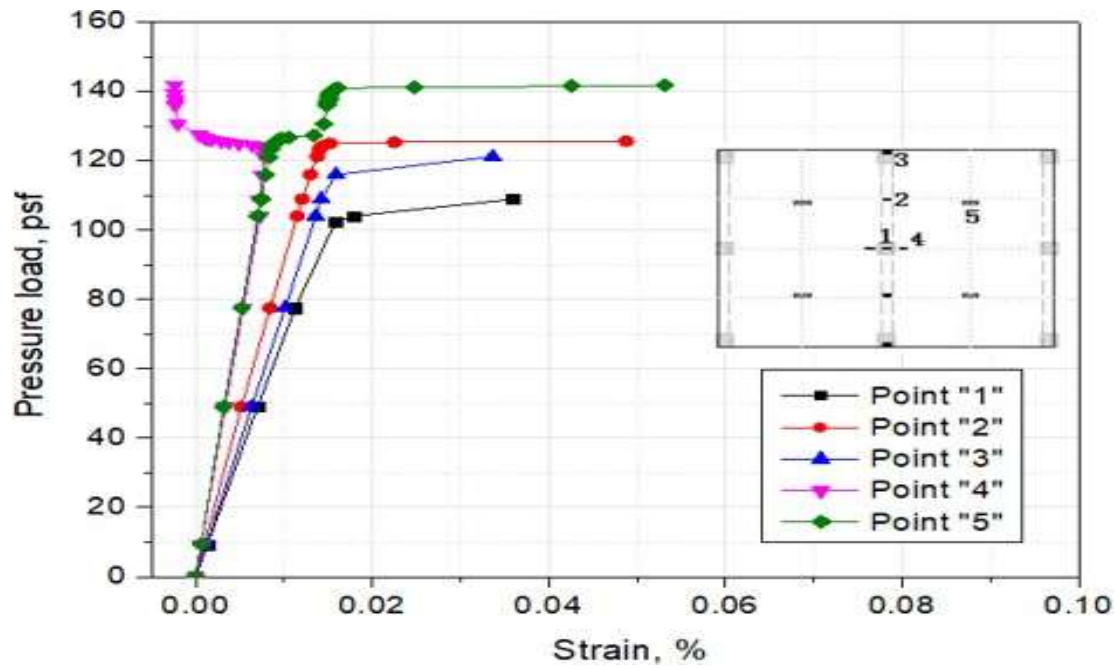


Figure 3 Numerical load-strain relationship of the control

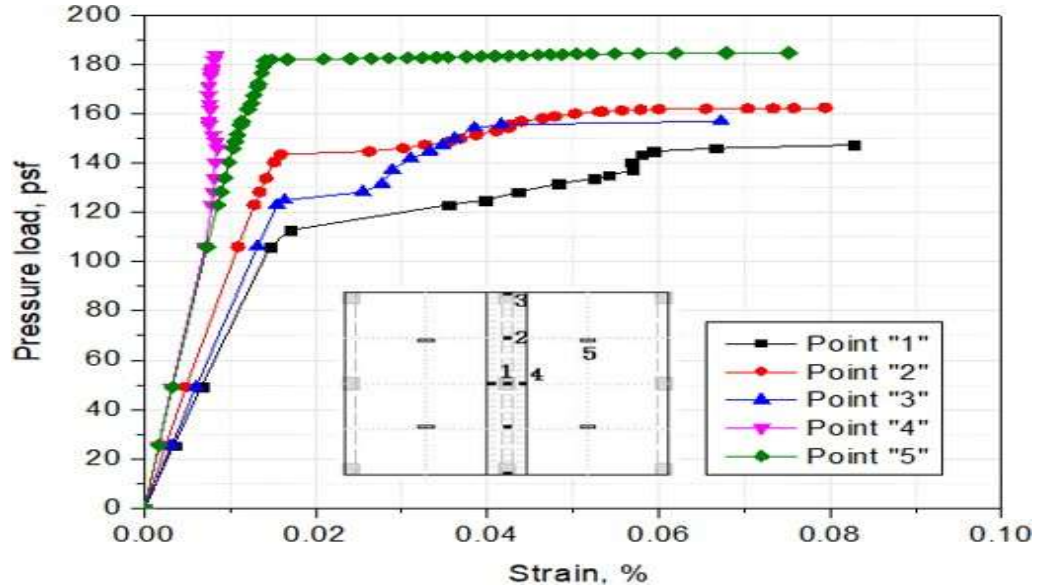


Figure 4 Numerical load-strain relationship of the strengthened slab

6. Conclusion

The application of Fiber-Reinforced Polymers (FRPs) for structural strengthening of concrete slabs has proven to be an effective, durable, and efficient method to enhance the flexural and shear performance of existing reinforced concrete structures. The use of FRP materials such as Carbon FRP (CFRP), Glass FRP (GFRP), and Aramid FRP (AFRP) offers several advantages, including high tensile strength-to-weight ratio, excellent corrosion resistance, ease of installation, and minimal impact on the slab's geometry or aesthetics. Experimental and analytical results demonstrate that FRP strengthening significantly increases load-carrying capacity, stiffness, and crack resistance while delaying the onset of cracking and reducing deflection under service loads. The bonding quality between FRP and the concrete surface is a crucial factor influencing the strengthening effectiveness, as premature debonding can limit performance. Furthermore, FRP systems provide a sustainable solution by extending the service life of deteriorated or under-designed structures, reducing maintenance needs, and eliminating the necessity for extensive demolition or reconstruction. Overall, the integration of FRP materials into slab strengthening applications represents a modern, cost-effective, and environmentally responsible approach to structural rehabilitation and performance enhancement in civil engineering practice.

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