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Utilization of Fiber-Reinforced Polymer (FRP) in Both New Constructions and the Enhancement of Existing Structures

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Abstract: The most used construction material in today`s buildings is concrete, due to the fact that it is versatile, can be molded into various shapes and it has excellent compressive strength. On the contrary, concrete is a brittle material that has lower tensile strength and is also prone to cracking and fracture propagation within the material. This research paper presents an extensive review of earlier research conducted on the early evolution of FRPs, their behaviour under different conditions through conventional structural loading methods such as the 4-point loading and their application. Addition of small fibres that behave as anchors, preventing the widening of micro cracks, resulting in changes in structural behaviour of concrete under tensile loading, expansions during extreme temperature exposures and regular shrinkage cracks, are gained through the use of fibre reinforced polymers (FRP) acting in a relatively similar manner to conventional steel reinforcement. In addition to FRP sourced from small hair like fibres, it also comes in the form of wraps which aid in element confinement on beams and columns lending to not only compressive increase in strength of the element but also tensile load reduction, much like the behaviour that prestressing tendons have on prestressed concrete.

Keywords: *Fibre reinforced Polymers, Carbon Fibres, Concrete, Flexural Cracks, Retrofitting.*

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I. INTRODUCTION

Concrete exhibits exceptional compressive strength, which led to its dominance in construction following the industrial revolution, particularly after the advent of affordable and mass-produced cement. However, it is deficient in tensile strength, causing inadequate performance in flat concrete sections that experience bending or tensile forces. The working stress design method aimed to address this limitation by considering concrete as primarily a compressive material while employing steel reinforcement to manage the tensile stresses resulting from bending. Nevertheless, this approach often resulted in less cost-effective structures and was ultimately replaced by the limit state method; this new technique allowed for greater compressive stresses within concrete but largely disregarded its capacity for tension.

Moreover, when the cement paste solidifies, concrete undergoes shrinkage which generates tensile stresses on beams and slabs due to fixed supports preventing volume changes. This condition can lead to crack formation prior to any load being applied onto the slab [1]. Such cracking undermines structural integrity and facilitates deterioration through water infiltration and carbonation over time—ultimately contributing to a gradual loss of strength and corrosion of embedded steel reinforcements. Fiber reinforced polymers are introduced as an enhancement.

Macro and micro wires enhance the structural integrity of concrete, thereby reducing crack propagation. They also provide minimal tensile strength that may arise in beams and slabs during low-frequency load reversals. However, one significant drawback of concrete construction is its limited capacity for retrofitting; unlike steel structures where dismantling offers notable advantages, such benefits do not extend to concrete systems. While interfacing beams can be easily replaced by introducing steel beams or precast elements, retrofitting columns has historically posed considerable challenges. Fiber-reinforced polymer (FRP) wrap sheets offer a promising solution to this issue. These wraps are applied to column surfaces similarly to how fiber glass components are utilized in race car repairs; upon curing, they generate confining pressure around the column. This confining effect mimics triaxial stresses and enhances the vertical load-bearing ability of the concrete column while preventing spalling—thus allowing for modifications like adding extra floors or changing building usage as long as foundational supports can handle these loads.

This paper aims to present a thorough literature review of existing research on FRPs and their commercialization

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potential in order to assess future applications of this technique. The objective is to compile high-quality studies regarding whether FRPs could serve as an alternative or at least an effective complement to traditional reinforcement methods used in reinforced cement concrete (RCC) structures.

II. TYPES OF FIBRES USED FOR REINFORCEMENT

Polyethylene-based fibers exhibit an elastic modulus similar to that of carbon fibers, yet they are available at a significantly lower cost. Additionally, these fibers demonstrate exceptional durability in harsh environments, making them particularly suitable for extreme exposure scenarios such as coastal regions and soils with high concentrations of sulfate and chloride. In contrast, polypropylene fibers can be produced as fibrillated strands that disperse evenly throughout the concrete matrix during mixing; they also maintain adequate mechanical bonding with the hardened concrete. However, these fibers have limited fire resistance and possess a relatively low Young's modulus. On the other hand, PVA (polyvinyl alcohol) fibers tend to lose strength when subjected to prolonged stress; while they bond well with the surrounding matrix, this characteristic may render them ineffective structural components after cracking occurs. To achieve specific directional strength characteristics akin to those found in carbon fibers, these materials are constructed from layers arranged in particular orientations. They remain highly inert even in aggressive conditions and feature an extremely low weight per unit volume. Such properties make them useful as wire strand reinforcements and confinement wraps.

III. FRP USAGE AS A REPLACEMENT OR SUPPLEMENT TO TRADITIONAL STEEL REBARS

FRPs have three main applications in new structures, as steel reinforcement substitute, stay in place formwork, and as prestressing tendons. For retrofitting, FRP fabrics are paste on a bottom of the beams to enhance their tensile load capacity, wrapped around the web section of the beams to enhance their shear capacity or help shear and axial load carrying capacity for columns through confinement in case of wrapped around.

➢ *Flexural Reinforcement*

Another typical use of FRP plates and fabrics involves the soffits of concrete beams. According to ACI 440.2R-08, this document provides guidance on proper FRP application as well as insight into prevalent failure mechanisms such as laminate rupture, debonding from surfaces, and separation related to the concrete cover perspective. Laminate rupture typically occurs when strain exceeds its ultimate threshold at any point along the beam where bonding takes place (see Figure 1). Debonding arises when the upper compression fiber reaches its crushing limit; in such cases, the epoxy adhesive fails to bear the axial loads required for transferring forces from both the concrete cover to the FRP laminate (refer to Figure 2). Cover delamination represents a form of brittle failure that manifests in areas with truncated laminates yet experiences sufficient stress for tensile load bearing by the cover itself. Over time, small cracks develop and extend downwards towards rebar levels, leading to complete delamination of all concrete within that covered zone away from its structural member (illustrated in Figure 3) [3].

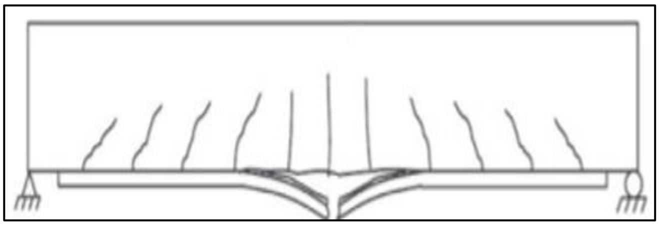

Fig 1 Rupture of FRP Sheet

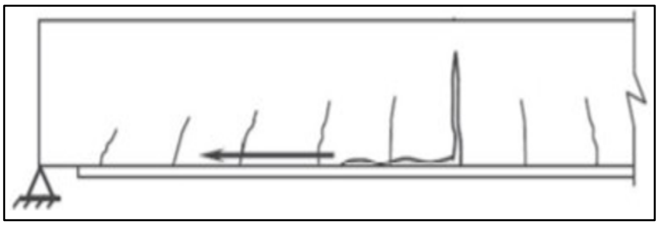

Fig 2 Debonding of FRP Sheet

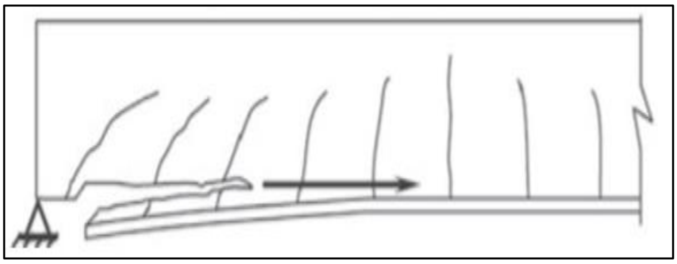

Fig 3 Concrete Cover Separation.

The notable enhancement in flexural capacity through the application of FRP plates has been extensively researched over time. A study by Ritchi (1991) examined 2.75 m long beams under high flexural loads, revealing that a minimum stiffness increase of 17% was achieved, with a maximum increase reaching up to 95%, as determined through deflection analysis. Additionally, the ultimate strength showed an improvement ranging from 40% to 97% compared to conventional RCC beams [4].

In another investigation conducted by Hawileh et al. (2013), various tests were performed on RC beam behavior when different types of glass and carbon fibers were utilized. The findings indicated a significant rise in the ultimate load-bearing capacity for beams subjected to four-point loading conditions. Furthermore, it was observed that ductility at failure exhibited superior performance for glass and hybrid sheets relative to traditional carbon fiber sheets [5].

The published results are illustrated in Figure 4: "B" denotes the control results using an RCC beam; "BC" represents a layer of CFRP; "BG" indicates a layer of GFRP; "BGC" refers to both GFRP and CFRP layers combined; while “BGCG” signifies each type layered together with one another.

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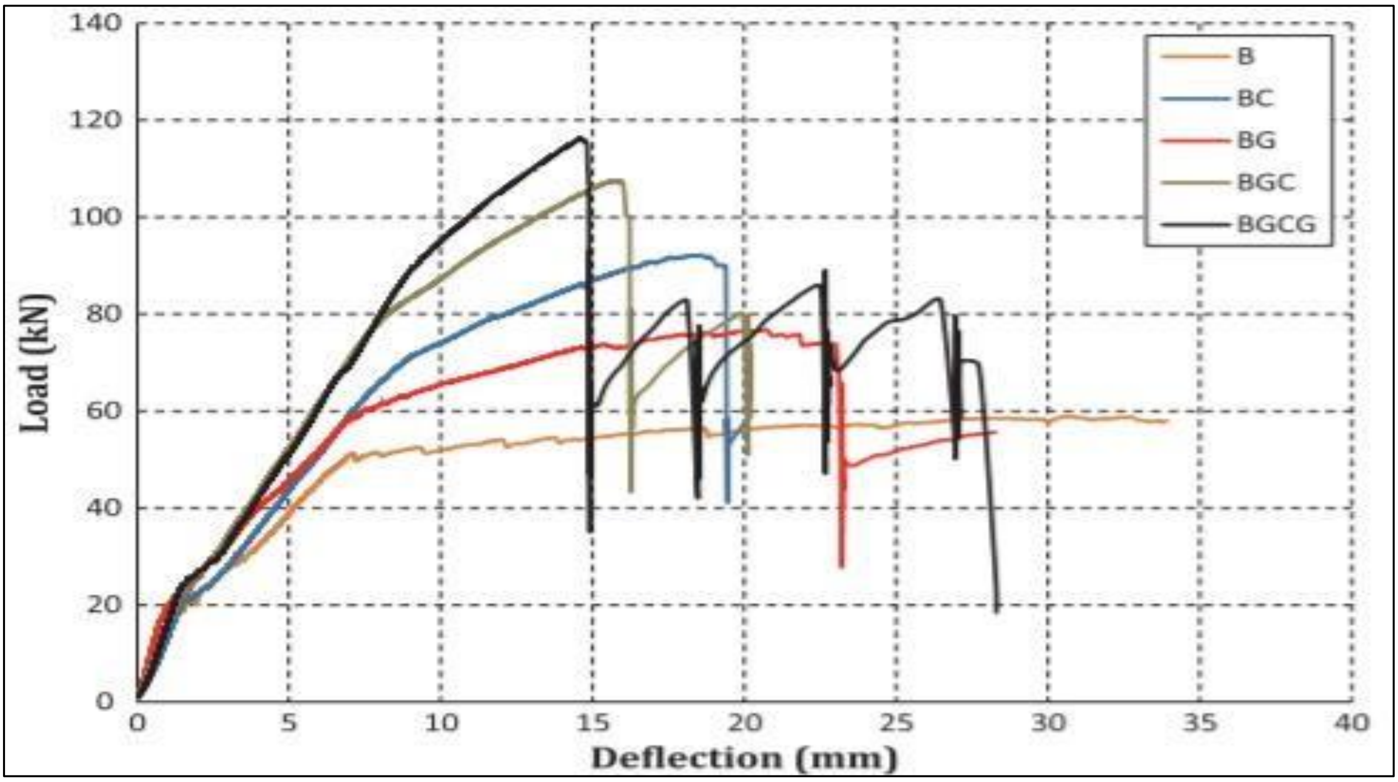

Fig 4 Loads Deflection at Mid Span for a 1.69 m Long Beam Subjected to 4 Point Bending

IV. SHEAR REINFORCEMENT

Concrete experiences shear failure when the principal stresses acting on a critical plane create tension that pulls the material apart. Historically, it has been noted that confining concrete using external methods improves the shear strength of structural elements. This situation presents an opportunity to utilize Fiber Reinforced Polymers (FRPs) in multiple ways (Figure 5).

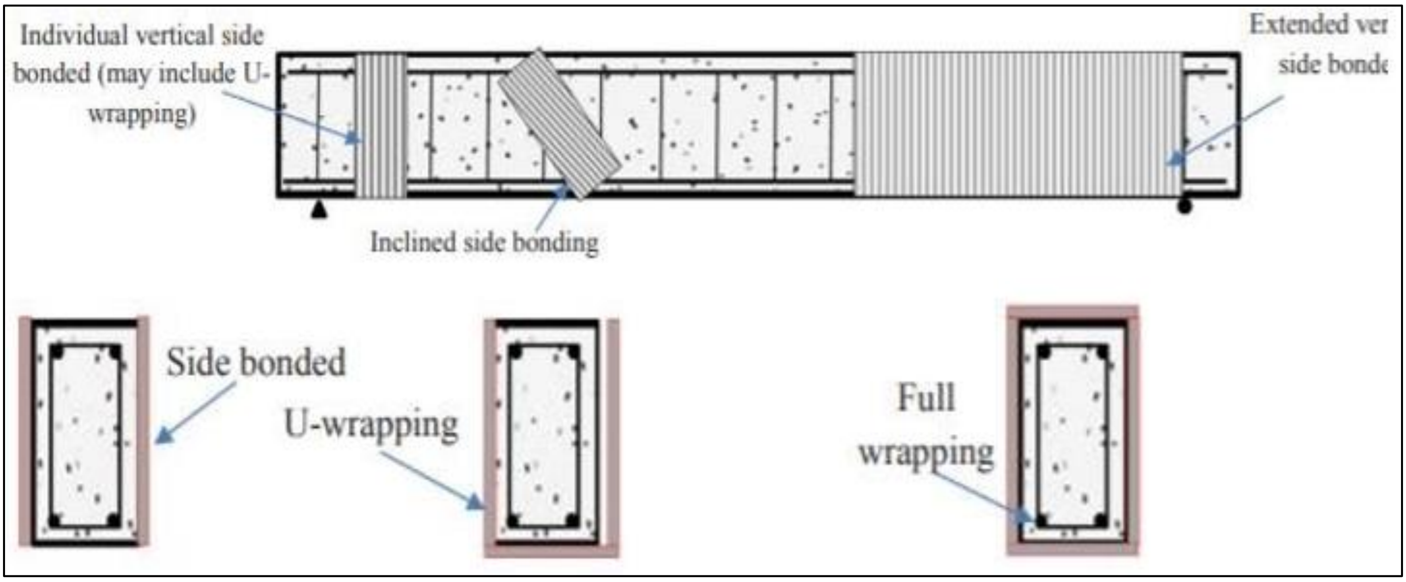

Fig 5 FRP as Shear Reinforcement

They are also used as external stirrups where they are pasted along with web of beam, usually at inclined angle based on the estimation of shear failure plane which will prevent the shear cracks propagation. Chajes et al (1995) reported a 150% increase in shear capacity based on testing of RCC T beams externally bonded with a composite fabric to the web[6].

A lot of work has been done since and it is common practice to retrofit deep beams as above, not only to restore lost shear capacities, but also to increase existing ones due to changes in the use of the floors above.

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V. AXIAL REINFORCEMENT

The initial application of Fiber Reinforced Polymers (FRPs) for retrofitting occurred on bridge piers that, while suffering considerable structural damage, withstood earthquakes. Since that time, extensive research has been conducted to explore the benefits and drawbacks of applying FRPs to axial members. The primary objective is to compress concrete laterally in order to prevent spalling and reduce the risk of buckling in the main reinforcement.

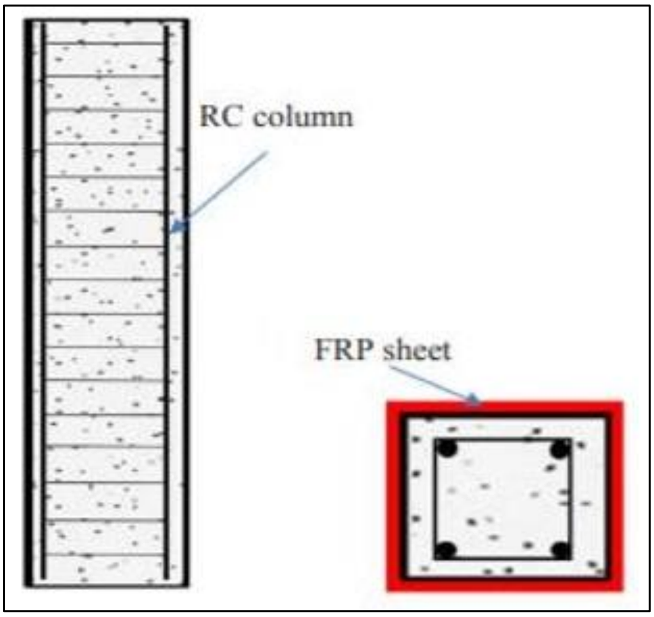

Fig 6 Test of Theory of using Longitudinal FRP Fibres

Siddiqui et al. (2014) examined their hypothesis regarding the application of longitudinal FRP fibers, positioning them along the vertical axis of columns. Their findings indicated that this approach enhanced both the strength and ductility of the columns (see Figure 6). Additionally, they conducted tests using horizontal layers; however, these horizontally arranged FRP layers demonstrated considerably lower effectiveness [7].

VI. RESPONSE TO EARTHQUAKE LOADING

FRPs were initially intended as a method for retrofitting buildings damaged by earthquakes; therefore, it was necessary to assess their performance under cyclic loading conditions. Research conducted by Barnes and Mays in 1992 [8] and later by Papakonstantinou et al. [9] allows us to confidently state that the fatigue characteristics of FRP-reinforced beams closely resemble those of traditional reinforced concrete (RCC). This suggests that the yielding of steel rebar and the debonding of FRP sheets are secondary failure mechanisms rather than primary ones. A conclusion drawn from Sakar et al.'s study in 2014 indicated that CFRP-reinforced beams exhibited enhanced load-bearing capacity, with displacement at failure showing an increase between 112% and 172% compared to their strengthened counterparts [10]. This implies they demonstrated significantly greater ductility before failure along with a high ductility factor. Given these attributes, FRPs represent promising materials for retrofitting applications in areas frequently subjected to seismic activity or long-term cyclic loading conditions such as bridges. In a study conducted by Totuanji et al., published in 2006, they examined the fatigue life of these beams and found improvements: specifically, resistance to fatigue increased by 55%, accompanied by nearly a 20% rise in ultimate loading cycle failure loads [11].

VII. CONCLUSION

Fibre reinforced polymers are an economic and effective method for enhancing the strength properties of existing reinforced concrete erections. As the production manufacturing costs of such materials decline, their growing adoption as substantiated substitutes for steel is slowly catching on. Moreover, as more and more regulations agencies issue design and use guidelines and a resurgence of academic interest in materials of this type, we may consider FRP as an alternative to reach the level of prestige that prestressed concrete currently holds. Due to the property of enhancement of axial, flexural and shear properties along with limiting structural cracks when

Microfibers are appropriate construction material as it enhances the tensile strength of cement concrete matrix. The whole frame of that papers is still rather one of theoretical concepts, and even the result presented from experiments are carefully controlled within given boundary conditions. For it to be more useful as true literature for FRPs, more effort needs to go into better comprehension of these mechanisms of load transfer, some long term durability testing, and reporting of experimental results that attempt to replicate true field conditions and loading conditions.

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