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Performance of concrete beams strengthened with FRP rods: A review

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ABSTRACT: Ductility is a critical property in structural engineering, ensuring that beams can undergo significant deformation before failure, thereby giving plenty of notice before disastrous collapse. This study investigates the ductility properties of constructions that have been reinforced using FRP rods, which are increasingly popular due to their corrosion resistance, superior strength with low mass, and durability. Traditional steel reinforcement has well-documented ductility properties, but FRP bars, due to their brittle nature, pose challenges in achieving the desired ductility levels in structural applications. This research evaluates various factors influencing FRP-reinforced beams' ductility, including the type of FRP material, the hybridization of FRP with other reinforcing materials, and the effect of utilizing fibres in the mixtures to enhance the mechanical characterstics of concrete. Studies have indicated that the ductility of beams can be enhanced using hybrid rebar systems, which integrate steel and fibre reinforced polymer. However, complex and expensive production methods limit their practical application. Using steel bars with FRP bars can significantly incresese seriviceability requiremts such as crack width and deflection, but they also lower corrosion resistance, especially in aggressive environments. The beams' overall ductile behavior is primarily determined by the concrete's characteristics. Fibres greatly increase the mechanical characteristics, toughness, and ductility of the concrete mix, strengthening the bond between bars and the concrete and improving the overall performance of the beam.

Keywords: Concrete beam, Deformation, Ductility, Hybrid Reinforcement

1. INTRODUCTION

Fiber-reinforced polymers (FRP) have been extensively employed as reinforcement in recent years[1]. FRP bars are widely considered a viable replacement of steel bars in reinforcing constructions due to their excellent corrosion resistance[2]. Furthermore, some of the most significant advantages of FRP reinforcement are in buildings with a need for non-metallic reinforcement, such as those containing medical equipment or those requiring a high capacity-to-mass ratio in a member. This material also has the significant benefit of being easy to handle, which minimizes application time and overall cost. Thus, this is quite advantageous, particularly for maintenance or retrofit projects. FRP bars' high strength, low weight, and corrosion resistance make them ideal for usage in a variety of hostile environments, including bridge engineering, maritime, and offshore projects. The US, Japan, Canada, and other nations accounted for the majority of the early development and implementation of FRP bars. But one of the primary issues with FRP bars is their brittleness. When FRP materials fail, they behave in a linearly elastic mode. This makes the concrete structure brittle[3]. Significant efforts have been made to enhance and establish the flexibility of specimens that are reinforced with fiber-reinforced polymer rebars. Three methodologies are employed to enhance ductility:

1.1 MEMBERS REINFORCED WITH DIFFERENT BAR MATERIAL

Traditionally, concrete structures have relied on steel rods for reinforcement. However, FRP (Fiber Reinforced Polymer) reinforcement bars have emerged as an alternative. These bars are often placed on the exterior of the member in tensile areas, while conventional steel rods are typically positioned in the interior of these zones. Utilizing steel rods in beams along with FRP rods can reduce cracking widths and deflections. However, it can also have a detrimental effect on corrosion resistance, especially in coastal or other corrosive environments. Several researchers investigated this concept as follows.

Akiel et al.(2018)[4] presented results from tests of 12 concrete beams with two spans, which were strengthened internally using either BFRP rods only or hybrid(steel and BFRP) rods. Half of the specimens were over-reinforced and the others were low-reinforced. Different ratios of reinforcement with (steel, BFRP) bars were developed to have equivalent positive and negative moment strengths to BFRP-only specimens. Hybrid steel-BFRP specimens had lower service load deflections and crack widths than BFRP-only specimens. However, hybrid-reinforced specimens could deform before failure like BFRP bar-only specimens. The beams strengthened with BFRP bars only varied from elastic behavior. The difference increased as the positive and negative reinforcement ratio decreased. Hybrid steel-BFRP bars reinforced specimens had smaller elastic response deviation than BFRP bars alone.

Lu (2022) [5]focused on comparing the bending performance of concrete specimens and steel-fiber-reinforced concrete (SFRC) members, both reinforced with hybrid (GFRP and steel) rods. The outcomes revealed that specimens with plane concrete had typical trilinear load-deflection curves with distinct turning points at cracking and steel yield. While, steel fiber concrete exhibited enhanced load-deflection responses with more gradual transitions, indicating improved ductility and energy absorption capacity. Concrete beams strengthened with steel fibers and hybridization of (GFRP) glass fiber-reinforced polymer and steel reinforcement rods exhibit superior flexural behavior concerning plain concrete specimens. The utilization of steel fibers enhances crack control, flexural capacity, ductility, and energy absorption, making SFRC beams a more robust option for structural applications requiring high performance.

The structural response of samples of hybrid reinforcement of concrete (FRP-steel bar) was examined by **Wei et al. (2024) [6].** The study aimed to explore the bending response of these hybrid reinforcements of concrete specimens and compared them with those reinforced solely with either FRP or steel bars.

Results illustrated that hybrid reinforcement using(FRP, steel) rods can considerably improve the response. The bending response of beams and the failure mode is comparable, with the concrete in the compression area experiencing crushing after yielding of bars, without FRP bar fracture. This approach optimized the use of both materials, achieving a balance between strength, ductility, and durability. Specimen-reinforced (FRP, and steel) bars illustrated enhanced serviceability requirements and ductility response concerning specimens reinforced by FRP bars. Nevertheless, the durability over an extended period may be compromised due to the use of steel reinforcement.

1.2 HYBRID FRP REBARS

Another approach entails utilizing hybrid FRP rods. Where Pseudo-ductile materials are formed by mixing multiple distinct FRP materials to replicate the elastoplastic characteristics of ordinary steel rebars. Several researchers investigated this concept as follows.

Harris et al. (1998) [7] presented the development and evaluation of a new composite FRP reinforcing rod designed for concrete structures that have a ductile property. This hybrid FRP bar aims to address the limitations of conventional FRP bars, particularly their lack of ductility and linear elastic behavior up to failure. A novel flexible FRP bar has been released, produced by Drexel University. These innovative bars have distinctive bilinear stress-strain relations that enable their application in both new and repaired concrete constructions. Concrete reinforcement made from this material exhibits High tensile strength minimal weight, and corrosion resistance, making it ideal for use in harsh environments. Results illustrated that the new ductile hybrid FRP reinforcing bar is a significant advancement in reinforcement technology for concrete structures. The hybrid bar successfully combines conventional FRP's resilience to corrosion and high tensile capacity with the essential ductility of steel, offering a balanced and robust reinforcement option.

Dong et al.(2019) [8] researched the bending properties of members that were strengthened with FRP bars and grouted within corrugated sleeves. Using corrugated sleeves to grout the FRP bars significantly enhanced the strength of a connection between the reinforcement and concrete matrix. As a result, the displacement and fracture widths of the concrete specimens, which were strengthened with FRP bars, showed a decrease. Nevertheless, this method proved to be quite costly.

Basaran and Donmez (2020) [9] investigated the adhesion strength between steel bars wrapped with GFRP bars and concrete. The primary focus is to measure GFRP wrapping enhancing capacity of the bond strength using pullout tests. This work involved the production of new composite reinforcement using the filament winding method, where resin-impregnated glass fibers were wrapped around the deformed steel bars. The study concludes that GFRP wrapping of steel reinforcement is an effective method to enhance bond strength and reduce slip at the steel-concrete interface. This technique can lead to more durable and ductile concrete structures, particularly in aggressive environmental conditions. While research trials have shown promising results for this approach, its widespread practical application has been hindered by the intricate and costly manufacturing process involved in producing hybrid rebars. The complexity of combining different materials into a single reinforcement bar has presented challenges in terms of material compatibility, production efficiency, and overall cost-effectiveness.

1.3 ENHANCING CONCRETE QUALITY

For the purpose of ensuring that failure occurs as a result of the crushing of concrete rather than bar rupture, the **ACI 440.1R-06 [10]** recommended that FRP-reinforced concrete beams be constructed with an excessive amount of reinforcement. Because of this, the ductility of the beam is contingent upon the properties of the concrete. In order to delay the occurrence of concrete crushing, it is possible to increase the ultimate compressive strain of the concrete. This will result in an increase in the flexural strength of the beams. It is possible to significantly increase the ultimate compressive strain of concrete by incorporating discrete short fibres into the mix of concrete [11-14].

Issa et al. (2011) [15] analyzed how fibers affect beams using GFRP bars as reinforcement for their flexural and ductile properties. The experiment had 7 beams. The examined beams were divided into four classes. All three first sets had two beams (normal and high strength) while the last had one normal. The standard group did not have any internal fibers. The subsequent group tested concrete with internal polypropylene fibers. Three groups tested the effects of introducing internal glass fibers to concrete, while the fourth explored steel fibers. Tests show that GFRP reinforcement for beams offers sufficient flexural strength. The results of the theory from ACI 440 code matched experimental data by 20%. The study indicated that all fiber types increased FRP-reinforced concrete beam ductility.

Zhu et al. (2020) [16] demonstrated the bending behavior of SFRC beams reinforced with FRP bars subjected to repeat load. A bending test was performed on 14 beams measuring (150 × 300 × 2100) mm. The parameters to consider include the bars ratio, kind of reinforcement, the form of steel fibers, concrete strength, volume percentage on beam failure modes, flexural strength, cracking moments, load-deflection curves, deflection, and, strength deterioration. The results indicate two types of failure mechanisms for SFRC members reinforced with FRP bars. The beams' flexural strength declined with more Load cycles at equivalent deflection levels. A higher reinforcement ratio of FRP, increased member strength, and greater steel fibers percentages resulted in higher flexural strength of the beam and less deflection. Moreover, flexural strength test data were simulated to some codes. According to the "(ACI 440.1R-15, CSA S806-12, and GB 50608-2010)" models, the beam flexural strength was underestimated, however, the values obtained from the recommended equivalent force block model were more precise.

Chellapandian et al. (2020) [**17]** macro synthetic structural fibers are examined to enhance the post-cracking and ductility of GFRP bar beams. 18 specimens with and without synthetic under flexure were examined. Samples tested include reinforced beams using steel reinforcement for control, Reinforced concrete beams using GFRP bars in the absence of synthetic fibers, and beams with various amounts of fibers between 0.35% to 1.0% volumes of fibers V_f. The impact of using fiber on: “cracking load, stiffness, and deformability in beams with bb 0.7% and 2.0% longitudinal reinforcement ratios are examined. Experimental data indicate that fibers considerably enhance post-cracking response. Additionally, increasing fiber dose considerably reduced crack widths at service loads. Adding 1% fibers improves the deformability of beams, transforming failure from brittle to ductile with increased pseudo-ductility. The test findings correlated closely with analytical estimations of deflections.

Tan et al. (2022) [18] conducted research on the flexural ductility model for ultra-high-performance concrete (UHPC) beams that were strengthened with fiber-reinforced plastic (FRP) bars. Due to the fact that FRP bars exhibit a linear-elastic behaviour up until the point of failure, they do not fulfill the requirements of the standard definitions of ductility. A new model for assessing flexural ductility in UHPC beams reinforced with FRP bars is proposed in this study, taking into account the distinct properties of both FRP and UHPC. The research indicates that the brittleness of FRP bars can be offset by the higher mechanical qualities of UHPC, resulting in enhanced flexural performance and ductility.

The safety of structures is significantly influenced by ductility. On the one hand, structures that are statically-determinate and have enough ductility can serve as warning signs for an upcoming deterioration. However, adequate ductility might delay local collapse by allowing internal forces in statically indeterminate structures to be redistributed the requirement for applying a single criterion for assessing ductility is a crucial factor in improving ductility in FRP-reinforced beams. At the same time, the ductility of steel reinforcement is defined as the deformation ratio at failure to yielding for steel reinforcement. Certainly, this criterion does not apply to FRP beams that do not show yielding.

2. DUCTILITY EVALUATION

By virtue of the fact that FRP bars possess linear elastic qualities up until the point where they fail, the conventional definition of ductility that is utilised for beams that are reinforced with steel bars does not apply to beams that are reinforced with FRP bars. In order to calculate the ductility performance of concrete reinforced with FRP reinforcement, it is required to develop a new technique and set of measures for ductility. This is due to the fact that the standard definition cannot be directly applied. Over the course of the last twenty years, this issue has been the subject of a great deal of discussion and controversy. Therefore, there are two fundamental approaches that are widely used.

2.1 ENERGY –BASED APPROACH GENERAL GUIDELINES

In this method, beam ductility is the capacity to absorb energy, which is expressed as the ratio of elastic energy to total energy. Naaman and Jeong (1995)[19] have conducted an expression to calculate the ductility index, μE:

$$\mu E = [ET/Eel + 1] \quad (1)$$

The total energy, Et, is determined as the area under the deflection-load curve. Eel, The elastic energy is calculated as the integral of the area under line S up to the intersection point with P failure, as seen in Fig. 1.

The determination of the elastic slope relies on the selection of locations "P1, P2, S1, and S2", as the load-deflection curves of FRP beams not exhibit these clear points. The elastic slope, denoted as S, as proposed by "Naaman and Jeong"[19], serves to measure the magnitude of elastic energy. The descending slopes refer to the incline of the unloading curve at a point where it reaches 80% of its total capacity.

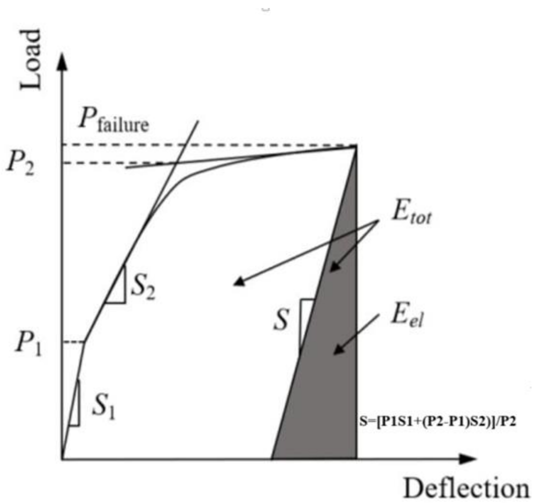

FIGURE 1. - **Ductility index**

2.2 DISPLACEMENT APPROACH

In the beginning, "Jaeger et al." (1997)[20] recommended the implementation of this method. In order to determine a material's ductility, one must first determine the difference in deformability that exists between the ultimate stage and the service stage. The influence of strength as well as the deflection are both taken into consideration.

To measure ductility it is recommended to measure the deflection factor (Cd) and the strength factor (Cs) [19] (or [curvature factor Cc). These properties are defined as the ratio of the load, deformation, and curvature measurements at failure to their corresponding values at a concrete compressive strain of 0.001. This strain level marks the onset of inelastic behavior in concrete. The ductility index (μE) can be calculated using the formula below:

$$\mu_E = C_S * C_d \ \text{ or } \mu_E = C_{S*} C_d \quad (2)$$

$$C_S = \frac{M_u}{M_{\varepsilon=0.001}} \quad (3)$$

$$C_d = \frac{\Delta_u}{\Delta_{\varepsilon=0.001}} \quad (4)$$

$$C_c = \frac{\psi_u}{\psi_{\varepsilon=0.001}} \quad (5)$$

Failure mode affects FRP-reinforced beam ductility/deformability, according to Vijay and Gana Rao (2001)[21]. They showed that GFRP beam deformability depended on: uniform FRP bar elongation against localized steel bar yielding, confinement effect; concrete-bar bond; consistent crack placement and spacing in FRP reinforced concrete; and concrete plastic hinge. FRP-reinforced beam compression failure has higher deformability than tension failure, according to the study. This occurred due to confinement, plastic hinge creation, and compression zone concrete cracking. They also discovered similar deformability and compression failure values for GFRP- and steel-reinforced concrete beams.

Newhook et al. (2011) [22] created a parametric technique for the bending design of FRP bar segments that restricts strain in tension for the FRP bars in service while meeting deformability constraints. The study recommended developing a cross-sectional area based on a maximum tensile strain of 0.002 in FRP bars in service. The study discovered that this permitted strain frequently results in a deformability factor (DF) larger than four. Thus, no deformability check is required.

3. CONCLUSIONS

Previous research on hybrid reinforcement in concrete structures has demonstrated significant potential to enhance the performance and durability of these materials. While traditional steel reinforcement has been the mainstay in the construction industry for decades, hybrid systems that combine steel with other materials, such as fiber-reinforced polymers (FRPs), have emerged as promising alternatives. These hybrid approaches offer a range of benefits, including improved corrosion resistance, enhanced mechanical properties, and increased design flexibility.

1. Impact of Fiber Reinforced Concrete (FRC) FRC significantly enhances the structural performance of concrete beams reinforced with FRP bars. FRC beams had smaller crack widths than plain concrete beams, particularly under service loads.

2. Enhanced Ultimate Concrete Strains: FRC beams exhibited higher ultimate concrete strains compared to plain or regular concrete beams. Design considerations should account for this increased strain capacity to fully leverage the benefits of fiber reinforcement. Fibers have been demonstrated to enhance concrete properties and improve ductility in FRP-reinforced systems.

3. Evaluation of Hybrid Rebar Systems: The research trials showed positive results for the approach of utilizing a hybrid rebar system, but the complex and costly production process of this type of rebar hindered its actual application.

4. Impact of Steel Bars in FRP-Reinforced Beams: Adding steel bars to FRP-reinforced beams can narrow cracks and limit beam deflection, but they can also make the beams less resistant to corrosion in salty or other corrosive environments.

5. Dependency on Concrete qualities: The ductile behavior is mainly dependent on the properties of concretes. Adding fibers to concrete beams reinforced with FRP bars greatly enhances concrete's mechanical properties, toughness, and ductility. This led to improving the ductility and bonding between the bars and concrete.

6. Since there haven't been many studies done, More research is required to investigate FRP-reinforced UHPC beams, hybrid fiber-reinforced polymer (HFRP) or steel-fiber composite bars (SFCB), pre-stressed FRP-reinforced concrete beam's, and adding different types of fibers to enhance the beams ability to withstand cracks and improving the flexural capacity.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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