A Comprehensive Review of Glass Fiber Reinforced Polymer (GFRP) Bars as Reinforcement in Concrete Beams: Flexural Behavior, Serviceability and Design Provision

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***Abstract*—The corrosion of steel reinforcement is highlighted as one of the most widespread and economically damaging durability issues facing reinforced concrete structures globally. GFRP (Glass Fiber Reinforced Polymer) bars are proposed as a viable alternative, possessing properties such as corrosion resistance, a high tensile strength-to-weight ratio and non-magnetic characteristics. This paper offers a comprehensive review of GFRP bar utilization as internal reinforcement in concrete beams, drawing upon experimental, analytical, and numerical studies from the last decade. It covers GFRP composite mechanical properties, manufacturing techniques, flexural and shear behavior, bond properties, and serviceability (deflection and crack). Durability under harsh conditions, finite element modelling and simulation and the application of machine learning also receive attention. A significant finding is that GFRP-reinforced concrete beams deflect 2.0 to 2.5 times more than steel-reinforced beams under service loads due to GFRP bars' lower modulus of elasticity (40 - 60 GPa) and linear-elastic behavior. Existing design provisions, notably ACI 440.1R-15 and ACI 440.11-22, are reported to underestimate service-level deflections by 15 - 25%, especially in under-reinforced and slender beams. Identified research gaps include the absence of integrated frameworks combining experimental, analytical, and numerical methods for equivalent strength design, the need to validate design provisions for specific regions and the requirement for improved serviceability prediction models. The research advocates for GFRP reinforcement in corrosion-prone structures, stressing the importance of serviceability driven design and code enhancements.**

***Index Terms*—Glass Fiber Reinforced Polymer (GFRP), reinforced concrete beams, flexural behavior, serviceability, bond-slip, durability, finite element analysis, machine learning, design codes.**

I. INTRODUCTION

RCC has been the go-to choose for the primary structural member when building the modern Infrastructure of civil engineering, it' s due to the combined action performed by Concrete and Steel reinforcement when load acts on it. The high resistance to compressive strength and excellent tensile strength offered by the steel reinforcements and High Yield Strength Deformed (HYSD) bars are researched when resisting the load in different scenarios which show the amazing bond to transfer the load between concrete and steel.

Though steel reinforcement is advantageous and possesses many good qualities, it has one failing quality. That is corrosion. This is a fatal flaw compromising the long-term performance of RCC structures as when the steel develops corrosion the iron oxide produced is several orders of magnitude higher than its steel volume giving rise to stress which tends to crack and spall the concrete cover. Thus, deterioration progresses leading to loss of bond and cross section resulting in premature failure of structure. Billions of dollars are spent annually repairing or replacing thousands of bridges, parking garages, marine structures, and buildings in aggressive environment.

The limitations of steel reinforcement in a corrosive environment have inspired research among researchers and design engineers for alternative reinforcement materials that can be more durable yet as cost effective. FRP composites offer the best promise as an alternative reinforcement material to plain carbon steel bars for concrete with Glass Fiber Reinforced Polymer (GFRP) bars offering the greatest balance between cost, mechanical properties, and corrosion resistance [1].

GFRP bars are made of continuous glass fibers distributed in a polymer resin matrix which is usually epoxy, vinyl ester or polyester. GFRP composites can be made by either pultrusion manufacturing technology, filament winding, resin transfer molding, or hand layup. However, for a GFRP bar with a constant cross section, it is common to use the pultrusion manufacturing technology because it allows highest volume fraction, best quality control, and lowest cost [1].

The objectives of this review paper were:

- To compile the most current information about the structural behavior of GFRP-reinforced concrete beams obtained from full-scale experimental tests, analytical models, and finite element analyses.
- To evaluate the robustness of existing design provisions and strength prediction models.
- To identify areas needing further study and outline challenges about design provisions
- To propose recommendations for future work and design applications.

II. MANUFACTURING TECHNOLOGIES AND MATERIAL PROPERTIES OF GFRP COMPOSITES

A. Glass Fibers and Carbon Fibers

Glass fibers are classified largely based on their chemical composition and different designations are known including A-Glass (alkali-lime), C-Glass (high boron oxide chemical resistant), D-Glass (Borosilicate low dielectric constant), E-Glass (alumina-borosilicate resistant the electrical current passed through. This class is primarily used for the reinforcement of polyester resins to compose GFRP bars), AR-Glass (alkali resistant), R-Glass (high mechanical properties) and finally S-Glass (one of the strongest in tensile strength). E-Glass fiberglass typically experiences a 2415-3450 MPa tensile strength whereas S-glass reaches 4890 MPa. Finally in relation to modulus, glass fibers achieve a range between only 68.9-85.5 GPa in comparison to the steel modulus of 200 GPa [1].

B. Manufacturing Approaches

There are several different composites manufacturing and fabrication processes commonly used, all have their advantages and limitations some examples are.

1. Pultrusion is like hot extrusion of Aluminum. Fibers are puller through a heated diet which produces cross sectional profiles (bars rods etc.) to a specific dimension. The fibers are first impregnated with a resin to bond before becoming fixed by the die and, hence, forming the desired product. This is used producing reinforcements and offers excellent quality control due to being completely automated and cost effective [1].
2. Filament winding involves continuous fiber being wound onto a rapidly spinning mandrel. Typically, carbon fibers are pre-impregnated with a resin to maintain them in place before the filaments begin the wrap around in an arrangement specific to the desired design. Filaments can be laid on specific patterns in specific directions and numbers producing products that can have very high strengths in comparison to weight such as pipes and pressure vessels. Once again due to automation, costs are lowered to a certain extent.
3. Resin Transfer Molding is a closed mold technique to inject the low viscosity resin over the reinforcement placed in molds for medium production of complex shapes with two good, finished surfaces.
4. Hand Lay-Up is the simplest and eldest technique of resin application in reinforcement manually. Requires small equipment but high labor is required. Suited low volume production of larger structures.
5. Injection Molding is suited for large production of complex parts using a thermoplastic material by injecting under high pressure into Molds. Gives a productive and high initial cost as well.

C. Mechanical Properties of GFRP Bars

The mechanical properties of GFRP bars are different from those of steel reinforcement bars due to the design consideration should be taken as follows,

1. Tensile Strength:
Glass fibers have an enormous tensile strength in nature about 2415 MPa for E - Glass to 4890 MPa for S-Glass with embedding into polymer the GFRP achieve a tensile strength within 400 - 1200 MPa this is compared to or greater than those HYSD bars (415 - 500 MPa) [1].

2. Modulus of Elasticity:
The modulus of elasticity of GFRP ranges from 40 to 55 GPa, i.e., it is about 1/4 to 1/3 of the density (200 GPa) of steel. This affects serviceability requirements (deflection, crack width) greatly.

3. Stress-Strain Behavior:
Unlike steel, GFRP behaves linear elastically with no plasticity until failure occurs. Moreover, GFRP composites have low elongation at break of 1.5 % to 3.5 %, lower than those encountered in the ductile failure typical for steel reinforcement [1].

4. Compressive Strength:
FRP rebars exhibit an anisotropic nature and therefore fibers are designed to be better oriented to resist tensile than compressive force. Test results showed GFRP bars range in compressive strength from 48 to 54 % of tensile strength, which agrees with the result in literature (30 – 50 %).

5. Density:
GFRP has a low density of ~ 2,000 kg/m³) which is approximately 1/4 of that of steel (approx. 7,850 kg/m³). Such a big saving of the density will result in lower loads, transportation cost and easy of handling.

D. Thermal and Physical Properties
GFRP bars have low thermal conductivity (Around 1.3 W/mK), eliminating thermal bridging effects. The coefficient of thermal expansion (CTE) of GFRP in the longitudinal direction ($6\text{-}10\times10^{-6}$/°C) is comparable to that of concrete ($10\text{-}12\times10^{-6}$/°C), reducing thermal incompatibility issues. The density of GFRP (1.9 - 2.2 g/cm³) is nearly one-fourth of that of steel (7.85g/cm³), leading to lighter reinforcements which reduce costs during transportation and handling.

E. Environmental Durability
One of the great advantages of using GFRP bars as concrete reinforcement is their immunity to electrochemical corrosion. Unlike steel GFRP does not rust in chloride rich and high moisture environment and under carbonation effect. Neither the glass fibers nor the polymer matrices are affected by alkalinity but can be eroded by high pH concrete pore solutions (typically 12.5 to 13.5). However, modern GFRP bars are manufactured with special resin systems and surface treatments to get over this problem successfully without any harm on the GFRP bars properties as reinforcement. Resistance to saltwater, chemical attacks, and freeze-thaw cycles of a GFRP composite are an important advantage in applications such as marine structures, bridge decks, and chemical plants [1].

III. FLEXURAL BEHAVIOUR OF GFRP-REINFORCED CONCRETE BEAMS

A. Comparative Studies with Steel Reinforcement
Numerous experimental studies investigate GFRP Reinforced concrete beams under flexure and correlate its behavior with steel Reinforced concrete.
Mohammed and Salih [2] conducted an experimental study, testing eight reinforced concrete beams of 200 × 250 × 2400 mm dimensions with GFRP and ordinary steel bars under central two points loading with a concrete compressive strength of 22 and 45 MPa, respectively. The steel reinforcement 2 Φ 10 mm was replaced by GFRP bars with equivalent cross-sectional area, where bar sizes such as Φ8, Φ10, Φ12 mm were used for GFRP bars as steel and polypropylene fibers were excluded in the manufacturing of concrete. Beams reinforced by GFRP bars had higher deflection and showed higher load capacities when compared to similar ones reinforced with steel bars, with earlier first crack occurring in the GFRP reinforced beams with subsequently a higher crack density than the steel reinforced ones. As the concrete compressive strength was 22 MPa the GFRP reinforced beams showed reduction in the load ranging between 10 to 22.8 % when correlated to the steel reinforced beams, whereas at 45 MPa the reduction ranged between 16.6 to 36.6 %. The effect of GFRP bar diameter and longitudinal reinforcement ratio did not have any effects on the compression strength and split tension strength as it had marginal results on the overall performance of each beam.
Elbawab et al. [3] studied the flexural behavior and performance of GFRP and BFRP reinforced concrete

and Hybrid GFRP Steel reinforced concrete beams. Experiments on 12 beams were done, subjected to test at three-point bending. GFRP reinforced beams had max. 8 % higher capacity and deflected 38 % less till failure whereas BFRP RC beams could take 12 % more load and deflect 58% less till failure in comparison with steel RC beams. The hybrids helped in increasing the performance of both loads as well as deflection capacity (7 % - 17 % more load, 11 % - 58 % deflected less than steel RC beams). The GFRP reinforced beams mostly failed by rupture of bar; BFRP re-bars mostly by de-bonding and concrete crushing.

B. Over Reinforced and Under-Reinforced

The design methodology for GFRP Reinforced concrete beams is not matching that of concrete beams reinforced with conventional bars. In case of steel bars most of times section is designed as under-reinforced resulting in yielding of steel preceding concrete crushing thereby ensuring ductility and appearance of warning signs before collapse whereas GFRP reinforced beams are reinforced such that no yielding appears thus designed such that failure mode is by crushing of concrete not yielding and is therefore designed as over-reinforced system.

Saleh, Sheikh, Remennikov and Basu [8] used LS-DYNA to simulate the flexural of GFRP-RC beams subject to monotonic loads. Concrete compressive beam, reinforcement ratio, and shear span-to-effective ratio engaged in the parametric study. Ratio of reinforcement bar varied from 0.5 % to 3 %. Compressive strength of concrete was set up from 30 to 60 MPa. While ratio of shear-span-to-effective depth ratio was increased from 4 to 8. An increase in reinforcement ratio could change the failure mode from rupture of GFRP bars to crushing of concrete. If reinforcement ratio rose from 0.5 % to 1 %, the load-carrying capacity of the beam could increase by 67 % and the energy absorption capacity is increased by 48 %. Comparing to this, increasing reinforcement ratio from 2.5 % to 3 % only provided 4 % increase in the load capacity of over-reinforced beams. So, it is not a wise decision to increase too much reinforcement ratio than the optimum amount. For over-reinforced beams, increase the ultimate load and energy by 40 % and 64 % is expected if we change the concrete compressive strength from 30 MPa to 60 MPa.

C. Hybrid GFRP-Steel Reinforcement

Hybrid structures which are consisting of GFRP, and steel bars are developed to take advantages of both materials.

In Nouri, et al., [4], they evaluated the flexural behaviour of RC beams with hybrid steel/GFRP reinforcement by experimental tests and by Explainable Machine Learning methods. The research results suggested that the strength performance of RC beams with hybrid reinforcement was improved over steel reinforcement ones, when mechanical reinforcing index exceeded 0.6 %. The average ratio of theoretical/experimental results equalled 0.96 with a deviation coefficient of 0.07 was obtained where the transformed section method was selected to estimate its cracked moment, which produced the most accurate results comparing the rest of the three options. It is noted that both the initial stiffness and of the stiffness upon crack decreased when increasing the area ration of Af/As, whilst an increase in the post - yield stiffness was seen during the process attributed to the contribution of GFRP bars. A ductility index which involved energy absorption for hybrid beams was also developed.

Shi, et al., [7] presented an experimental research project to discuss various flexural behaviour of steel fibre reinforced and hybrid FRP as well as steel bars reinforced Recycled Aggregate concrete beam. The result obtained suggested an 8.1 % gain could be obtained overusing one row hybrid reinforcing bars alone (only hybrid reinforcing bar near neutral and the bar for BFRP at the tension face) by adding two rows of hybrid reinforcing bars.

An increase of in the crack and ultimate loads by some 18.2 % and 16.3 % respectively would be noted by adding 1 % steel fibre to improve reduction of crack width by 21.1 %. 100 % replacement in the cases of RCAS suggested that reduction of load capacity from hybrid reinforcing bars alone in the test could obtain 7.1 %.

D. Flexural behavior of Hybrid GFRP-Steel Reinforcement

From flexural behavior reviews can be found:

1. The beams showed a ductile (bilinear) load-deflection response with the glass RC beams having a higher load capacity (+ 8 to 12 % than Steel RC)

but having less deflection (- 38 to - 58%) and absorbed less energy (41 to 59% of steel RC).
2. The failure modes are of steel-RC beams fail by yielding steel (tension controlled). GFRP-RC beams designed to be over reinforced fail by the crushing of concrete (compression-controlled). While, for a certain ratio of reinforcement, it is balanced failure occurred.
3. This leads to a change in the mode of failure from bar rupture to concrete crushing but a 67 % increase in the predicted ultimate load when ρ is increased 0.5 % to 1 %.
4. The over-reinforced beams concrete compressive strength (from 30 to 60 MPa) has greater effect than the under-reinforced beams at 40 % enhancement.
5. Hybrid reinforcement (Steel + GFRP) provides a mixed response with load capacity larger than steel-only (7 – 17 %) and improved ductility over GFRP only.

IV. SHEAR BEHAVIOUR OF GFRP-REINFORCED CONCRETE BEAMS

A. Concrete Shear Contribution

The concrete shear contribution in sections reinforced with GFRP bars is lower when compared to those reinforced with steel, this results from the reduction of dowel action of GFRP bars unlike steel bars. ACI committee 440.1R-15 mentions this reduction and provides provisions for calculation of concrete shear strength of GFRP reinforced sections. Due to these facts, more shear reinforcement may be required in beams reinforced with GFRP bars compared to steel reinforced beams.

B. GFRP-Steel Hybrid Stirrups

He et al. [5] conducted experimental research into the shear performance of RC beams reinforced with GFRP and steel hybrid stirrups. Nine reinforced beams containing hybrid stirrups and one reinforced beam containing conventional steel stirrups were tested under four-point loading. Results from these tests mentioned that hybrid stirrup reinforced concrete beams in case of shear compression failure mode had a ductile type of failure while conventional RC beams in comparison experience brittle type of failure due to shear tension and diagonal tension. Increasing concrete strength and stirrup ratio increased strength in shear of these beams while increasing shear span ratio resulted in shear strength reduction. Also, comparison between conventional steel stirrup reinforced beams and GFRP steel hybrid stirrup reinforced concrete beams indicate that, in comparison with steel ones, later had 10 % more shear strength and 22 % more deflection at shear corresponding strength. Machine learning algorithms such as decision tree models like random forest (RF), AdaBoost, gradient boosting regression tree (GBRT) and extreme gradient boosting (XGBoost) were used for prediction of the shear strength and provided accurate results in accordance with experiments carried out. GBRT delivered the best results with R^2 for validation of 0.97. Based on the studies of failure modes, the ultimate shear capacity was estimated using the ACI 440.1R-15, CSASC002 and FIB bulletin 80 models, all of which made sufficiently accurate predictions. The proposed shear capacity model has been shown to give conservative predictions in cases where shear tension and diagonal tension shear failure occur.

C. GFRP Stirrups

Li et al. [29] Experimental investigation & theoretical analysis on shear behavior of RC beams reinforced with GFRP stirrups was done. They observed three shear failure modes: shear compression, diagonal compression & diagonal tension, akin to conventional RC beams. Increasing shear span ratio and stirrup spacing led to decrease in shear capacity. Maximum strain in GFRP stirrups reached 0.008, exceeding ACI code limit of 0.004, indicating code limits are conservative. Thus, they suggested modified formula for determining allowable tensile strain of FRP stirrups.

D. Shear Behavior of Circular Members

Chen et al. [28] Experimental research work to study the shear behavior of new forms of GFRP stirrup & GFRP bar-reinforced circular concrete members was done. GFRP grid spiral reinforced concrete cylinders, a new form was discovered & they found shear strength 16.2 % more and failure mode from shear tension to flexure compression compared to GFRP hoop reinforced concrete cylinders in which the stirrup reinforcement ratio was increased from 0.32 % - 0.72 % where shear strength increased 26.0 %.

V. BOND BEHAVIOR BETWEEN GFRP BARS AND CONCRETE

The bond behavior between GFRP bars and concrete is crucial for serviceability, cracking behavior, and ultimate capacity of GFRP reinforced concrete members. Compared to steel, GFRP has anisotropic, non-homogeneous and elastic behavior thereby demonstrating a dissimilar bond behavior.

Bai, Xue, and Luo [12] studied via experimentation and FE method, the bond behavior between GFRP bars and RAC. Bond strength was inversely proportional to RA replacement ratio; it declined by 17 % in 100 % RA replacement compared to NAC. Bond strength and RAC strength showed proportional relationship, but strength growth slowed after C35 due to a tendency in failure mode from pull out to splitting. Bond strength was also directly proportional to cover thickness but weakened after bond exceeded 40 mm.

The bond of the GFRP bars to marine concrete sustained to the loads investigated by Zhou et al. [13]. Bond strength decreased with increased sustained load. Reductions 9.93, 16.04 and 21.54 %, for 0.25, 0.45 and 0.65 Pu, respectively. The Sustained load had a negative influence of the bond stiffness and bond toughness. The presence of stirrups increased bond strength by a mere 1.8 %, while it increased to 13.3 % in the presence of steel bars, this is because of the lower rib heights and weaker engagement of GFRP ribs to concrete.

A. Bond Durability in Aggressive Environments

The bond durability of GFRP bars concrete prepared with seawater in the exposure of seawater at controlled temperatures of 20°C, 40°C, 60°C for 2 years was evaluated respectively by Nepomuceno, Sena-Cruz, Lourenco, and Pereira [14]. Transverse shear strength decreased to 22.7 % after being reduced in 60°C for 2 years. The seawater unconditioned concrete reduced bond strength by approximately 43 % then, while the concrete specimens, seasoned in seawater for two years have reduced by only 13%.

Sun et al. [15] studied the bond durability of GFRP reinforcement in HVFA-SCC prepared by seashore and sea sand. The bond strength decreased with time under sustain loads, greater the load level greater the decrease occurred in bond strength. The bond durability performance of greater diameter bars (13 mm) was better than the small (19 mm). Predictions by Fib Bulletin 40 were estimated bond retention after 50 years to be 96.7 % for natural G13, 70.4 % from seawater for G13; 71.4 % from natural G19 and 52.2 % from seawater in G19.

B. Bond-Slip Modelling and Machine Learning

A neural network-based approach for modelling GFRP-concrete bond-slip behavior was proposed by Devaraj, Olofinjana and Gerber [16]. The approach combined experimentation with FEA and neural networks. Training with a feedforward neural network (FFNN) featured 5 inputs, 12 hidden layers and 1 output layer i.e., 5-12-1 architecture on actual experimental data based on varying bar diameters (ranging from 8 mm to 16 mm) and varied concrete strengths (ranging from 18 MPa to 50 MPa). An accuracy of $R^2 = 0.99$ for training and 0.88 with testing was received using the proposed bond-slip model through ANN to predict the actual experimental data representing the complete bond-slip relationship for GFRP bars in concrete compared to conventional mBPE model with a low accuracy value of ($R^2 = 0.72$). It was seen that the developed bond-slip relationship proposed using ANN gave impressive results and was implemented in FEM models used in FEA utilizing the COMBIN39 spring element which delivered an accuracy value of R^2 on average of 0.93 compared to the experimental results.

It allows to carry out bond-slip behavior between the FRP reinforcement and concrete into FEM models and is presented by Torres, Vilanova, Llorens and Baena [17]. Bond behavior between the reinforcement and the concrete is divided into friction and actual mechanic behavior. In such a case, friction is modelled by surface-to-surface interaction while the mechanical part is modelled through connector element. The method has shown efficient results against the numerical values which has resulted in good accuracy for load deformation curves, stress distribution in rebar, crack pattern, strain distribution over concrete tensile members under FRP rebars as tension component which was compared to actual experimental results.

VI. SERVICEABILITY PERFORMANCE: DEFLECTION AND CRACK CONTROL

A. Deflection Behavior

The governing design criterion, especially in GFRP-RC flexural members, is the serviceability criteria because FRP has a lower modulus of elasticity hence causes larger deformations and deflections in case of RC beam flexure under similar loading scenario as with steel RC beams.

A systematic review by Rafani et al. [9] analyses over 20 peer reviewed documents from 2012 to 2023 on deflection of GFRP-RC beams. GFRP-RC beams suffer much greater (average 2 - 2.5 times) deflections at service load compared with steel-RC beams, attributed to GFRP's lower modulus of elasticity (40 - 60 GPa versus 200 GPa of steel). Current design provisions based on ACI 440.1R-15 underestimated the service deflections of up to 15 – 25 % for small under-reinforced beams and/or slender beams; and the use of ACI 440.11-22 resulted to 18 % less precise deflection prediction. With inclusion of tension stiffening (Analytical models used), deflection prediction was within a deviation of less than ± 10 %. Important influential parameters for GFRP-RC beams are: The reinforcement ratio increases with deflection (increasing ρf decreases 15 % - 30 % deflection increase), beam depth (increasing depth leads to lowered deflection), span-to-depth ratio, concrete strength, and number of reinforcement layers.

Ribbed FRP Reinforced concrete beams were tested by Shabani et al. [11] who focused on flexural and serviceability behavior. The beams with 0.5 % addition of Macro-synthetic fibers showed an improvement of ultimate moment capacity by up to 19.3 %, while the mid-span deflection at service-load level (0.33 Mn) was reduced up to 12 %. Fibers also led to 32.8 % reduction of the kb coefficient (coefficient based on bond) when concrete strengthened using fibers, increasing the number of cracks and decreasing crack width.

B. Crack Width

Crack width is proportional to the stain of the reinforcement. Based on the fact that GFRP bars experienced higher strains than steel bars due to their lower modulus of elasticity at the same stresses, at the same amount of opening (crack width), the cracks of GFRP reinforced members usually appear wider and are more widely spaced than those in steel reinforced members Crack width is proportional to the strain of the reinforcement. Since GFRP bars undergo greater strains than steel bars under equivalent stress because of their reduced modulus of elasticity, the cracks in GFRP reinforced segments tend to be wider and spaced further apart than those found in steel reinforced parts.

Hu et al. [18] explored the influence of bond performance on flexural crack width of GFRP bar UHPC beams using theoretical modelling and finite element analysis. Crack width decreased with increasing bond stiffness. This effect was substantial when bond stiffness was less than 10 MPa/mm. Both bond strength and bond damage displacement had negligible effect on crack width. A trilinear model was proposed to represent the variation of crack width with bond stiffness.

The impact of bond performance on flexural crack width in GFRP bar-UHPC beams was studied by Hu et al. [18] using theoretical modelling and Finite Element Analysis based on experiments of concrete beams reinforced with GFRP-bars. Crack width decreased as bond stiffness increased; effect substantial when bond stiffness < 10 MPa/mm; bond strength & crack damage displacement had negligible effect on crack width. Crack width decreases with increased bond stiffness; impact substantial when bond stiffness < 10 MPa/mm; bond strength and bond damage displacement had negligent effect on the variation in fracture gap width.

C. Fiber Addition for Serviceability Improvement:

Fiber Addition for Serviceability Improvement Crack width is proportional to the strain experienced by the reinforcement. Given that GFRP bars exhibit higher strains than steel bars under equivalent stress due to their lower modulus of elasticity, the cracks in GFRP reinforced components tend to be wider and spaced further apart than those found in steel reinforced structures. The crack width is proportional to the strain in the reinforcement. Since GFRP bars experience higher strains than steel bars at the same stress levels due to their lower modulus of elasticity, cracks in GFRP reinforced members typically appear wider and more widely spaced than those in steel reinforced counterparts. The crack width is proportional to the strain in the reinforcement. As GFRP bars exhibit higher strains than steel bars under the same stress, due to their lower elastic modulus, cracks in GFRP reinforced members often appear wider and more widely spaced than those in steel reinforced members. Crack width is linked to the strain in reinforcement. GFRP bars endure higher strain than steel bars under identical stress (lower modulus of elasticity). Consequently, cracks in GFRP reinforced members typically present wider and more widely spaced than those in the steel reinforced counterparts.

Hu et al. [18] investigated the effect of bond performance on flexural crack width of GFRP bar UHPC beams using theoretical modelling and finite element analysis. Crack width decreased with increasing bond stiffness; the effect was significant when bond stiffness < 10 MPa/mm. Bond strength and bond damage displacement had negligible effect on crack width. A trilinear model was proposed for crack width variation with bond stiffness. Hu et al. [18] studied the effect of bond performance on flexural crack width of GFRP bar UHPC beams through theoretical models & Finite Element Analysis. Bond stiffness led to a decrease in the crack width, & when the bond stiffness was below 10 MPa/mm, this effect was substantial. Bond strength and bond damage displacement held negligible effect on the crack width. Proposed was a trilinear model to represent the variation of the crack width with the bond stiffness. In a study by Hu et al. [18], the effect of bond performance on the flexural crack width of GFRP bar UHPC beams was researched using theoretical modelling and finite element analysis. The crack width was found to decrease with increasing bond stiffness; the effect was significant only when bond stiffness was less than 10 MPa/mm. Bond strength and bond damage displacement had negligible effect on the crack width variation. Lastly, they proposed a trilinear model to represent crack width's variation with bond stiffness. Hu et al. [18] carried out a study concerning the effects of bond performance
on flexural crack width of the GFRP bar UHPC beams. For this they used theoretical modelling and Finite Element Analysis. As bonding stiffness increased, crack width decreased & the effect was considerable when bond stiffness was below 10 MPa/mm. Both bond strength & bond damage displacement had negligible impact on crack width & crack damage displacement. They postulated the idea of a trilinear model which modelled the variation of the crack width by the bond stiffness that was measured in.

Balaji and Prakash [10] have explored the influence of discrete fiber (polyolefin and hybrid steel-polyolefin) on the serviceability response of GFRP-RC beams subjected to flexure. The hybrid fibers consisting of 0.5 % steel fiber and 0.5 % Polyolefin fiber resulted in noticeable escalation of stiffness after cracking (64 % drop in crack width and 55 % reduction in displacement under 15 kN loading compared to Control). Concrete failure strain is increased and hence the mode of concrete crushing is switched from direct to GFRP bar rupture. A novel empirical modification factor is proposed for ACI 440.1R-15 equation used for crack width and deflection prediction by incorporating fibers.

VII. DURABILITY AND LONG-TERM PERFORMANCE

A. Environmental Effects

Rolland et al. [19] have investigated the response of GFRP reinforcing bars exposed to accelerating aging tests. The bars subjected to direct and indirect immersion in alkaline solution with a pH of 13.5 at 20 °C, 40 °C and 60 °C for up to 240 days were identified based on comparison of both methods. Under direct immersion up to 60 °C for 240 days significant decrease to the point of 42 % decrease in residual tensile strength was depicted, with indirect immersion showed less decrease. The activation energy value obtained using an Arrnhenius plot showed after 20 °C for 2.5 years that there was decreased bar life expectancy, resulting after 40 % loss of strength under indirect immersion conditions on prediction in accordance to only a few 6°C at more than 100 years at only a marginal 20 % loss.

Mazzu and Dalfre [20], researchers who have worked for some time on FRP composite materials looked into the chloride exposure of steel and GFRP reinforced concrete beams in the year 2025 by taking use of the accelerated conditioning protocols of ACI 440.9R which basically accelerates the effect in an short amount of time using different temperatures, pressures and the such so as to get results early and predict the changes that will take place. Concrete beams having chloride exposure produced a detriment of 12 % in the load bearing capacity, which was 10 % in case of some beams. Such reduction was attributed to steel reinforcement corrosion and respectively water intake by GFRP. Failure occurred by concrete crushing followed by tensile rupture of GFRP, whereas a steel reinforced column would exhibit failure by steel yield followed by concrete crushing under same conditions.

B. Bond Durability of GFRP bond against Marine water

Long term durability by means of testing the retention of bond strength of newly designed GFRP composite bars in a few aquatic environments for 25, 40 and 60°C temperatures with ageing from 0, 30, 60 to 90, 120 and 180 days with a certain type of concrete, viz and unsaturated polyester resin concrete or UPC was tested by Li, Cao et.al [21], an active research group focusing on the use of modern materials in civil engineering application. It was established by their experiments that bond strength of GFRP reduced as the temperature and exposure time to increase to some extent and that the initial rise of bond strength caused by GFRP expansion at higher temperatures for some time actually is the reason an improvement of bond strength has appeared by 3 to as high as 12 % under 25 and 40 °C. It was found a bond strength of 92.2 % was retain by samples aged 180 days at 60 °C. Due to prolonged exposure at high temperature in adverse environment, the physical properties of GFRP degrade. This in combination with the effects that water from water has on concrete leads to a combined degradation. The bond strength between UPC and GFPR rebar decreases with the rise of temperature and aging time of the aquatic system up to 180 days at most temperatures.

Ahmed, Tabatabaiean [22] reviewed bond behavior of BFRP bars embedded in concrete in harsh conditions. With increased temperature, bond strength decreased for FRP bars to 80 - 90 % of value for ambient conditions at 300 °C compared to 38 % reduction for steel. The most influencing factor of BFRP deterioration in the surrounding concrete is alkalinity. This can be countered either by concrete having alkalinity below the specified limit in standards or through the concrete cover' s chemical composition which has increased amount of silica fumes for mitigating the attack on bar surface. Arrhenius relationship is adopted from FRP handbook models and has predicted long term performance. However, these models do not consider bond degradation caused by temperature variation. In general, it is predicted that depending on resin type and climate condition bond retention is between 47 – 93 % over 50 years.

C. Long term field performance

Cores from real life bridge were tested for bond and found 98 % bond retention. This was 17 years of service, indicating good long-term performance from FRP. Its predicted long-term performance for real use should not rely on current database. As it does not specify long duration between the testing and installing of the element and ambient conditions such as temperature fluctuations.

VIII. FINITE ELEMENT METHOD MODEL FOR FRP BEAMS

A. Modelling approaches and Validation:

GFRP reinforced beams can be accurately analyzed in simulation software. Researchers like [10] can carry out different levels of analysis through the analysis software used these include. The material behavior and boundary conditions can be modelled to give the best prediction of how the beam acts and behaves this can be carried out.

Sumer and Oztemel [23] explored impact of GFRP bars on flexural strength utilizing CDP model in ABAQUS. CDP parameters simulated concrete: Ψ=31, ε=0.1, fb0/fc0=1.16, K=0.667, μ=0.0001. GFRP bars acted linearly elastic until failure, steel was elastic plastic. Numerical experiments revealed: up-sizing GFRP bars by 2 mm (from 10 mm to 12 mm) yielded 15 % rise in load capacity; concrete enhancement (C25 to C40) heightened stiffness and delayed crack initialization; reducing stirrup spacing by 50 % (from 100 mm to 50 mm) augmented GFRP reinforced C25 beams capacity by 40 %. Junaid et L. [24] conducted ABAQUS parametric FE analysis of FRP beams flexural behavior subjected to bending. Four concrete types (PCC, AAC, FRC, FRAAC) with GFRP, BFRP, AFRP and CFRP bars were considered. Higher CFRP elastic modulus (150 GPa vs 83 GPa) provided 90 % load increase. Increasing reinforcement ratio (0.5 % to 3.28 %) increased capacity by 11 – 132 % and reduced deflection by 54 %. Enlarging beam depth (from 250 mm to 400 mm) produced up to 172 % increase in load capacity.

B. Bond-Slip Interface Modelling

Ma, Sun & Xu [25] numerically investigated the shear contribution of CFRP-strengthened RC beams with different bond slip models (Nakaba, Monti & Lu models). All three bond slip models agreed well with the results of the experiments (load errors at ultimate capacity - 14.1 ~ + 7.5 %). Nakaba's model gave an overestimation to the increase of diagonal-shear capacity by CFRP (ratio at average 1.18). It failed to simulate the U-wrap jacket failure due to debonding. Lu's bond slip model was the most efficient for performing numerical analysis (ratio at average 0.80) with a good balance of accuracy and convergence.

Studies on GFRP-Reinforced concrete columns under cyclic loading

Selmy and El-Salakawy [26] developed a nonlinear finite element model to simulate the response and behavior of circular GFRP reinforcement concrete columns subjected to reversed cyclic loading with combined torsion. Higher concrete strengths increased lateral load resistance and stiffness, but at the expense of drift capacity. Lowering the stirrup pitch increased both the drift and twist capacities, which is attributed to the limited propagation of diagonal cracking. A new model was thus derived from the design GFRP confinement reinforcement under a combined set of seismic loads and applied to spiral stirrups.

IX. USE OF MACHINE LEARNING (ML) TECHNIQUES.

The use of machine learning has been popular in recent works in predicting responses of GRP and RC beams and columns where higher accuracy is achieved than any formulas provided by the design codes and standards.

XGBoost with Bayesian hyperparameter optimization was employed by Nouri, Ghanbari, and Fakharian [4], to model the ultimate moment estimation of hybrid steel/GFRP RC beams, securing an R^2 of 0.9958 for training and 0.9478 for testing data through XGBoost. Moreover, SHAP analysis was utilized where the outcomes showed the steel reinforcement area, beam width, FRP area and FRP depth as the top parameters affecting the model's prediction. Additionally, this analysis also demonstrated the model's significant higher accuracy as compared to analytical models (2.7 % max error in case of the proposed model versus the 12.2 % in case of analytical one).

Thereafter, Karabulut [6] proposed 18 ML regression models (Gradient Boosting, K Neighbors, AdaBoost, Random Forest, Light GBM.) for the deflection estimation of RC beams, reinforced with steel and GFRP rebar from the early days. Karabulut [6] also identified Gradient Boosting Regressor as the most accurate (it was the best performer five times) and it has an average R^2 value of 0.913 in case of all studied beam types with different rebars, loading and dimensions. Additionally, it has been demonstrated that the ML models predict the deflection with a far higher accuracy over the analytical model especially in case of GFRP columns, beams, and slabs.

For its part, He et al. [5] provided an accurate shear strength prediction of beams reinforced by GFRP steel hybrid stirrups using RF, AdaBoost, GBRT and XGBoost, with GBRT demonstrating to be the best model due to its high accuracy in shear strength estimation resulting in an R^2 value of 0.967 on validation.

X. DESIGN PROVISIONS AND CODE IMPLICATIONS

A. Current Design Codes

Many design codes already include detailed provisions for the design and construction of GFRP reinforced Concrete (GFRP-RC) structures. Some important codes are:

Design provisions for FRP reinforced concrete structures are available in the ACI 440.1R-15, which are developed from reliability analyses for ensuring consistency in their failure safety factors with those of steel reinforcements which are subjected to brittle failure. Based on latest revisions ACI 440.11-22 replaces ACI 440.1R-15 for more robust results.

The CSA for civil infrastructure has provided CSA S806-12 standards while ACI standard for civil construction is now mainly ACI 440.11-2022 replacing ACI 440.1R-15; further, GB 50608 - 2020 which is a standard produced by an association in China in which all countries which use steel in infrastructure can take standard guidance. For more realistic designing purposes all standards have taken GFRP reinforcement characteristics for safety considerations into account such as linear elastic behavior of GFRP due to GFRP is an elastic material having low ductility property. Therefore, only serviceability of the structure is significant due to the elastic nature of these structures.

B. Design Philosophy

The serviceability (limiting the deflection and crack width) than ultimate load capacity is a major criterion in designing GFRP reinforced concrete whereas if designing it using steel only strength takes priority over serviceability (ultimate load capacity). To safety under ductility condition ACI standard has made it compulsory for having compression-controlled failure, where the concrete crushes when $\rho f \geq 1.4 \times \rho fb$ where the designing approach of over-reinforced is applied for reducing brittleness.

C. Limitation of Current Provisions

The following are some of the deficiencies of the design recommendations:

1. Deflection underestimates ACI 440.1R-15 and ACI 440.11-22 result in similar underestimates for deflections at service load level slender and under reinforced beams may be underestimated by 15 – 25 %.
2. Limited Coverage: The provisions concerning multilayer reinforcement, long-span configurations/effects due to lateral loads acting on beams or on slabs (spanning in one direction), creep & shrinkage effect and confinement contributions, the provisions need to be refined.
3. The design provisions have been based on experimental databases which do not fully represent the actual ranges of existing materials and construction practices.

D. Recommended design practices:

The following recommendations for good practice are made based on this project's results:

1. It is required to provide design charts for GFRP RC beams which satisfies the criteria of depth ≥ 300 mm and GFRP reinforcement ratio 1.5 % and the limits on service deflection, span/240, or span/360.
2. Use equivalent strength design instead of equal area replacement when GFRP bars are replaced with steel bars.
3. Use some analytical models with the consideration of tension stiffening and calculated by crack-width for improved prediction of deflection.
4. Compensation for the loss in concrete shear contribution through introduction of adequate shear reinforcement.
5. Addition of fiber or the use of hybrid reinforcement to improve serviceability performance.

XI. RESEARCH GAPS AND FUTURE DIRECTIONS

A. Limited studies on comparative analysis at equivalent strength design

Steel and Glass Fiber Reinforced Polymer (GFRP) rebars in reinforced concrete (RC) elements are mostly compared based on equal area replacement than replacement to give the same tensile force carrying capacity. The comparisons in existing studies provide information that is not reflective of the true picture, considering actual cases where reinforcement is designed to carry the same tensile load using either type of reinforcement. Therefore, more work comparing the behaviors of the two types of reinforce that are designed to carry same tensile load should be carried out.

B. Limited studies using a combination of testing, experimental design, and finite element methods.

Even though studies into the use of GFRP in concrete beams are extensively being conducted in different parts of the work and researchers from different regions use different design codes for this, few studies compare test data, empirical design using design codes and Finite Element Analysis. There is a need for researchers to use these more in comparative studies.

C. Limited studies on serviceability behavior of GFRP reinforced beams having equivalent tensile strength as similar steel reinforced beams.

The studies that present cracking behavior and ultimate deflections in GFRP reinforced beams mostly use a design method where they replace an equal area of steel with GFRP hence GFRP is insufficient and does not develop the same strength as its twin with steel reinforcement. There is therefore a need to assess the serviceability limits of real sized GFRP reinforced beams.

Few studies use GFRP to reinforce beams and compare them to similar beams reinforced in part 1 above.

D. Unvalidated Finite Element Models to predict mechanical response of beams subjected to the failure due to crushing of unconfined concrete.

Numerous FE models are already available for GFRP RC beams. But these FE models need to be validated in the light of experimental results for GFRP RC beam designed for equivalent strength so as able to formulate a predictive tool suitable for parametric studies.

E. Studies in Continuous Beams and Deep Beams (Limited)

There are limited studies conducted on FRP bar reinforced continuous beams and deep beams. Future investigations need to be conducted on the behavior of these structural systems to be able to extend provisions for the usage of GFRP rebars for continuous beams and deep beams.

F. Studies on Advanced ML Techniques (Limited)

Advanced machine learning approach needs to be incorporated with prediction curves developed for GFRP RC beams to address any limitations inherent within the available design code equations. Extensive experimental studies provide large sets of databases. However, limited studies employed ML to study the flexural response characteristics of GFRP RC beam designed for equivalent bending moment replacement. Predictive machine learning models for GFRP RC beam needs to be developed and validated to be able to predict the entire performance curve.

G. Studies in Long-term Field

Long term filed testing and implementation on real concrete structure reinforced with glass fiber reinforced polymers would be promising direction for future studies to consolidate the laboratory findings and encourage confidence in using more advanced material in practice application.

XII. CONCLUSIONS

This literature review has synthesized findings from multiple studies on glass fiber reinforced polymer (GFRP) bars as internal reinforcement in concrete beams, including experimental, analytical, and numerical approaches resulting conclusions are discussed below:

1. In property, GFRP bars offer 400 - 1200MPa tensile strength (more than 415 - 500MPa steel bars) and 40 - 60GPa Modulus (1/4 to 1/3 of steel bars). Due to their linear-elastic property and no yielding they should be designed with a view to serviceability.
2. In flexure, GFRP RC beams can accommodate bigger load at ultimate limit-state (8 - 12 %) than steel RC, but their deflection at failure is lower (38 – 58 %), thus their absorbed energy is lower (41 – 59 %). Over-reinforced design means ($\rho f \geq 1.4\ \rho fb$), results in compression-controlled failure which is safer and gradual instead of immediate rupture of the bars.
3. In shear GFRP RC beams lack dowel action; hence, the concrete shear contribution is less. Hybrid stirred (GFRP steel hybrid) result in ductile shear failure, a 10% stronger shear resistant member and with 22% higher deflection, than steel stirred members.
4. In bond the bond-stress is effected size diameter, concrete strength to name some. Exposure to aggressive conditions with a 0.25 - 0.65 Pu sustained loading leads to a decline (9 – 22 %) in the bond-strength of the beam. Small diameter bars offer a better solution to long-term bond degradation issues. Conventional bond-slip models are not accurate. With the aid of ANN-based bond-slip models R2 > 0.93 can be achieved which makes more precise predictions using it.
5. Serviceability: With GFRP-RC beams deflecting 2 - 2.5 times more than steel-RC beams, current codes fail to accurately predict deflections at service load (underestimates 15 – 25 %). Fiber addition might enhance serviceability while hybrid reinforcement improves it.
6. Durability: GFRP is more corrosion resistant than steel. Long term bond retention ranges from 52 – 97 %. Field study found a retention of around 98% of original bond strength after 17 years in service.
7. Finite Element Modelling (FEM): CDP models with correct parameters can reproduce concrete properties. The bond slip model by Lu et al. gives the best result for FRP reinforced concrete. FE models after validation produced excellent matching with experimental results (R2 > 0.93 with cracking and ultimate load error less than 10 %).
8. Machine Learning: XGBoost, GBRT and ANN models with R2 greater than 0.95 showed excellent prediction of ultimate moment, shear strength,

deflection, and bond strength. Predicted results outperform analytical calculations given in codes.

9. Design Considerations: Serviceability (deflection and crack width limits) will govern the design of members reinforced with GFRP. Equivalent strength, i.e., larger area of GFRP will need to be provided to maintain equivalence with steel in terms of load carrying capacity. Adequate shear reinforcement should be provided to make up for decreased shear resistance exhibited by concrete reinforced by GFRP.

XIII. FUTURE RESEARCH.

Some future critical researches are integrated experimental-analytical-numerical approaches of equivalent strength design, validation of existing design provisions to regional conditions, studies of continuous beams, studies of deep beams and long-term validation against field performance. Improved model for serviceability performance prediction.

Therefore, GFRP bars in concrete beam are viable and sustainable substitute for steel reinforcement, especially in corrosive areas. It can decrease the life cycle cost and increase the service life to be several times longer. The critical consideration will be for its serviceability requirement, required shear reinforcements and the approach it could be designed for.

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