

Understanding Deflection in GFRP-RC Beams: A Systematic Review of Parameters, Models, and Code Implications

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Abstract The use of Glass Fiber Reinforced Polymer (GFRP) bars as internal reinforcement in concrete beams has emerged as a viable alternative to conventional steel, particularly in corrosive and aggressive environmental conditions. GFRP offers advantages such as corrosion resistance, low weight, and electromagnetic neutrality. However, its lower modulus of elasticity and linear-elastic behavior result in greater deflection and wider cracks under service loads, raising concerns about serviceability. This study presents a systematic review of experimental, numerical, and analytical research on the deflection behavior of GFRP-reinforced concrete (GFRP-RC) beams. A total of over 20 peer-reviewed studies from 2012 to 2023 were analyzed, focusing on key influencing parameters including reinforcement ratio, span-to-depth ratio, concrete strength, and beam geometry. The performance of current predictive models—especially those from ACI 440.1R-15 and ACI 440.11-22—was evaluated against measured results. The findings show that while existing code models provide practical guidance, they tend to underestimate service-level deflections, particularly in under-reinforced and slender beams. Enhanced analytical methods that incorporate tension stiffening and crack-width-based calculations offer improved accuracy. Limitations of current design provisions and their implications for structural safety and comfort are also discussed. The study contributes to advancing GFRP-RC beam design by identifying key areas for code refinement, including

multilayer reinforcement, long-term deformation prediction, and deflection modeling for high-span configurations. Practical implications include safer design solutions for infrastructure in corrosive regions, while research implications suggest the need for broader experimental validation and regional code adaptation. This review supports the development of reliable, serviceable, and sustainable GFRP-RC structures.

Keywords Analytical Models, Deflection Behavior, GFRP-RC Beams, Serviceability, Sustainable Infrastructure

1. Introduction

One of the major concerns regarding the durability of concrete structures is the corrosion of steel reinforcement. The use of steel bars has been widely recognized and implemented for over a century [1]. Their applications extend to beam elements [2], column elements [3]–[5], and other structural members [6]. In recent years, several innovative reinforcement materials have been introduced as alternatives to traditional steel bars, such as various types of fibers used internally [7]–[10] or externally in concrete [11], [12]. These aim to enhance the structure's

performance, especially when degradation affects its strength and durability.

The growing demand for durable and corrosion-resistant construction materials has driven the development and adoption of alternative reinforcement systems in reinforced concrete (RC) structures. Among these innovations, Glass Fiber Reinforced Polymer (GFRP) bars have gained significant attention due to their high resistance to corrosion, lightweight nature, and non-conductive properties [13]–[15]. The use of GFRP reinforcement is particularly promising in harsh environments, such as coastal areas or chemical exposure zones, where traditional steel reinforcement is vulnerable to deterioration.

However, the mechanical properties of GFRP differ significantly from those of conventional steel reinforcement. GFRP bars exhibit a lower modulus of elasticity and absence of yielding, which may lead to brittle failure modes that present unique challenges in the structural design of GFRP-reinforced concrete (GFRP-RC) members. One of the critical issues is the flexural response and serviceability performance, including deflection and crack width, which tend to be more pronounced in GFRP-RC beams compared to their steel-reinforced counterparts [16]–[19]. These concerns affect user comfort, aesthetic performance, and regulatory compliance.

Numerous experimental and analytical studies have been conducted to investigate the flexural behavior of GFRP-RC beams and to develop accurate predictive models for serviceability performance [20]–[25], including comparative testing using normal- and high-strength concrete as conducted by El-Nemr et al. [26]. The findings suggest that, in addition to reinforcement ratio, parameters such as concrete strength, span length, and beam cross-sectional geometry significantly affect flexural capacity and deformation characteristics [19], [22]–[29]. On the regulatory front, design provisions such as ACI 440.11-22 [24], CSA S806-12 [30], SNI 8970:2021 [31], and Ospina and Gross [32] have begun to address the unique aspects of FRP-reinforced structures. However, the validation of these provisions through experimental evidence remains a critical area of research.

This research examines the flexural performance of GFRP-reinforced concrete beams through laboratory testing complemented by an extensive review of recent literature. Emphasis is placed on evaluating moment capacity, ductility, and crack width, alongside comparisons with traditional steel-reinforced concrete counterparts. The findings aim to advance knowledge of GFRP-RC flexural behavior and contribute to the development of safer, more reliable design approaches for the future use of GFRP reinforcement in structural concrete.

2. Materials and Methods

This study employs a structured, systematic literature review approach to assess the deflection behavior of

concrete beams internally reinforced with Glass Fiber-Reinforced Polymer (GFRP) bars. The primary focus is on experimental and numerical studies that provide quantitative mid-span deflection data, enabling comparisons with analytical models and existing design code predictions.

A total of eleven peer-reviewed publications from 2012 to 2023 were selected based on the following inclusion criteria: GFRP bars used exclusively as internal reinforcement (excluding externally bonded or hybrid systems), availability of mid-span deflection measurements from static loading tests, clearly reported beam dimensions, material properties, and reinforcement details.

Regarding the material properties of GFRP-RC beams, literature reports indicate that GFRP bars generally possess a tensile strength of 600–1200 MPa, a modulus of elasticity between 40 and 60 GPa, and an ultimate strain capacity of approximately 1.2%–2.5%. The concrete compressive strength (f_c') applied in experimental programs spans from 25 to 105 MPa. Various surface treatments, including sand coating and ribbing, have been employed to modify bond performance and tension stiffening behavior. Collectively, these characteristics have a considerable effect on the deflection response of GFRP-reinforced concrete beams.

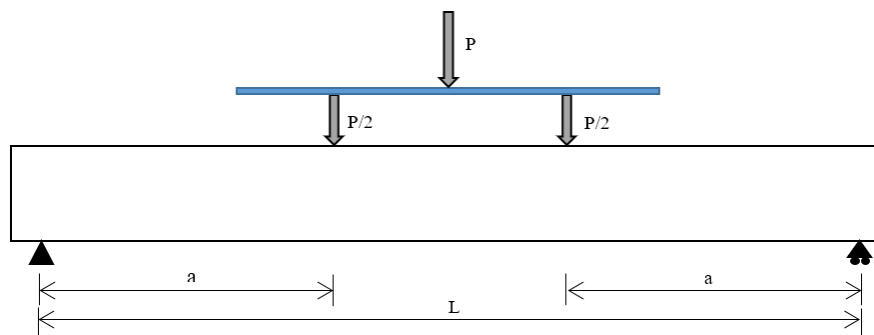
The selected studies are categorized into three groups: (1) experimental investigations, such as those conducted by Elnemr et al. [26], [33], Abdelkarim et al. [29], and Gouda et al. [15], [16]; (2) numerical simulation, including finite element modeling (FEM), such as carried out by Gouda et al. [16]; and Sarhan and Al-Zwainy [23]; (3) comparative analyses involving design codes or analytical models, exemplified by Barris et al. [34] and Tu et al. [35], and Shabani et al. [36].

To ensure the accuracy and consistency of the comparison, detailed data on beam geometry, reinforcement ratio, and loading configurations were systematically extracted and are summarized in Table 1. The majority of experimental studies employed simply supported rectangular concrete beams tested under two-point loading (four-point bending). Beam spans generally ranged from 1800 mm to 4250 mm, with typical cross-sectional dimensions of 150 × 250 mm or 200 × 400 mm. The GFRP reinforcement ratio (ρ_f) varied from approximately 0.36% to 3.85%, depending on the study's design objectives. Most specimens used either ribbed or sand-coated GFRP bars, and both normal-strength concrete (NSC) and high-strength concrete (HSC) were represented in the reviewed literature.

A representative layout of the GFRP-reinforced concrete beams examined in the reviewed literature is presented in Figure 1. The schematic depicts the loading arrangement, overall span length (L), shear span (a), and cross-sectional configuration, emphasizing the positioning of longitudinal GFRP bars, shear reinforcement, and concrete cover thickness. This illustration complements the dimensional and reinforcement data provided in Table 1.

Table 1. Summary of beam dimensions and test configurations in the reviewed studies

Researchers	Beam Length (mm)	Width × Depth (mm)	ρ (%)	Loading Type	Notes
Elnemr et al. [26]	4250	200 × 400	0.36 – 1.78	4-point	12 beams with GFRP bars of different grades and surface types; NSC and HSC; mid-span deflection and crack width data provided
Abdelkarim et al. [29]	3000	200 × 300	0.59 – 1.26	4-point	Deformed GFRP bars
Gouda et al. [16]	2100	150 × 250	1.0 – 2.0	4-point	Experimental + FEM model for deflection and crack width
El-Nemr et al. [33]	4250	200 × 400	0.38 – 3.85	4-point	12 beams with GFRP bars of different grades (CSA S807), sand-coated surface, NSC
Gouda et al. [15]	4350	200 × 400	0.55 – 1.51	4-point	Crack width, curvature, ductility, and bar size influence
Shabani et al. [36]	—	—	—	—	Review of 9 analytical crack width equations for GFRP RC beams
Barris et al. [34]	—	150 × 250	0.63 – 1.38	4-point	Model validation
Tu et al. [35]	2400	150 × 250	1.12 – 1.76	4-point	Crack-width-based flexural beam tests
Sirimontree et al. [19]	2500	150 × 250	—	4-point	GFRP vs. steel bars
Wang and Belarbi [37]	1829	178 × 229	2.13 – 3.17	4-point	GFRP and CFRP bars
Ashour [22]	2500	200 × 350	0.14 – 1.39	4-point	Flexural and shear behavior, no stirrups
Theriault and Benmokrane [28]	2400	200 × 300	0.72 – 1.38	4-point	Effects of reinforcement ratio
Masmoudi et al. [21]	2000	150 × 300	0.85 – 1.62	4-point	Deformed GFRP bars
Alsayed [38]	2000	150 × 250	0.95 – 1.80	4-point	Effect of bar type on deflection
Al-Sunna et al. [39]	2600	150 × 300	0.14 – 0.28	4-point	Varied, without shear reinforcement
Benmokrane et al. [40]	3300	200 × 300–550	0.18–0.39	4-point	Varying depth; no shear reinforcement
Bischoff [20]	3750	150 × 300	0.35 – 1.41	4-point	GFRP & steel bars; pure moment region
Habeeb and Ashour [41]	2400 – 3000	150 × 300	0.47 – 1.41	4-point	2 simply supported and 3 continuous GFRP RC beams; one steel RC beam as a comparison; investigated under-, over-, and balanced reinforcement; focus on crack width, deflection, and flexural behavior.
Ospina and Gross [32]	—	—	1.0 – 4.0	Uniform	Basis for ACI 440.1R crack control provision
Sarhan and Al-Zwainy [23]	2400	100 × 150	1.0 – 2.0	4-point	Analytical study using Strips Analysis Method (S-A-M); validated against experiments; effect of concrete strength, span length, and loading points; concrete strength 75–105 MPa
Toutanji and Deng [18]	3000	180 × 300	0.52 – 1.10	4-point	6 GFRP-RC beams; verified ACI 440.1R-01 equations for deflection and crack width; failure mode: concrete crushing; crack width vs. reinforcement layers studied



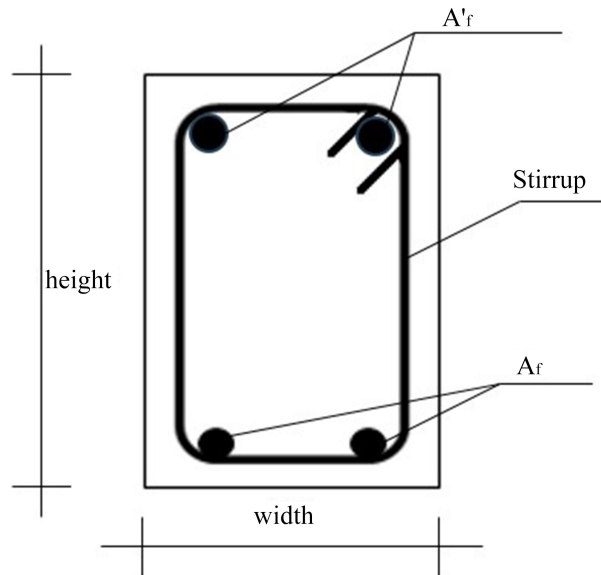


Figure 1. Loading configuration and cross-section of a GFRP-RC beam

Figure 1 presents a representative arrangement of the GFRP-reinforced concrete beams analyzed in this study. In the elevation view, the beam is simply supported with a clear span (L) and subjected to four-point bending, where equal shear spans (a) on both sides create a constant-moment region between the loading points. The cross-sectional view illustrates the reinforcement scheme, comprising longitudinal GFRP bars placed in both compression and tension zones and confined by closed-loop GFRP stirrups. The section dimensions—width (b) and depth (h)—along with the concrete cover are consistent with the geometric and material specifications summarized in Table 1, ensuring adequate protection of the reinforcement.

All selected studies measured mid-span deflections and compared them with theoretical predictions derived from design guidelines such as ACI 440.1R-15 [13] and ACI 440.11-22 [14], as well as rational analytical approaches including effective moment of inertia models (e.g., Barris et al. [34]) and crack-width-based equations (Shabani et al. [36]). The deflection results were compared at service load and ultimate load levels, concerning serviceability limits such as $\text{span}/240$ and $\text{span}/360$ criteria. The influence of cracking behavior and post-cracking stiffness degradation was also examined, as these factors significantly affect the long-term deflection performance.

Validation of analytical and code-based predictions was further supported by experimental data and finite element simulations, particularly those by Gouda et al. [16] and Bischoff [20], which offered additional insights into flexural stiffness reduction and full-span deflection profiles. This comprehensive methodology aims to synthesize and evaluate current knowledge on deflection prediction accuracy for GFRP-reinforced concrete beams,

while identifying key parameters that govern serviceability performance.

3. Results and Discussion

The deflection performance of GFRP-reinforced concrete (GFRP-RC) beams shows distinct differences from that of traditional steel-reinforced members, primarily due to the lower modulus of elasticity and linear-elastic behavior of GFRP bars until failure. This section analyzes the experimental and numerical findings from selected studies, comparing measured mid-span deflections with predictions from ACI code provisions and analytical models.

3.1. Experimental Deflection Behavior

Across the reviewed experimental studies [20, 26, 29], all GFRP-RC beams exhibited larger deflections than comparable steel-reinforced concrete beams at both service and ultimate load levels. For example, in Elnemr et al. [26], deflections of GFRP-reinforced beams were 2.0 to 2.5 times higher at service loads compared to their steel counterparts, particularly in normal-strength concrete (NSC). Similarly, Abdelkarim et al. [29] observed that deflections at service load exceeded the $\text{span}/240$ and $\text{span}/360$ serviceability limits in beams with lower reinforcement ratios ($\rho_f \leq 0.7\%$).

Gouda et al. [15] reported that even with optimized reinforcement ratios ($\rho_f \geq 1.5\%$), GFRP-RC beams experienced stiffness degradation post-cracking that resulted in nonlinear load-deflection responses. The effective moment of inertia dropped significantly after cracking, a trend also observed in the numerical parametric studies by Gouda et al. [16].

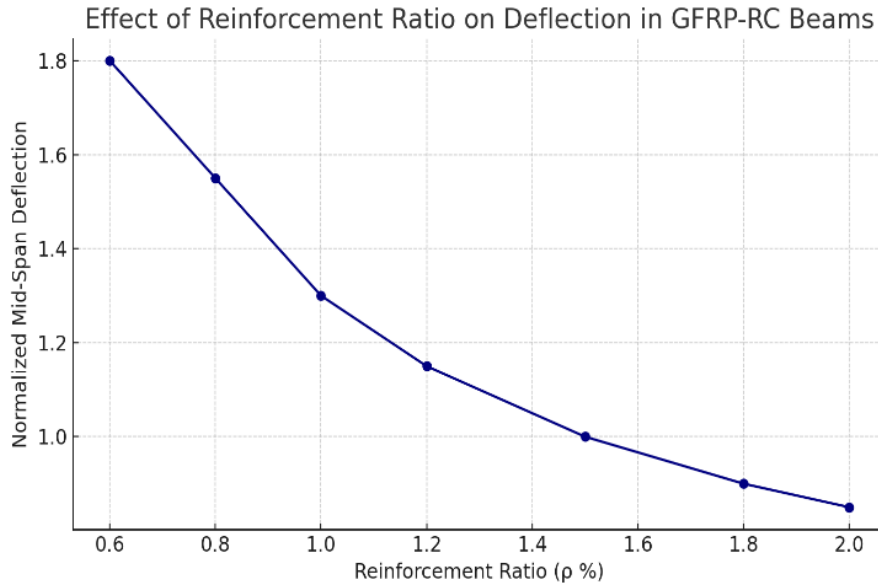


Figure 2. Load vs. midspan deflection

Figure 2 illustrates the relationship between the applied load and the mid-span deflection. Aggregated results from Elnemr et al. [26], Abdelkarim et al. [29], and Gouda et al. [16] show that increasing the GFRP reinforcement ratio (ρ_f) from 0.5% to 2.0% leads to an approximate 30% reduction in mid-span deflection under service load conditions. This trend highlights the substantial effect of reinforcement ratio on post-cracking stiffness and the overall serviceability performance of GFRP-RC beams.

3.2. Comparison with ACI Code Predictions

A consistent theme among the studies was the inaccuracy of ACI 440.1R-15 [13] and ACI 440.11-22 [14] in predicting service-level deflection for GFRP-RC beams. Both codes rely on a modified Branson's equation to estimate the effective moment of inertia (I_e), but experimental results showed that this method often underestimates deflection, particularly for beams with lower reinforcement stiffness ratios (EI_f/EI_{cr}).

El-Nemr et al. [26] and Tu et al. [35] confirmed that the ACI provisions produced non-conservative predictions when reinforcement ratios were below balanced conditions. Barris et al. [34] noted that even when ACI predictions were conservative at ultimate load, they failed to capture early-stage cracking behavior and the associated deflection surge.

Figure 3 compares experimentally recorded mid-span deflections with the values predicted by ACI 440.1R-15 [13] across five representative studies. In most cases, the ACI 440.1R-15 approach underpredicts deflections by approximately 15–25% at service load levels, underscoring the necessity for improved serviceability prediction models specifically calibrated for GFRP-RC beam behavior.

3.3. Accuracy of Analytical Models

Several analytical models proposed in the literature provided improved deflection estimates over the ACI codes. For instance, Barris et al. [34] employed a nonlinear interpolation approach for I_e that better matched measured deflections, especially in lightly reinforced beams. Tu et al. [35] introduced a crack-width-based model that indirectly estimated deflection by coupling crack spacing and bar stiffness—this approach achieved deviations within $\pm 10\%$ of experimental values for 150×250 mm beams with ρ_f between 1.2–1.7%.

Shabani et al. [36] presented a review of multiple empirical equations and concluded that models that incorporate post-cracking tension stiffening or bar bond-slip mechanisms yield superior prediction accuracy.

3.4. Influence of Beam Dimensions and Reinforcement Ratio

Beam depth and reinforcement ratio were found to influence deflection behavior significantly. As reported by Abdelkarim et al. [29], increasing the beam depth from 250 mm to 300 mm resulted in a 20–25% reduction in deflection at identical loading levels, due to the higher moment of inertia. Similarly, reinforcement ratios above 1.5% helped maintain deflections within serviceability limits, as confirmed by Gouda et al. [15].

Conversely, under-reinforced sections ($\rho_f \leq 0.7\%$) suffered early cracking and pronounced mid-span deflections that far exceeded code-based limits. This effect was exacerbated in high-span-to-depth ratios ($L/d > 12$), which are typical in practical designs.

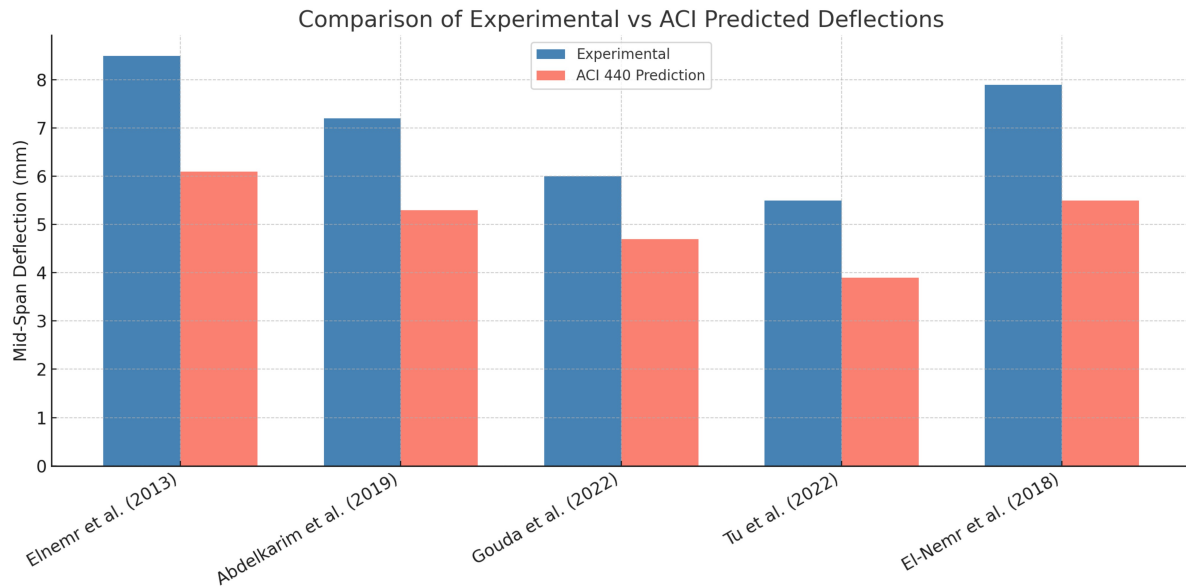


Figure 3. Comparison of Experimental vs ACI Predicted Deflections

3.5. Role of Finite Element Analysis

Finite element models validated by Gouda et al. [16] replicated the nonlinear deflection response accurately, including crack initiation and stiffness loss. These models incorporated concrete damage plasticity and discrete cracking zones, providing more granular insight into the role of bond behavior and stress redistribution.

The numerical data further supported the conclusion that ACI 440-based I_e predictions are generally non-conservative and that calibration with experimental benchmarks is necessary for reliable serviceability design.

In summary, the reviewed literature demonstrates that GFRP-RC beams exhibit significantly greater deflection than steel-RC beams, and current code provisions often underestimate this behavior, particularly at service load levels. Analytical and numerical approaches offer improved accuracy, especially when accounting for tension stiffening and cracking mechanisms. Beam depth, span-to-depth ratio, and reinforcement ratio all play critical roles in deflection performance, underlining the need for refined prediction tools tailored specifically for GFRP applications.

3.6. Parameters Influencing Deflection in GFRP-RC Beams

The reviewed studies consistently highlight the critical influence of several physical and mechanical parameters on the deflection behavior of GFRP-reinforced concrete (GFRP-RC) beams. Chief among these is the longitudinal reinforcement ratio (ρ_f), which directly affects member stiffness and crack distribution. Studies by El-Nemr et al. [26], Abdelkarim et al. [29], and Bischoff [20] demonstrate that increasing ρ_f reduces mid-span deflections (by approximately 15–30% based on reviewed studies) and

improves post-cracking stiffness. However, excessively high reinforcement ratios may result in inefficient material use without significantly improving serviceability performance.

Another key parameter is the modulus of elasticity of GFRP bars, which is typically in the range of 40–60 GPa, considerably lower than that of steel. This reduced stiffness leads to larger deflections (up to $2.5\times$) and wider cracks (up to $1.8\times$) under service loads, as discussed by Ashour [22], Abdelkarim et al. [29]. To maintain acceptable serviceability levels, GFRP-RC beams often require higher reinforcement ratios (e.g., above 1.5% of cross-sectional area) than their steel-reinforced counterparts. Furthermore, the number of reinforcement layers (e.g., single vs. double) can impact crack width predictions, as reported by Abdelkarim et al. [29], where ACI 440.1R-15 [13] underestimated crack widths in beams with multiple layers.

The concrete compressive strength (f'_c) also plays a secondary but relevant role in stiffness and cracking behavior. According to Toutanji and Deng [18] and Rafani et al. [25], high-strength concrete (HSC) enhances the cracking moment and initial stiffness, yet it cannot fully mitigate the increased deflection caused by the low stiffness of GFRP reinforcement.

Span length and beam geometry are also influential. Longer beams or those with smaller cross-sectional inertia show higher deflections even when they are constant (Bischoff [20], Barris et al. [34]). This is particularly relevant in slender beam design or slab systems (Sirimontree et al. [19]).

3.7. Evaluation of Analytical and Code-Based Prediction Models

Several models and code provisions have been assessed

against experimental data. The ACI 440.1R-15 [13] guideline is the most widely referenced, providing equations for effective moment of inertia and crack width. Toutanji and Deng [18] found that ACI 440 predictions align well for beams with a single layer of reinforcement, but modifications (e.g., adjusting the bond factor) are needed for multilayer arrangements.

Ospina and Gross [32] conducted a parametric study that underpins the current ACI provisions for span-to-depth ratio limits based on reinforcement stiffness and strain. They emphasized the importance of indirect deflection control when direct prediction models lack sufficient precision.

Recent FEM studies by Gouda et al. [16] validated the use of nonlinear numerical modeling to capture both service and ultimate behaviors, although simplified models based on Branson's modified equation remain dominant in design practice.

Tu et al. [35] and Barris et al. [34] evaluated the differences between predicted and observed deflections (ranging from -15% underestimation to +25% overestimation) and recommended context-specific modifications to the effective moment of inertia formulations, particularly at low reinforcement ratios where deflections are often underestimated.

3.8. Code Implications and Gaps

The findings of this review have implications for current design provisions. ACI 440.1R-15 [13] and 440.11-22 [14] offer practical and relatively conservative models, but their accuracy diminishes for extreme reinforcement scenarios (e.g., very low ($\leq 0.5\%$) or very high ($\geq 3.0\%$)) and for multi-layered reinforcement configurations.

While CSA S806-12 [30] includes empirical adjustments, it similarly lacks detailed provisions for crack width control beyond single-layer assumptions. The SNI 8970:2021 [31] regulation in Indonesia largely mirrors ACI provisions but requires localization and validation through domestic experimental studies.

These limitations are further supported by findings from recent comprehensive reviews on FRP pultruded material standards [42]. Overall, current codes need refinement in the following areas:

1. Better crack width modeling (e.g., integrating bar bond-slip relationships and multilayer reinforcement effects) for multilayer GFRP reinforcement.
2. More accurate models (with $\pm 10\%$ deviation from experimental deflection results) for high-deflection cases.
3. Integration of confinement effects (considering lateral FRP wrapping or transverse steel to delay stiffness degradation) for serviceability improvements.
4. Long-term deflection models incorporating creep and shrinkage specific to FRP-RC systems.

4. Conclusions

This systematic review consolidates two decades of research on the deflection behavior of GFRP-reinforced concrete (GFRP-RC) beams, emphasizing the influence of reinforcement characteristics, material properties, and geometric parameters on serviceability performance. The following conclusions can be drawn:

1. **Serviceability Challenges:** GFRP-RC beams exhibit significantly greater deflections (e.g., 2.0–2.5 times higher at service load than steel-RC beams) than conventional steel-reinforced concrete beams, primarily due to the lower modulus of elasticity and linear-elastic behavior of GFRP bars. This leads to concerns about exceeding allowable deflection limits (span/240 or span/360, as per code provisions) under service loads, especially in lightly reinforced or slender beams.
2. **Code Limitations:** Current design provisions, such as ACI 440.1R-15 and ACI 440.11-22, provide a foundational framework but frequently underestimate service-level deflections. These models often fail to capture early cracking behavior, post-cracking stiffness degradation, or the effects of multilayer reinforcement.
3. **Improved Prediction Models:** Analytical models incorporating tension stiffening, crack width behavior, and nonlinear interpolation of the effective moment of inertia (I_e) have demonstrated superior accuracy over traditional code equations. These approaches offer deflection predictions within $\pm 10\%$ of experimental results in many cases.
4. **Key Influencing Parameters:** The reinforcement ratio (ρ_f), beam depth, span-to-depth ratio, modulus of elasticity of GFRP, and concrete strength are primary factors governing deflection behavior. While increasing ρ_f and beam depth helps reduce deflection, over-reinforcement (above a 3.0% reinforcement ratio) may lead to inefficient designs without proportional serviceability gains.
5. **Role of Finite Element Analysis (FEA):** FEA provides valuable insights into cracking behavior, bond-slip effects, and stress redistribution in GFRP-RC beams. Validated models enhance the ability to predict deflection behavior with greater detail and can guide code development.
6. **Design and Research Recommendations:**
 - a. Design codes should be revised to include more robust models for multilayer reinforcement and high-span-to-depth configurations.
 - b. Long-term deflection behavior due to creep and shrinkage in GFRP-RC systems remains inadequately addressed and requires targeted research.
 - c. Confinement effects and bond behavior between GFRP and concrete should be more explicitly considered in future guidelines.

- d. Empirical data from tropical and corrosive environments, especially in regions like Indonesia, should inform localized code development.

In summary, the use of GFRP as internal reinforcement presents promising advantages in durability and corrosion resistance, yet introduces new challenges in deflection control. Bridging the gap between experimental evidence and current design practices will be essential to ensure safe, serviceable, and cost-effective applications of GFRP in structural concrete systems.

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