

An Analysis of Strength Enhancement Mechanisms in Heterogeneous Steels and GFRP-Concrete Composites

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ABSTRACT

Abstract: This literature review examines the fundamental strengthening mechanisms governing two advanced material systems: heterostructured lightweight steels and Glass Fiber-Reinforced Polymer (GFRP)-concrete composites. In lightweight steels, superior strength–ductility synergy is achieved through the deliberate engineering of microstructural heterogeneity, primarily via Hetero-Deformation Induced (HDI) strengthening, grain boundary refinement, and optimized hetero-unit size. These mechanisms enhance back stress, dislocation storage, and work hardening, enabling performance levels unattainable in homogenous alloys. Conversely, GFRP-concrete composites rely on macro-scale strategies to overcome the limitations of traditional steel reinforcement, focusing on improved bond behavior, innovative mechanical anchorage systems, and external confinement to enhance tensile load transfer, compressive strength, and durability. Comparative analysis reveals a unifying principle: strategic introduction of mechanical heterogeneity—internally within metals and interfacially in composite systems—serves as a powerful method for controlling deformation and suppressing brittle failure. This synthesis highlights a universal framework for designing high-performance materials, emphasizing that optimal composite behavior emerges from carefully engineered structural heterogeneity at critical physical scales.

Keywords: Mechanical anchorage; Bond behavior; GFRP confinement; Strength–ductility synergy; Composite materials design



Article History:

Received: 13-01-2026

Revised : 05-05-2026

Accepted: 05-05-2026

Online : 07-05-2026



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A. BACKGROUND

The strategic development of advanced composite materials is critical for overcoming the inherent performance limitations of conventional monolithic systems. By engineering materials with tailored properties at multiple scales, it is possible to achieve functionalities that are otherwise unattainable. This review focuses on two distinct classes of advanced composites that address significant engineering challenges: heterostructured lightweight steels and Glass Fiber-Reinforced Polymer (GFRP)-concrete composites. The objective of this literature review is to analyze and synthesize the fundamental strengthening mechanisms that govern the macroscopic mechanical performance of these systems, focusing on the interplay between microstructure, interfacial design, and constituent material properties.

Recent literature highlights the core challenges unique to each material class. For lightweight steels, the primary obstacle is the classic strength-ductility trade-off, where enhancing strength typically leads to a detrimental loss of plasticity [Cheng et al., 2026; Dong et al., 2025]. In civil infrastructure, GFRP-concrete systems have emerged as a promising solution to the pervasive issues of steel corrosion, weak bond between

reinforcement and concrete, and the general need for more durable reinforcing materials in aggressive environments (Shakiba et al., 2022; Sasikumar & Manju, 2024).

This review will first deconstruct the microstructural strengthening mechanisms in lightweight steels and then shift focus to the macro-scale reinforcement strategies in GFRP-concrete composites, culminating in a comparative synthesis of the underlying principles governing strength enhancement in both systems.

B. IMPLEMENTATION METHODS

Strengthening Mechanisms in Heterostructured Lightweight Steels

Engineering microstructural heterogeneity is a primary strategy for transcending the traditional strength-ductility paradox in metallic alloys. By creating a microstructure composed of distinct regions with significant disparities in mechanical properties, it is possible to activate unique deformation mechanisms that synergistically enhance both strength and toughness. This section deconstructs the key mechanisms identified in recent literature for advanced lightweight steels, namely Hetero-Deformation Induced (HDI) strengthening and the optimization of grain boundary effects

1) The Role of Hetero-Deformation Induced (HDI) Strengthening

Hetero-Deformation Induced (HDI) strengthening is a mechanism arising from the strain gradients that develop between mechanically dissimilar micro-zones during deformation (Cheng et al., 2026). These gradients lead to the accumulation of geometrically necessary dislocations (GNDs) and the development of long-range back stress, which enhances the material's work hardening capacity. HDI mechanisms manifest differently depending on the specific microstructural architecture. In austenite-B2 dual-phase lightweight steels, HDI strengthening is primarily driven by the interactions between soft, ductile lamellar austenite phases and hard, high-strength granular B2 phases (Cheng et al., 2026). In contrast, for V-alloyed austenitic steels, the heterogeneity arises from strain gradients between soft, defect-free recrystallized (RX) regions and hard, high-dislocation-density non-recrystallized (NRX) regions (Dong et al., 2025).

2) The Synergy of Grain Boundary Strengthening and Hetero-Unit Size Optimization

Alongside HDI effects, grain boundary (GB) strengthening remains a fundamental mechanism for enhancing the strength of metallic alloys. According to the classical Hall-Petch relationship, refining the grain size increases strength by providing more barriers to dislocation motion (Cheng et al., 2026). Recent research has shown that this principle can be synergistically combined with heterostructure design to achieve even greater performance gains. Cheng et al. identified a "coupling effect" describing the synergistic interaction between heterostructure design and the optimization of hetero-unit size (Cheng et al. 2026). The key to this effect lies in the concept of the "hetero-zone boundary affected region" (Hbar), defined as the area near hetero-boundaries where significant GND gradients develop during deformation. The volume fraction of the Hbar within a grain is critical for amplifying HDI effects. By carefully controlling the size of the microstructural hetero-units (e.g., individual grains or phases), it is possible to maximize this volume fraction.

A theoretical model was proposed to identify the ideal hetero-unit size, given by $d_{\text{optimal}} = 2 * l_{\text{Hbar}}$, where l_{Hbar} is the characteristic length of the affected region. At this optimal size, the design maximizes both the volume fraction of the Hbar and the disparity in GND density between the hetero-boundary and the grain core. This condition leads to the highest possible HDI stress, creating a powerful synergy between grain boundary refinement and HDI strengthening (Cheng et al., 2026).

3) Microstructural Design for Optimal Performance

The synthesis of these findings reveals that deliberate microstructural design is paramount for achieving superior mechanical performance. Comparative studies show that a size-optimized heterostructure (e.g., the HS1 sample) significantly surpasses the performance of conventional homogeneous, partially recrystallized, or non-recrystallized structures, establishing it as the optimal design paradigm for lightweight steels (Cheng et al., 2026). Alloying elements serve as a powerful tool for achieving this microstructural control. The work by Dong et al. [2025] demonstrates how the addition of Vanadium (V) strategically modifies the microstructure of lightweight steel. Vanadium induces the formation of fine vanadium carbide (VC) precipitates, which act as potent pinning agents at grain boundaries. This pinning effect effectively retards recrystallization at elevated temperatures, allowing for the creation of stable heterostructures composed of RX and NRX regions. Furthermore, this approach simultaneously suppresses the precipitation of brittle B2 intermetallics, which are known to compromise ductility. This strategic use of alloying to control phase transformations and grain growth is essential for creating stable, high-performance heterostructures. Ultimately, the performance of these advanced steels is dictated by the precise, atom-to-micron scale manipulation of their internal architecture. This philosophy of *intrinsic* material design contrasts sharply with the *extrinsic* reinforcement strategies seen in GFRP-concrete systems, which focus on macro-scale interfaces and external confinement to overcome the limitations of the constituent materials.

C. RESULT AND DISCUSSION

Strengthening and Anchorage Mechanisms in GFRP-Concrete Composite Systems

Shifting focus from the microstructural engineering of metallic alloys to macro-scale composite systems, this section examines the use of Glass Fiber-Reinforced Polymer (GFRP) in concrete. This technology is primarily driven by the need to overcome the significant durability challenges of traditional steel reinforcement, most notably its susceptibility to corrosion in aggressive environments. This section will analyze the mechanisms related to bond behavior, anchorage systems, and external confinement that are used to enhance the strength and service life of GFRP-concrete structures.

1) Enhancing Bond Behavior through Mechanical Interlocking and Anchorage

A primary challenge in GFRP-reinforced concrete is achieving an adequate bond and efficient load transfer between the GFRP bar and the surrounding concrete, particularly when the development length is insufficient to rely on friction and chemical adhesion alone (Shakiba et al., 2022). To address this, innovative anchor heads fabricated from glass fibre cloth and epoxy resin have been developed. These anchors function primarily by increasing mechanical interlocking and friction at the bar end, providing a robust mechanism for transferring tensile loads from the bar to the concrete (Shakiba et al., 2022). From a materials science perspective, this challenge is analogous to ensuring load transfer across a phase boundary in a metallic composite; failure at the interface or within the weaker matrix material (concrete) prevents the high-strength reinforcing phase (GFRP) from reaching its full potential. The efficiency of these anchorage systems is critically dependent on several factors, with concrete compressive strength being the most significant. A comparative analysis of experimental data reveals a stark difference in performance based on concrete quality:

- a) In low-strength concrete (e.g., 20.4 MPa), anchor systems are not promising. The stress concentrations at the anchor head exceed the concrete's shear capacity, leading to premature failure within the concrete itself, manifesting as partial or full concrete splitting (Shakiba et al., 2022).

- b) In higher-strength concrete (e.g., 40.2 MPa), the same anchor systems effectively transfer load, increasing the ultimate developed tensile load by a range of approximately 14% to over 70%, depending on the specific bar diameter and anchor geometry. In this case, the concrete is strong enough to resist the localized stresses, allowing the anchorage to perform its function (Shakiba et al., 2022).

Anchor geometry also plays a crucial role. Research indicates that anchor shapes with gradually changing cross-sections (Type IV) are the most efficient at distributing stress and maximizing performance, while those with a constant cross-section (Type II) are the least efficient (Shakiba et al., 2022).

2) Confinement as a Compressive Strengthening Mechanism

Beyond addressing tensile bond, GFRP is also highly effective at enhancing the compressive performance and ductility of concrete members. This is achieved through GFRP confinement, a technique where external wrapping is applied to concrete columns to provide lateral confining pressure (DarvishaliNezhad et al., 2026). This confinement restricts lateral expansion of the concrete under axial load, which significantly increases both its ultimate compressive strength and strain capacity. The impact of GFRP confinement is substantial, with studies showing an increase in compressive strength ranging from 39.3% to 82.6%, depending on the number of layers applied. For instance, the application of two GFRP layers to a concrete column achieved a peak compressive strength of 53.5 MPa (DarvishaliNezhad et al., 2026). In addition to strength, GFRP confinement drastically enhances ductility and energy absorption capacity, transforming the brittle failure mode of plain concrete into a more controlled, ductile one. This makes it a highly effective and widely adopted strategy for the seismic retrofitting of existing columns (DarvishaliNezhad et al., 2026).

3) Influence of Design Parameters on Flexural and Durability Performance

The overall performance of GFRP-concrete systems is governed by a set of key design variables that influence their flexural behavior, durability, and service life. A synthesis of recent findings highlights the following effects:

- a) **Reinforcement Ratio:** In flexural members like beams, increasing the GFRP reinforcement ratio leads to a higher ultimate load-carrying capacity. It also helps control serviceability by reducing mid-span deflection and limiting crack widths under load (Sasikumar & Manju, 2024).
- b) **Concrete Strength:** Higher concrete compressive strength directly improves the flexural capacity of beams and reduces deflection. As previously noted, it is also a critical prerequisite for the effectiveness of mechanical anchorage systems, which rely on the concrete's ability to resist localized splitting forces (Sasikumar & Manju, 2024; Shakiba et al., 2022).
- c) **Bar Diameter:** In pull-out tests, the ratio of developed tensile stress to the bar's nominal strength (f_s/f_{ps}) tends to decrease as the bar diameter increases, a phenomenon attributed to shear lag effects and a less uniform stress distribution across the larger cross-sections (Shakiba et al., 2022).
- d) **Durability and Service Life:** The most significant advantage of GFRP reinforcement is its long-term sustainability. Its inherent resistance to corrosion can extend the service life of structures in corrosive environments to a predicted 75-100 years, a substantial improvement over the 20-30 years typical for steel-reinforced concrete in similar conditions (DarvishaliNezhad et al., 2026).

The mechanisms discussed here, which operate at the component and structural level, provide a compelling contrast to the microstructural phenomena in lightweight steels, setting the stage for a comparative synthesis.

4) Synthesis and Comparative Analysis

This section synthesizes the findings from both material systems to draw higher-level conclusions about the governing principles of strength enhancement in advanced composites. While heterostructured steels and GFRP-concrete composites operate at vastly different physical scales and address distinct engineering problems, a comparative analysis reveals common underlying strategies rooted in the deliberate introduction of mechanical heterogeneity. The following table directly compares and contrasts the primary strengthening strategies employed in the two material systems:

Table 1. Comparison Steel and Concrete Composite

Feature	Heterostructured Lightweight Steels	GFRP-Concrete Composites
Primary Locus of Strengthening	Internal microstructure (grain boundaries, phase interfaces at the nano/micro-scale).	Macro-scale interface between distinct materials (bar-concrete bond) and external structural reinforcement.
Governing Physical Mechanism	Control of dislocation dynamics (e.g., GND pile-ups, back stress from HDI).	Efficient stress transfer and load distribution (mechanical interlocking, friction) and imposition of confining pressure.
Source of Heterogeneity	Engineered disparities in mechanical properties between adjacent micro-zones (e.g., soft austenite vs. hard B2 phase; RX vs. NRX regions).	Intrinsic material difference between high-strength, low-modulus GFRP and brittle, compressive concrete.
Key Design Strategy	Thermo-mechanical processing and alloying to control phase transformation, recrystallization, and grain size.	Geometric design of the interface (anchor heads) and external application of reinforcement (GFRP wrapping).
Critical Limiting Factor	Preventing premature plastic instability or embrittlement from undesirable phases (e.g., B2).	Failure of the weaker constituent (concrete splitting) or interfacial debonding.

The common principle uniting both systems is the strategic introduction of mechanical heterogeneity to manage deformation and suppress catastrophic failure. Lightweight steels achieve this *internally*, using engineered microstructural gradients to delocalize strain, multiply dislocation pathways, and elevate work hardening, thereby delaying the onset of plastic instability. Conversely, GFRP-concrete systems achieve this *externally and interfacially*. Anchorage and confinement introduce new load paths and a triaxial stress state in the concrete, suppressing its inherent tensile weakness and brittle fracture, thus allowing the high-tensile capacity of the GFRP to be utilized.

This comparative analysis demonstrates that the strategic engineering of heterogeneity is a universal and powerful paradigm for designing advanced composite materials.

D. CONCLUSION AND RECOMMENDATIONS

This review has analyzed the fundamental strengthening mechanisms in two disparate classes of advanced composite materials: heterostructured lightweight steels and GFRP-concrete composites. The analysis distills several critical insights into the design of high-performance materials.

For lightweight steels, exceptional strength-ductility synergy is achieved through the deliberate engineering of microstructural heterogeneity. This is principally governed by Hetero-Deformation Induced (HDI) strengthening, which generates internal back stress, and the synergistic optimization of grain boundaries and hetero-unit size to maximize dislocation storage and work hardening. For GFRP-concrete systems, performance enhancement operates at the macro-scale, relying on mechanical interlocking via

innovative anchorage systems to ensure robust load transfer and external confinement via GFRP wrapping to drastically improve the compressive strength and ductility of concrete.

The central thesis emerging from this review is that the macroscopic performance of these advanced composites is governed by the strategic design of heterogeneity. In lightweight steels, this is achieved through precise microstructural control of phases and grain structures. In contrast, GFRP-concrete systems achieve this through interfacial and external design to create a composite structure that leverages the strengths of its constituents while mitigating their weaknesses.

ACKNOWLEDGEMENTS

Ultimately, these principles point toward a universal framework for composite design, where performance is maximized by engineering heterogeneity at the most critical length scale. For monolithic materials approaching their intrinsic limits, the path forward lies in nano-to-micro scale architectural control. For multi-material systems, the focus must be on robust interfacial design and macro-scale synergy. Mastering the interplay between these scales is the key to creating the next generation of high-performance, durable, and sustainable structural materials.

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