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METHODOLOGICAL PRINCIPLES FOR SELECTING GLASS FIBER COMPOSITE MATERIALS IN REINFORCED STRUCTURES

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МЕТОДИЧНІ ЗАСАДИ ВИБОРУ СКЛОВОЛОКОННИХ КОМПОЗИТНИХ МАТЕРІАЛІВ ДЛЯ ЗАСТОСУВАННЯ У АРМОВАНИХ КОНСТРУКЦІЯХ

Purpose. To provide a materials-science-driven comparison between steel and glass fiber reinforced polymer reinforcement in concrete structures, with emphasis on how chemical composition, fiber fraction, and interfacial engineering influence mechanical behavior, durability, fatigue, and heat resistance, thereby identifying microstructural strategies to enhance glass fiber reinforced polymer performance.

Methodology. Integrates a comparative materials-science analysis using micromechanical modeling (rule of mixtures, strength efficiency factors), normalized property metrics, and durability data, combined with literature-based experimental evidence on mechanical, thermal, and fatigue performance of steel and glass fiber reinforced polymer.

Findings. The findings show that while steel maintains superior stiffness, ductility, and fire resistance, glass fiber reinforced polymer offers higher tensile strength-to-weight ratio, corrosion immunity, and electromagnetic neutrality. Mechanical modeling confirms that fiber chemistry, fraction, and matrix selection govern glass fiber reinforced polymer performance, upgrading to S- or AR-glass, adopting high thermal transition matrices, nanoscale modifiers, and hybrid fiber architectures significantly improve fatigue life and thermal stability.

Originality. The originality of this research lies in framing the comparison between steel and glass fiber reinforced polymer reinforcement not only at the structural scale, but at the microstructural and chemical levels, linking fiber composition, polymer matrix selection, and interfacial engineering to mechanical performance, fatigue, and thermal stability. Unlike conventional studies that assess only as a corrosion-resistant alternative, identified targeted material design strategies, such as high-transition matrices, nanoscale tougheners, and hybrid fiber architectures, that can systematically extend the serviceability and safety of glass fiber reinforced polymer in reinforced concrete, thereby positioning composites as a scientifically optimized, rather than merely substitute, reinforcement solution.

Practical value. Value of this research is in guiding engineers toward microstructurally optimized glass fiber reinforced polymer rebars with improved fatigue and heat resistance, enabling safer, longer-lasting concrete structures in aggressive environments where steel rapidly degrades

Keywords: *reinforced concrete, steel reinforcement, GFRP, microstructural design, durability.*

Introduction. Reinforcement of concrete elements is a cornerstone of modern structural engineering because it governs service life, reliability, and safety. Conventionally, steel has been the default reinforcement owing to its high tensile strength, ductility, and thermal compatibility with the cementitious matrix, which together enable reinforced concrete (RC) to dominate building and infrastructure applications [1], [2]. Nevertheless, the recurring liabilities of steel-foremost corrosion in humid and chemically aggressive environments, high density, and electrical/magnetic conductivity-continue to motivate the search for alternative reinforcing systems that can extend durability while reducing self-weight and maintenance burdens [3].

Polymer-matrix fiber-reinforced polymer (FRP) bars-typically based on glass (GFRP), basalt (BFRP), or carbon (CFRP) fibers in thermosetting resins-represent the most mature non-metallic alternative [4, 5]. At the material level, FRPs are fundamentally different from steel: they are anisotropic, fiber-dominated composites whose stiffness and strength depend on fiber type, volume fraction, and fiber orientation, as well as on the quality of the fiber-matrix interface and the manufacturing route (e.g., pultrusion). These microstructural and processing parameters control macroscopic properties and failure modes to a degree far exceeding that of conventional metals.

In structural practice, FRP bars provide key advantages: low density (≈1.5–2.0 g cm^{-3}), non-corrosivity, and dielectric behavior, all of which are beneficial in marine, chemically aggressive, or electromagnetically sensitive facilities. Reported tensile strengths for GFRP commonly exceed those of mild reinforcing steels, while CFRP attains even higher ranges [6]. However, FRP elastic moduli are markedly lower than steel (for GFRP by a factor of roughly 3–5), a point that directly affects serviceability (deflection and crack width) of RC members [7].

The shift from metallic to composite reinforcement, however, introduces trade-offs grounded in materials science. First, FRPs exhibit linear-elastic behavior up to rupture with minimal plasticity; consequently, member-level failure can be brittle, and warning deformations before collapse are limited. Second, the lower axial modulus of GFRP/BFRP implies larger curvatures under comparable bending moments, necessitating explicit serviceability checks and often higher reinforcement ratios or hybrid solutions to meet deflection and crack-control criteria. Third, the fire performance of FRP is constrained by the thermo-oxidative degradation and softening of polymer matrices at elevated temperature, which undermines load transfer across the fiber-matrix interface despite the high intrinsic stability of some fibers (e.g., carbon). As a result, design with FRP in high-temperature scenarios demands protective measures (cover, coatings) or material innovations (thermally stable matrices, hybrids) [7].

Comparative experimental and analytical studies at the member scale consistently reflect these material contrasts [1, 4]. Beams reinforced with GFRP can attain adequate ultimate capacities but often show larger service-level crack widths and a more brittle failure response than their steel-reinforced counterparts; pull-out tests generally indicate that surface treatments (e.g., sand-coating, ribbing, helical wraps) are essential to achieve bond performance commensurate with RC design needs. Cost comparisons further indicate that although unit prices of FRP bars may exceed those of steel, whole-life economics can be favorable when corrosion risk and maintenance are accounted for [2].

From the durability perspective, the non-corrosive nature of FRP eliminates the dominant degradation mechanism of conventional reinforcement. Conservative projections and field evidence report long service lives for GFRP in chloride-rich and moist environments, with estimates extending beyond a century under appropriate exposure and detailing, underscoring the technology's potential for bridges, quay structures, parking facilities, and de-icing salt-exposed decks [6, 7].

Designers thus face a materials-informed selection problem: steel remains unmatched for ductility, stiffness, and robustness under fire, whereas FRP provides superior corrosion resistance, low mass, and electromagnetic neutrality. The most rational deployment follows the exposure profile: FRP is compelling in marine, chemical, or de-icing contexts and in facilities where low weight or non-magnetic behavior is critical; steel retains advantages in high-temperature risk scenarios and where large stiffness at moderate reinforcement ratios is required [3, 7, 8].

Emerging hybrid strategies-such as combining steel and FRP or adopting carbon-based bars for high-stiffness zones-aim to reconcile these competing demands. At the same time, advances in composite design (e.g., optimized fiber architectures, improved matrices, and controlled anisotropy) continue to mature, supported by comprehensive manufacturing and design frameworks that link laminate-scale mechanics, joining, and quality assurance to structural performance.

Against this backdrop, the present work provides a materials-science-centric comparison between steel and composite reinforcement for RC members. We synthesize property-structure-processing relationships for representative FRP systems, assess mechanical performance and failure phenomenology at material and member scales, and discuss durability mechanisms and environmental resistance relevant to real exposures. The analysis is anchored in established comparative data and experimental evidence from RC beams and bond tests, and it is framed to inform serviceability-driven design choices, durability-based material selection, and pathways for hybridization and fire resilience.

Main part. The scientific novelty of this research lies in establishing microstructural design strategies-through targeted modification of glass fiber chemistry, fiber fraction, matrix composition, and interfacial engineering-that enhance the fatigue endurance and thermal resistance of GFRP reinforcement beyond conventional formulations, thereby narrowing the performance gap with steel in structural applications.

Glass fiber reinforced polymer (GFRP) reinforcement derives its performance directly from the chemistry and structure of its constituents. The glass fibers, most often of E-glass, S-glass, or alkali-resistant (AR-glass) type, provide the load-bearing capacity, while the polymeric matrix-typically epoxy, vinyl ester, or polyester-ensures cohesion, protection, and load transfer. The chemical composition of the fibers determines their baseline properties: E-glass consists of ~50–70 wt% SiO_2 with additions of Al_2O_3, CaO, MgO, and B_2O_3, producing a modulus of elasticity of about 72 GPa and tensile strength near 3.4 GPa. S-glass, with higher Al_2O_3 and less alkali content, reaches ~88 GPa modulus and ~4.6 GPa tensile strength. AR-glass incorporates 15–20% ZrO_2 to resist alkali attack in concrete pore solutions. The polymer matrix, with modulus values of only 2-4 GPa, cannot contribute much stiffness but provides chemical resistance and toughness. Silane coupling agents chemically bond the glass surface to the resin, enhancing interfacial shear strength and long-term durability.

Unlike steel, which is a homogeneous Fe-based alloy with an elastic modulus E_s≈200 GPa and ductile yielding behavior, GFRP is a heterogeneous anisotropic system. Its longitudinal modulus and tensile capacity are described by micromechanical models. The axial modulus of a unidirectional composite can be estimated by the rule of mixtures:

$$E_1 = V_f E_f + (1 - V_f)E_m \quad (1)$$

where V_f – the fiber volume fraction, wt%; E_f – fiber modulus, GPa; E_m – matrix modulus, GPa.

For example, with V_f = 0,55, E_f = 72,5 GPa, and E_m = 3 GPa, one obtains

$$E_1 = 0{,}55 \times 72{,}5 + 0{,}45 \times 3 = 41{,}5 \text{ GPa} \quad (2)$$

which is consistent with experimental GFRP bar values of 35–50 GPa. The tensile strength follows a similar proportionality:

$$\sigma_{1u} = \eta_{L\eta_0} V_f \, \sigma_{f,u}, \quad (3)$$

where η_L – length efficiency factor; η_o – orientation factor; $\sigma_{f,u}$ – ultimate strength of individual fibers, MPa.

This relation (3) explains why higher fiber volume fractions and optimized orientations increase the bar's tensile capacity, while poor bonding or fiber waviness reduce effective strength.

In comparison, steel reinforcement provides yield strengths in the range of 280–520 MPa and ultimate tensile strengths between 480–690 MPa, but with significant ductility (ε_u~6–12%). GFRP, depending on fiber grade and processing, achieves bar tensile strengths of 900–1500 MPa but with ultimate strains of only 1,2–2,5%. This distinction leads to a brittle failure mode for composites, in contrast to the plastic reserve of steel.

Specific performance is also better understood through normalized metrics. The stiffness per unit area of GFRP relative to steel is

$$\frac{E_{GFRP}}{E_S} \approx \frac{40-50}{200} = 0{,}20 - 0{,}25, \quad (4)$$

while the stiffness per unit mass is much closer:

$$\left(\frac{E}{\rho}\right)_{GFRP} \Big/ \left(\frac{E}{\rho}\right)_S \approx \frac{45/1{,}9}{200/7{,}8} \approx 0{,}9, \quad (5)$$

since the density of GFRP is ~1.9 g cm^{-3} compared with steel's 7.8 g cm^{-3}. Thus, on a weight basis, GFRP approaches steel in efficiency, even though on a cross-sectional basis it is only about a quarter as stiff.

The influence of chemical and fractional composition extends to durability. AR-glass with ZrO_2 demonstrates superior alkali resistance in cement pore water, while optimized fiber-matrix coupling limits moisture ingress and preserves strength after long exposures. Moisture absorption of GFRP bars is typically only 0.2–0.5%, with negligible impact on strength. Chloride attack, which devastates steel, has no effect on glass fibers or resins, leading to long-term durability in marine structures. However, the polymer matrix undergoes thermal degradation above 250–300 °C, meaning that GFRP loses capacity rapidly in fires, unlike steel, which, despite losing strength at 500–600 °C, retains ductility and redistribution capability.

In summary, the chemistry of the glass phase defines the intrinsic modulus and strength, the fiber fraction and orientation determine stiffness and capacity at the bar level, and the matrix-interface system controls durability and bond. Compared with steel, GFRP bars deliver higher tensile strength and lighter weight but at the cost of lower stiffness, no yielding, and reduced thermal stability. These differences necessitate different design philosophies: serviceability and fire protection govern FRP design, while ductility and stiffness make steel irreplaceable in many contexts. Hybrid reinforcement systems and improved glass chemistries aim to bridge these contrasts, combining the corrosion resistance of composites with the ductility and stiffness of steel.

To push GFRP rebar toward higher fatigue and heat resistance, the levers live at the micro-scale: fiber chemistry and architecture, matrix chemistry, and the fiber-matrix interface (sizing/interphase), all under tight process control (voids, cure, V_f).

Upgrading the glass grade from E-glass to S-glass raises filament modulus and strength (≈88 GPa and ≈4.6 GPa vs ≈72 GPa and ≈3.4 GPa), which directly lifts the bar's axial stiffness/strength through the rule of mixtures,

$$E_1 = V_f E_f + (1 - V_f) E_m, \tag{6}$$

$$\sigma_{1u} \approx \eta_L \eta_o V_f \sigma_{f,u}, \tag{7}$$

so long as keep the load-transfer factors η_L, η_o high (minimal waviness, good sizing). For alkaline pore solutions, AR-glass (ZrO_2-bearing) protects fibers from stress-corrosion and helps preserve fatigue strength under wet-alkaline cycling. Filament downsizing (e.g., from ~16→13 μm) increases specific surface area for better interfacial shear and crack deflection; it typically tightens strength scatter and improves high-cycle fatigue when paired with compatible sizings. Hybridizing a small carbon fiber fraction into the outer wrap (G/C-hybrid) raises local modulus and delays tensile hot-spots and matrix cracking, improving S-N response and thermal sag resistance without fully abandoning glass economics.

At constant V_f, the matrix choice controls glass-transition temperature T_g, thermo-oxidative stability, and crack-growth resistance. Replacing commodity polyesters with epoxies or vinyl esters already improves hydrolysis and fatigue; moving to benzoxazine or bismaleimide/cyanate-ester systems pushes T_g well above 200 °C and markedly improves hot-wet modulus retention (at higher cost/processing temperatures). A robust post-cure (ramp/soak above initial T_g) increases crosslink density, raising T_g and fatigue limit (matrix cyclic yield) and reducing creep at service temperatures. For deployability and recyclability, high-T_g thermoplastics (e.g., PEI, PEEK) with continuous glass tows are a promising rebar matrix class: they provide superior crack-growth resistance and heat deflection at equal V_f, and their energy-absorbing interlaminar yielding benefits fatigue.

Fatigue in GFRP often nucleates at the fiber-matrix interface. Two microlevel routes are synergistic. Match sizing chemistry (epoxy-, amine-, or vinyl-functional silanes) to the chosen resin so that the interphase forms covalent bridges, lifting interfacial shear strength τi and suppressing debond under cyclic shear. Add nanoscale tougheners-core-shell rubber (CSR), nano-silica (≈10–50 nm), or nanoclays-in 1–5 phr to the resin to raise fracture energy G_{IC} and slow matrix-crack coalescence, which directly flattens the S-N slope. Graphene/CNT traces (<0.5 phr) can raise both T_g (restricted chain mobility) and fatigue strength by crack bridging and energy dissipation. Introduce a helical glass wrap or a thin braided veil around the unidirectional core during pultrusion. This arrests longitudinal splitting, lifts torsional and interlaminar fatigue, and-bonus-improves bond to concrete without sacrificing axial properties. Surface sand-coating or ribbing increases effective η_L at the concrete interface (less slip, lower crack widths), reducing cyclic strain peaks in the rebar.

Heat resistance is matrix-limited long before glass fibers soften. Combine a high-T_g resin family with inorganic nano-fillers (SiO_2, Al_2O_3, BN, or layered silicates, 3–10 wt%) to raise thermal conductivity slightly (spreading heat), suppress micro-void growth, and elevate Tg and storage modulus above service temperatures. Phosphorus/nitrogen intumescents (e.g., DOPO derivatives) can be used judiciously for flame retardancy; pick grades that minimize plasticization so fatigue isn't compromised. If alkaline durability is critical (wet hot concrete), favor AR-glass with optimized zirconia content and moisture-resistant sizings; if high-temperature excursions are unavoidable, a carbon/glass hybrid face or a BMI/benzoxazine matrix is the right lever.

Regardless of chemistry, keep void content below ~1–2% (degassed resin, controlled pull speed, stable die temperature), minimize fiber waviness and residual cure stresses (balanced exotherm, staged post-cure), and target $V_f \approx 0.50–0.60$ (above ~0.6 you risk dry zones and poorer hot-wet performance; below ~0.45 you leave fatigue and stiffness on the table). These controls raise both E_1 and σ_{1u} through the relations above and, more importantly, extend the fatigue knee by removing early crack initiators.

Swapping E-glass/epoxy (E_f≈72,5 GPa, E_m ≈3 GPa, V_f=0.55) for S-glass/benzoxazine (E_f≈88GPa, E_m≈3.5-4 GPa, same V_f) lifts axial modulus by the rule of mixtures from ≈41.5 GPa to ≈50 GPa; adding 5 wt% nano-silica typically adds a few percent more effective E_1 and increases G_{IC}, flattening fatigue damage accumulation (qualitatively, a right-shifted S-N). A helical wrap plus sand-coat reduces slip and peak cyclic strains at service, which field and lab studies correlate with narrower cracks and delayed brittle events in GFRP-RC beams.

If chloride/alkali durability dominates and fire is not governing, all-glass + AR chemistry + high-T_g epoxy/vinyl ester with nanofillers and optimized sizing is cost-optimal. If service temperature or thermal spikes are credible, step to benzoxazine/BMI and consider a thin carbon wrap to hold stiffness above T_g and suppress matrix-crack growth under heat-fatigue coupling. In both cases, keep pultrusion parameters tuned to minimize defects; the fatigue gain from lower voids often rivals that from fancier chemistries.

Microlevel upgrades that reliably move the needle are: (i) higher-grade glass (S- or AR-), (ii) high-T_g, toughened matrices (epoxy→benzoxazine/BMI or high-T_g thermoplastics) with nano-tougheners, (iii) resin-sizing compatibility for a strong, moisture-resistant interphase, (iv) thin helical/braided wraps and sand/ribbed surfaces for crack arrest and bond, and (v) disciplined processing for low voids, low waviness, and V_f≈0.5-0.6. Together these changes raise T_g, slow fatigue crack initiation and growth, and keep the composite in the elastic regime under real service spectra-while maintaining the corrosion immunity that is GFRP's core advantage.

Conclusion. Reinforcing concrete with either steel or fiber-reinforced polymers (FRPs) reflects a balance between long-proven metallic performance and emerging composite solutions. Steel remains the standard due to its high modulus, ductility, and thermal stability, yet its major drawbacks, corrosion, high density, and electromagnetic activity, create costly durability challenges. GFRP, by contrast, is lightweight, corrosion-immune, and non-conductive, offering clear advantages in marine, chemically aggressive, and electromagnetically sensitive environments. However, its lower modulus, brittle failure, and limited heat resistance necessitate a different design philosophy focused on serviceability, protection from high temperatures, and careful detailing.

At the microstructural level, GFRP's behavior is governed by fiber chemistry, matrix composition, fiber volume fraction, and interfacial adhesion. The rule of mixtures shows how fiber modulus and content dictate stiffness and tensile strength, while the brittle rupture mode stems from the absence of yielding. Compared with steel, which deforms plastically before failure, GFRP fails suddenly after elastic loading, requiring conservative design and redundancy. Nevertheless, long-term field studies confirm that GFRP bars retain strength over decades in chloride-rich and wet environments, where steel reinforcement would undergo severe corrosion damage.

The essential result of this research is the demonstration that targeted microstructural modifications can substantially close the performance gap with steel. Substituting E-glass with higher-grade S-glass or alkali-resistant (AR) glass improves stiffness, tensile strength, and durability in concrete pore solutions. Advanced polymer matrices-benzoxazines, bismaleimides, or high-Tg thermoplastics-raise heat resistance and slow fatigue degradation, while optimized silane sizings, nanosilica, or graphene additives strengthen the fiber-matrix interface against cyclic debonding. Hybrid glass/carbon fiber configurations further elevate stiffness and thermal stability without abandoning the economic advantage of glass.

Thus, while steel remains unmatched for ductility and fire resistance, GFRP can be engineered into a high-performance, durable alternative when corrosion resistance, low weight, and electromagnetic neutrality are decisive. The study highlights that the future of reinforced concrete lies not in a binary choice between steel and composites, but in material- and environment-driven selection, hybrid strategies, and microstructural innovations that extend service life and reliability.

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АНОТАЦІЯ

Мета. Сформулювати матеріалознавчо орієнтоване порівняння між сталевою та скловолоконною композитною арматурою в бетонних конструкціях із встановленням впливу хімічного складу, частки волокон на механічну поведінку, довговічність, втому та термостійкість, із подальшою ідентифікацією мікроструктурних стратегій підвищення ефективності скловолоконного композитного матеріалу.

Методика. Інтегрує порівняльний матеріалознавчий аналіз із використанням мікромеханічного моделювання (правило сумішей, коефіцієнти ефективності міцності), нормалізованих показників властивостей та даних щодо довговічності у поєднанні з експериментальними результатами з літератури стосовно механічних, теплових та втомних характеристик сталі й скловолоконного композитного матеріалу.

Результати. Дослідження показало, що сталь зберігає вищу жорсткість, пластичність і вогнестійкість, тоді як скловолоконний композитний матеріал забезпечує вищу міцність на розтяг відносно маси, імунітет до корозії та електромагнітну нейтральність. Механічне моделювання підтверджує, що хімія волокон, їхня частка та вибір матриці визначають характеристики скловолоконного композитного матеріалу; застосування S- або AR-волокна, високотемпературних матриць, наномодифікаторів та гібридних архітектур волокон суттєво покращує втомну міцність і термостійкість..

Наукова новизна. Полягає у порівнянні сталевої та скловолоконної композитної арматури не лише на механічному рівні, але й на мікроструктурному та хімічному, із встановленням зв'язку між складом волокон, вибором полімерної матриці та механічними властивостями, втомною та термостійкісними характеристиками. Науково обгрунтовано, що високотемпературні матриці, наномодифікатори та гібридні архітектури волокон підвищують експлуатаційну надійність і безпеку використання в різних експлуатаційних умовах скловолконного композитного матеріалу у кінцевих виробах, де традиційно застосовується сталевий матеріал.

Практична цінність. Практичне значення результатів дослідження полягає у сформлюваних інженерних рекомендаціях щодо використання мікроструктурно оптимізованої скловолокон-

ної композитної арматури з покращеною втомною та термостійкою характеристиками, що забезпечує підвищенні показники безпеки експлуатації та довговічності у бетонних конструкціях, у яких сталева арматура проявляє ознаки деградації початкових характеристик.

Ключові слова: *залізобетон, сталева арматура, скловолоконний композитний матеріал, мікроструктурний стан, довговічність.*

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