METRO INFRASTRUCTURE COMPOSITE MATERIALS APPLICATION: GLOBAL EXPERIENCE AND FUTURE DIRECTIONS

Shaumarov Said Sanatovich
Vice-Rector for Research and Innovation, Tashkent State Transport University, Doctor of Technical Sciences, Professor.
https://orcid.org/0000-0001-8935-7513
Azamov Nodirbek Fakhriddin ugli
1st-year PhD student at Tashkent State Transport University.
https://orcid.org/0000-0001-9311-0273
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ABSTRACT

This study examines the integration of advanced composite materials into metro infrastructure systems with particular emphasis on corrosion-resistant reinforcement technologies, composite-based protective linings, and innovative strengthening solutions. International implementation practices, engineering performance indicators, economic implications, and long-term sustainability aspects are systematically evaluated. The findings reveal that fiber-reinforced polymer (FRP) systems significantly enhance structural durability, extend operational lifespan, and reduce lifecycle maintenance costs when compared to conventional steel-based solutions. The research further identifies technological challenges and outlines strategic directions for future development in underground transportation infrastructure..

Introduction

Urban rail transit systems form the backbone of modern metropolitan mobility. Due to continuous exposure to underground moisture, chemically aggressive soils, stray currents, and dynamic train-induced loads, metro structures demand materials with exceptional mechanical reliability and environmental resistance. Traditional reinforced concrete systems rely heavily on steel reinforcement, which is susceptible to corrosion, particularly in chloride-rich and humid underground conditions. Progressive deterioration of steel bars compromises structural integrity and increases maintenance costs.

In response to these limitations, composite materials - particularly glass fiber reinforced polymer (GFRP), basalt fiber reinforced polymer (BFRP), and carbon fiber reinforced polymer (CFRP) - have emerged as viable alternatives. These materials combine high tensile capacity with corrosion resistance and low density, making them increasingly attractive for tunnel linings, structural segments, and seismic retrofitting applications.

Literature Review

Over the last three decades, composite reinforcement technologies have been extensively investigated in civil engineering research. Early experimental studies confirmed that FRP reinforcement bars exhibit substantially higher tensile strength and superior resistance to electrochemical corrosion compared to conventional steel reinforcement. Subsequent research expanded to include durability assessments in aggressive environments and long - term exposure conditions.

Investigations into tunnel infrastructure demonstrated that polymer-based protective coatings significantly reduce chloride penetration and mitigate concrete deterioration mechanisms. Field implementations in major metro networks provide valuable practical evidence of performance:

- In seismic retrofitting initiatives, CFRP systems have been applied to enhance structural ductility and energy dissipation capacity in the Tokyo metro system.
- Experimental BFRP reinforcement has been introduced in new tunnel segments within the Moscow metro network to address corrosion issues associated with persistent humidity.
- Accelerated construction techniques in the Beijing metro have incorporated GFRP - reinforced precast segments to reduce structural weight and improve installation efficiency.
- The Berlin underground railway has implemented advanced polymer linings to enhance moisture resistance and long-term durability.

These documented applications demonstrate that composite materials contribute not only to technical performance enhancement but also to sustainability objectives through prolonged service life and reduced rehabilitation frequency.

Materials and Methods

Characteristics of Composite Reinforcement

The composite systems evaluated in this research include:

- **GFRP:** Offers high tensile resistance, low weight, and immunity to corrosion in aggressive environments.
- **BFRP:** Provides improved chemical stability and cost-efficiency compared to other fiber systems.
- **CFRP:** Delivers superior stiffness and strength, particularly suitable for seismic strengthening applications.

Material properties were reviewed in accordance with internationally recognized standards, including ASTM and ACI guidelines. Mechanical parameters such as tensile capacity, modulus of elasticity, density, and durability performance were compared with those of traditional steel reinforcement.

Research Methodology

A combined qualitative and quantitative analytical framework was adopted. The methodology consisted of:

- ✓ Systematic review of peer-reviewed academic publications and technical reports.
- ✓ Comparative assessment of mechanical, durability, and economic performance indicators.
- ✓ Evaluation of case studies from operational metro systems using composite materials.
- ✓ Lifecycle cost analysis considering maintenance, repair frequency, and service interruptions over a 50-year period.

Result

Durability Performance

Experimental data indicate that FRP reinforcement exhibits negligible corrosion when exposed to chloride-rich environments. In contrast, steel reinforcement typically demonstrates measurable degradation within one to two decades under similar conditions. Long-term testing confirms that GFRP and BFRP materials retain more than 90% of their original tensile capacity after extended environmental exposure.

Mechanical and Structural Performance

A comparative evaluation of structural parameters is summarized below:

Parameter	Steel Reinforcement	FRP Reinforcement (GFRP/BFRP/CFRP)
Tensile Strength	400 - 600 MPa	800 - 1500 MPa
Corrosion Resistance	Limited	Excellent
Density	7850 kg/m^3	1600 - 2000 kg/m^3
Expected Service Life	50 - 70 years	80 - 100+ years
Seismic Energy Dissipation	Moderate	High (especially CFRP)

The reduced density of composites significantly lowers structural dead load, facilitating transportation and installation of precast tunnel elements. Moreover, CFRP strengthening systems enhance ductility and improve structural behavior under seismic excitation.

Economic Evaluation

Although composite reinforcement materials generally involve higher initial procurement costs-approximately 20-30% above conventional steel-lifecycle economic modeling indicates substantial long-term savings. Reduced corrosion-related repairs, minimized operational disruptions, and extended service intervals collectively compensate for the higher upfront investment over a 50-year analysis horizon.

Discussion

The integration of composite materials into metro infrastructure yields multiple engineering and economic benefits:

- **Corrosion Control:** Elimination of electrochemical degradation mechanisms enhances structural reliability.
- **Extended Operational Life:** Increased durability reduces the need for major rehabilitation.
- **Improved Seismic Response:** CFRP-based strengthening systems significantly increase energy absorption capacity.
- **Construction Efficiency:** Lightweight materials enable modular construction techniques and lower labor demands.

Despite these advantages, several barriers remain. Design standard harmonization, accumulation of long-term field performance data, and further cost optimization are required to facilitate broader implementation. Continued refinement of international standards and design codes will play a key role in expanding adoption.

Conclusion

Global practice demonstrates that composite materials offer a technologically advanced and economically viable alternative to traditional steel reinforcement in metro infrastructure systems. Their superior resistance to aggressive underground environments, reduced structural weight, and enhanced seismic performance make them particularly suitable for modern underground transportation projects.

Future research should prioritize comprehensive monitoring of large-scale applications, development of optimized design methodologies, and expansion of implementation strategies in emerging metro systems. Adoption of composite technologies can significantly contribute to sustainable and resilient urban transport infrastructure development.

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