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Comparative study of composite and conventional materials in building structures

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ABSTRACT

The choice of construction materials significantly influences the structural performance, durability, and sustainability of modern buildings. This study presents a comparative analysis between composite materials such as fiber-reinforced polymers (FRP) and steel-concrete composites and conventional materials, including reinforced concrete and structural steel, in building applications. The research employs both experimental testing and finite element modeling to evaluate key parameters such as compressive and tensile strength, load-bearing capacity, deformation behavior, and long-term durability under environmental stressors. Life cycle cost analysis and environmental impact assessment are also conducted to determine overall material efficiency. Results indicate that composite materials generally offer superior strength-to-weight ratios, enhanced corrosion resistance, and reduced maintenance needs compared to conventional materials, though they often involve higher initial costs and require specialized construction techniques. These findings provide valuable insights for architects, engineers, and policymakers seeking to optimize material selection for sustainable and high-performance building structures.

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1. INTRODUCTION

The selection of construction materials has always played a pivotal role in the design, performance, and sustainability of building structures. From ancient stone and timber to modern high-performance composites, the evolution of materials reflects advances in technology, engineering knowledge, and societal demands. In contemporary construction practice, engineers and architects must balance multiple criteria structural strength, durability, cost, environmental impact, and aesthetic value when determining the most suitable material for a project. Traditionally, conventional materials such as reinforced concrete, structural steel, and masonry have dominated the industry due to their proven performance, widespread availability, and well-established design standards. However, the increasing demand for lighter, stronger, and more durable materials, coupled with heightened sustainability requirements, has accelerated the adoption of composite materials in building structures.

Composite materials, broadly defined as materials made from two or more constituent components with significantly different physical or chemical properties, offer synergistic benefits that cannot be achieved by individual materials alone. Fiber-reinforced polymers (FRPs), steel–concrete composites, laminated timber products, and hybrid cementitious materials are examples of composites that are now entering mainstream construction. Their appeal lies in their superior strength-to-weight ratios, corrosion resistance, and flexibility in design. Nonetheless, their relatively high initial costs, specialized fabrication requirements, and limited long-term performance data compared to conventional materials pose challenges for universal adoption. This duality creates a crucial point of inquiry: when and where do composite materials offer tangible advantages over conventional options in building structures, and under what circumstances do traditional materials remain preferable.

The debate is not merely academic. As cities expand vertically, as climate change increases environmental stress on infrastructure, and as sustainable construction becomes a legal and ethical imperative, the choice between composite and conventional materials can determine the economic viability, environmental footprint, and safety of a building over its entire life cycle. This comparative study aims to investigate these trade-offs systematically, offering evidence-based guidance for material selection in various structural contexts. Historically, building materials evolved in response to resource availability, technological capabilities, and cultural preferences. Early human shelters relied on natural materials such as wood, clay, and stone, chosen primarily for accessibility and ease of manipulation. With the advent of metallurgy, iron and steel began to replace timber in critical structural applications, enabling longer spans and taller buildings. The industrial revolution brought about mass production of steel and cement, ushering in an era dominated by steel-framed skyscrapers and reinforced concrete high-rises.

The second half of the 20th century saw growing awareness of the limitations of conventional materials—steel's susceptibility to corrosion, concrete's vulnerability to cracking and spalling, and masonry's relatively low tensile capacity. Advances in polymer chemistry and materials engineering led to the development of composites that could overcome some of these shortcomings. Initially, composites such as FRPs were used primarily in aerospace and marine industries due to their high performance and cost. Over time, as manufacturing processes improved and costs declined, these materials found their way into civil engineering applications, first in specialized retrofitting projects and later in new structural designs. In parallel, sustainability considerations emerged as a dominant force in material choice. The environmental costs of cement production, the embodied energy of steel, and the depletion of natural resources such as hardwoods pushed researchers and practitioners to seek greener alternatives. Composites particularly those incorporating recycled fibers or low-carbon matricesoffered a potential pathway toward reduced environmental impact without compromising structural performance. This evolution has set the stage for a direct, evidence-based comparison between composite and conventional materials in building structures. Composite materials in construction encompass a wide range of combinations, each tailored for specific structural and performance requirements

Fiber-Reinforced Polymers (FRPs): These include glass fiber-reinforced polymer (GFRP), carbon fiber-reinforced polymer (CFRP), and aramid fiber-reinforced polymer (AFRP). They are widely used for strengthening existing structures, manufacturing lightweight panels, and fabricating non-corrosive reinforcement bars. FRPs offer high tensile strength, excellent corrosion resistance, and reduced maintenance needs. Steel–Concrete Composites: A hybrid structural form that combines the compressive strength of concrete with the tensile strength of steel. Common applications include composite beams, columns, and floor systems in high-rise buildings. They provide high stiffness, rapid construction, and favorable seismic performance. Engineered Timber Composites: Cross-laminated timber (CLT) and laminated veneer lumber (LVL) are examples of composites in the timber category. These materials offer renewable, lightweight solutions with competitive structural performance and reduced carbon footprint.

Hybrid Cementitious Composites: These incorporate fibers, polymers, or supplementary cementitious materials to enhance ductility, crack resistance, and durability. The inherent advantage of composites lies in the tailored combination of constituent materials, allowing engineers to optimize structural properties for specific design challenges. For example, FRP reinforcement can be strategically placed in areas prone to corrosion, extending service life without overdesigning the entire structure. Conventional materials reinforced concrete, structural steel, masonry, and timber remain the backbone of the construction industry. Their dominance is supported by decades of performance data, well-established codes of practice, and familiarity among construction professionals. Reinforced Concrete (RC): Known for its versatility, durability, and ability to be cast into complex shapes. RC performs well under compression and, when reinforced with steel bars, offers adequate tensile capacity. Structural Steel: Offers high strength, ductility, and ease of assembly. Its uniform properties and recyclability make it suitable for rapid construction and long-span structures. Masonry: Durable and fire-resistant, masonry remains popular for low-rise and non-structural applications. Advances in block manufacturing have improved its strength and thermal properties. Solid Timber: Traditional wood remains common for residential construction due to its availability, ease of use, and aesthetic appeal.

Despite these strengths, conventional materials have limitations that drive the exploration of composites. Steel requires protective coatings or treatments to prevent corrosion; concrete is heavy and prone to cracking; masonry lacks tensile strength; and solid timber is susceptible to decay and insect attack. Strength-to-Weight Ratio: Composites generally outperform conventional materials in terms of load capacity per unit weight, enabling lighter structures and reduced foundation loads. Durability: Composites, particularly FRPs, are resistant to corrosion, chemical attack, and freeze–thaw cycles, whereas conventional materials require ongoing maintenance to achieve similar lifespans. Fire Resistance: Conventional materials such as concrete and masonry have inherent fire resistance, whereas many composites require fireproofing treatments or protective layers. Seismic Performance: The ductility and energy dissipation capacity of steel–concrete composites make them attractive for seismic zones, while lightweight composites can reduce seismic loads on structures. Construction Efficiency: Prefabricated composite components can accelerate construction timelines, but specialized fabrication and skilled labor may offset time savings.

Sustainability in construction is measured not only by the operational performance of a building but also by the environmental impact of the materials used. Cement production accounts for approximately 8% of global CO_2 emissions, and steel production is similarly carbon-intensive. Composites have the potential to reduce embodied energy through lightweight designs, longer service life, and incorporation of recycled or renewable components. However, their environmental benefits must be weighed against challenges in recycling and end-of-life disposal, as many composites are difficult to separate into constituent materials. Life cycle assessment (LCA) is a valuable tool for this comparison, encompassing extraction, processing, transportation, installation, operation, maintenance, and disposal phases. Some studies suggest that steel–concrete composites offer lower life cycle impacts than pure steel or concrete systems due to material efficiency, while FRPs can significantly extend the life of rehabilitated structures with minimal environmental cost.

Cost remains a decisive factor in material selection. Conventional materials generally have lower initial costs due to economies of scale, established supply chains, and local availability. Composite materials often involve higher upfront costs due to raw material prices, manufacturing complexity, and specialized labor requirements. However, when considering total cost of ownership including maintenance, repair, and replacement composites may offer competitive or even superior value over the structure's life span. For example, FRP reinforcement in a coastal building may cost more initially than steel rebar, but the absence of corrosion-related maintenance could offset the initial premium. Similarly, prefabricated composite panels can reduce labor costs and construction time, providing indirect financial benefits. While numerous studies have examined specific aspects of composite or conventional materials in isolation, comprehensive comparative analyses covering structural performance, durability, sustainability, and economics remain limited.

Most existing literature focuses on one performance criterion such as strength or durability without integrating life cycle and economic perspectives. Additionally, variations in testing methodologies and performance benchmarks hinder direct comparison between materials. This gap in holistic evaluation creates uncertainty for decision-makers, particularly in projects with complex performance and sustainability requirements. The findings of this research will contribute to the body of knowledge guiding material selection in modern building design. By providing a holistic comparison that integrates structural, environmental, and economic factors, the study will assist engineers, architects, and policymakers in making informed decisions. Furthermore, it will highlight opportunities for innovation in composite manufacturing and applications, potentially accelerating their adoption where they offer clear advantages.

2. RESEARCH METHOD

This study adopts a comparative experimental and analytical research design to evaluate the performance, sustainability, and economic feasibility of composite and conventional materials in building structures. The research is conducted in two phases: (1) laboratory testing of selected material specimens and (2) life cycle and cost analysis based on experimental results and secondary data. Finite element modeling (FEM) is conducted using ANSYS to simulate full-scale structural performance under static, dynamic, and seismic loads. The experimental data are used to validate the simulation models, ensuring accuracy in predicting real-world behavior. A life cycle assessment (LCA) is performed following ISO 14040 standards, covering raw material extraction, manufacturing, transportation, operation, and end-of-life disposal or recycling. The environmental indicators analyzed include embodied energy, carbon footprint, and resource depletion. Economic evaluation is carried out through life cycle cost analysis (LCCA), incorporating initial material costs, construction expenses, maintenance, and replacement over a projected 50-year service life. Results are compared using statistical analysis (ANOVA) to determine significant differences between material categories at a 95% confidence level. The combined mechanical, environmental, and economic findings are synthesized to formulate recommendations for material selection in various building contexts.

3. RESULTS AND DISCUSSIONS

3.1. Mechanical Performance

The compressive strength tests revealed notable differences between composite and conventional materials. Steel–concrete composite specimens exhibited the highest compressive strength, averaging 72.4 MPa, compared to 52.8 MPa for conventional reinforced concrete beams. This represents a 37% improvement in load-bearing capacity under compression. The cross-laminated timber (CLT) samples achieved an average compressive strength of 38.2 MPa, surpassing that of conventional solid timber (32.5 MPa) by 17.5%, owing to the engineered lamination process that improves uniformity and reduces defects. Fiber-reinforced polymer (FRP) panels demonstrated exceptional tensile strength, averaging 1,240 MPa, significantly exceeding structural steel's 490 MPa. However, steel's ductility was notably higher, with an elongation at break of 19.2%, compared to 1.8% for FRPs. While FRPs provide a higher ultimate tensile capacity, their brittle failure mode requires careful design to avoid sudden catastrophic failure.

In three-point bending tests, FRP panels achieved a flexural strength of 850 MPa, compared to 550 MPa for structural steel beams and 92 MPa for reinforced concrete beams. Steel–concrete composite beams demonstrated the highest flexural stiffness, with an average midspan deflection of only 5.8 mm under a 50 kN load, indicating superior deformation control. Composites consistently outperformed conventional materials in strength-to-weight ratio. FRP panels had a ratio of 900 kN·m/kg, nearly 5 times higher than steel's 185 kN·m/kg and 12 times higher than reinforced concrete's 74 kN·m/kg. CLT's ratio was also superior to solid timber, offering a 28% improvement due to reduced density and increased stiffness. Accelerated corrosion tests (ASTM G109) showed negligible mass loss in FRP reinforcement after 90 days in a chloride-rich environment, while steel rebar lost 5.6% of its mass. Steel–concrete composites performed better than conventional reinforced concrete, with corrosion rates reduced by 43%, attributed to reduced steel exposure and improved concrete compaction in composite sections.

In ASTM C666 freeze–thaw tests, FRP and CLT specimens maintained 98% and 95% of their original compressive strength after 300 cycles, respectively. Reinforced concrete retained 88%, and solid timber dropped to 81%, primarily due to microcracking and moisture-induced dimensional changes. Moisture absorption tests (ASTM D570) indicated that FRP panels absorbed less than 0.2% of water by weight after 24 hours, whereas solid timber absorbed 6.5%. CLT absorbed 4.2%, benefiting from adhesive layers acting as partial moisture barriers. Reinforced concrete showed 4.8% moisture ingress, which could accelerate reinforcement corrosion in service. Finite element modeling (FEM) using ANSYS validated the experimental findings and extended them to full-scale building components. Seismic Loads: Steel–concrete composite frames displayed 14% lower inter-story drift compared to pure steel frames, indicating enhanced stiffness and energy dissipation. Wind Loads: FRP façade panels reduced overall building weight by 22%, lowering base shear demands in high-wind simulations. Dynamic Loads: CLT floors demonstrated 12% lower natural frequencies than reinforced concrete slabs, offering improved vibration comfort in service.

Life cycle assessment (LCA) revealed substantial environmental benefits for some composite materials. Over a 50-year life span. FRP panels emitted 43% less CO_2 than equivalent steel cladding, largely due to reduced mass and transportation energy. CLT floors exhibited a 65% lower embodied carbon compared to reinforced concrete slabs, with the added advantage of storing approximately 0.8 tonnes of CO_2 per m^3 of timber. Steel–concrete composites reduced embodied carbon by 18% compared to pure steel frames, owing to material efficiency and reduced steel content. Timber-based composites scored highest in renewable material use. FRPs, however, scored lower in recyclability due to difficulties in separating fibers from resin matrices. Reinforced concrete and steel remain more recyclable in established waste management systems. Lightweight composite systems (e.g., FRP façades, CLT floors) contributed to a 3–5% reduction in operational energy due to better thermal insulation properties compared to conventional steel and concrete cladding. FRP panels resulted in a 12% lower LCC than steel panels, primarily due to negligible maintenance costs. CLT floors had a 6% lower LCC than reinforced concrete, benefiting from faster installation and reduced foundation costs. Steel–concrete composites achieved a 9% lower LCC compared to pure steel frames, due to reduced painting/recoating needs and improved durability.

3.2. Sustainability Assessment

Measured Coefficient of Performance (COP) values for HVAC chillers ranged from 2.9 to 3.4, below the Life cycle assessment (LCA) revealed substantial environmental benefits for some composite materials. FRP panels emitted 43% less CO_2 than equivalent steel cladding, largely due to reduced mass and transportation energy. CLT floors exhibited a 65% lower embodied carbon compared to reinforced concrete slabs, with the added advantage of storing approximately 0.8 tonnes of CO_2 per m^3 of timber. Steel–concrete composites reduced embodied carbon by 18% compared to pure steel frames, owing to material efficiency and reduced steel content.

Timber-based composites scored highest in renewable material use. FRPs, however, scored lower in recyclability due to difficulties in separating fibers from resin matrices. Reinforced concrete and steel remain more recyclable in established waste management systems. Lightweight composite systems (e.g., FRP façades, CLT floors) contributed to a 3–5% reduction in operational energy due to better thermal insulation properties compared to conventional steel and concrete cladding.

3.3. Economic Analysis

he initial material costs varied significantly, FRP panels: +65% higher than equivalent steel panels. CLT floors: +25% higher than reinforced concrete slabs. Steel–concrete composite frames: +15% higher than conventional steel frames. When factoring in maintenance, repair, and replacement over a 50-year life span: FRP panels resulted in a 12% lower LCC than steel panels, primarily due to negligible maintenance costs. CLT floors had a 6% lower LCC than reinforced concrete, benefiting from faster installation and reduced foundation costs. Steel–concrete composites achieved a 9% lower LCC compared to pure steel frames, due to reduced painting/recoating needs and improved durability. For FRP panels, the payback period for the higher initial cost was estimated at 15 years, primarily from reduced maintenance and extended service life. CLT floors had a payback period of 10 years, while steel–concrete composites achieved cost neutrality within 8 years.

3.4. Comparative Summary Table

Table 1. Comparative Summary Table

Property / Indicator	FRP Panels	Steel Panels	CLT Floors	RC Slabs	Steel–Concrete Composite	Steel Frame
Compressive Strength (MPa)	—	—	38.2	52.8	72.4	—
Tensile Strength (MPa)	1,240	490	—	—	—	—
Strength-to-Weight Ratio	900	185	210	74	260	185
Corrosion Mass Loss (%)	0.0	5.6	—	—	3.2	5.6
Carbon Footprint Reduction (%)	43	0	65	0	18	0
LCC Reduction (%)	12	0	6	0	9	0

Discussion

The results of this study offer a detailed comparison of composite and conventional materials in building structures across four critical dimensions: mechanical performance, durability, sustainability, and economic feasibility. The findings highlight both the strengths and the limitations of composites relative to established materials such as reinforced concrete, structural steel, and solid timber. This discussion contextualizes those results within existing research, explores potential applications, and addresses the challenges that remain for broader adoption of composite materials in the construction industry. The superior compressive strength of steel–concrete composites over conventional reinforced concrete aligns with findings by Bansal and Shukla (2020), who reported that hybrid systems often outperform monolithic materials due to the synergistic combination of constituent strengths. The 37% improvement observed in this study confirms that integrating steel and concrete can provide both high stiffness and enhanced load-bearing capacity, especially beneficial for high-rise or heavy-load structures.

The tensile performance of FRPs, which significantly exceeded that of structural steel, reinforces earlier reports by Ali and Al-Mahaidi (2018) that composites can deliver ultra-high tensile capacity.

However, the brittleness of FRPs, evidenced by their low elongation at break, remains a critical design consideration. In practical terms, this means that while FRPs can carry much greater loads per unit area, they must be used in configurations that prevent sudden failure, such as in prestressed or hybrid assemblies. The high flexural strength and stiffness of steel–concrete composites indicate strong suitability for long-span applications, bridge decks, and floor systems where deflection control is crucial. In contrast, FRP beams, while strong, are prone to vibration issues if not adequately stiffened — a point noted in both the experimental and simulation phases of this study. For architects and structural engineers, this means composites may reduce weight and material usage but require careful tuning of stiffness to meet serviceability criteria.

The finding that composites like FRP panels can achieve strength-to-weight ratios several times higher than conventional materials has major implications for both structural design and transportation efficiency. Lighter materials reduce foundation demands, crane loads, and transport fuel consumption. For multi-story buildings in seismic zones, this weight reduction translates directly into lower seismic base shear, enhancing overall earthquake resistance. The negligible corrosion in FRP reinforcement compared to the substantial steel mass loss confirms the suitability of FRPs in aggressive environments, such as coastal and industrial zones. This is consistent with Mohammed and Al-Fakih's (2021) conclusion that corrosion is a primary driver of life cycle costs in conventional reinforced concrete structures. The 43% reduction in corrosion rate for steel–concrete composites relative to standard RC also suggests that partial steel encasement and optimized concrete placement can significantly extend service life.

The freeze–thaw performance of FRP and CLT specimens underscores the role of material porosity and moisture absorption in durability. The moisture resistance advantage of CLT over solid timber is due to its engineered lamination, which interrupts moisture pathways — a factor also reported by Zhang and Li (2017) in their sustainability study. These results indicate that in climates with seasonal temperature variations, composite timber products may outperform both conventional timber and, in some cases, unprotected concrete in maintaining structural capacity. The LCA results clearly demonstrate that timber-based composites, particularly CLT, have the greatest potential for carbon footprint reduction. This is due to both the renewable nature of wood and its capacity to sequester carbon. The 65% reduction in embodied carbon for CLT floors compared to reinforced concrete is in line with other studies that promote mass timber as a viable alternative in low- to mid-rise structures.

FRPs showed a substantial 43% reduction in carbon emissions over their life cycle when compared to steel, primarily due to weight savings that lower transport and operational energy demands. However, the inability to easily recycle FRPs at end-of-life remains a concern. The industry is actively researching thermo-reversible resins and fiber reclamation processes, but these technologies have yet to reach commercial maturity. Steel–concrete composites' 18% lower embodied carbon than pure steel frames illustrates that even partial substitution of high-energy materials can yield meaningful environmental benefits. This is particularly relevant for large-scale projects where steel remains unavoidable for structural reasons.

The higher initial costs of composites are a consistent barrier to adoption. FRP panels, at 65% higher upfront cost than steel panels, illustrate this clearly. However, life cycle cost analysis revealed 12% savings over 50 years due to reduced maintenance and longer service life. This supports the argument that capital expenditure should be evaluated alongside operational expenditure when selecting materials. CLT floors' 6% lower life cycle cost compared to reinforced concrete, despite being more expensive initially, highlights the combined economic benefits of faster installation, lighter foundations, and lower labor requirements. For steel–concrete composites, the relatively short 8-year payback period makes them an attractive option for clients concerned with both performance and cost efficiency. One factor influencing cost is the maturity of supply chains. Conventional materials benefit from widespread production facilities, competitive pricing, and a skilled labor pool. Composites, by contrast, often require specialized manufacturing equipment and trained personnel, which can increase project costs, particularly in regions where these capabilities are limited.

The statistical analysis confirmed that differences in key performance metrics such as strength-to-weight ratio, compressive strength, and corrosion resistance were highly significant ($p < 0.01$). This reinforces the reliability of the observed performance advantages for composites. However, the lack of a statistically significant difference in fire resistance ($p = 0.18$) indicates that with proper fire protection measures, composites can meet the same safety standards as conventional materials, alleviating one of the common concerns among regulators and clients. This comparative analysis confirms that composite materials can outperform conventional building materials in several key metrics, notably strength-to-weight ratio, corrosion resistance, and sustainability, while offering competitive life cycle costs despite higher initial expenditures. The choice between composite and conventional materials should therefore be driven not solely by upfront cost but by a holistic evaluation of structural performance, environmental impact, and long-term economic return. For designers and policymakers aiming to balance performance with sustainability, this research provides quantitative evidence supporting the strategic adoption of composites in modern building structures.

4. CONCLUSION

This comparative study between composite and conventional materials in building structures has provided a comprehensive understanding of their respective performance, durability, environmental impact, and economic viability. By integrating experimental testing, finite element modeling, and life cycle assessment, the research offers a holistic evaluation relevant to contemporary construction demands. From the mechanical performance perspective, composite materials—such as fiber-reinforced polymers (FRP), steel–concrete composites, and cross-laminated timber (CLT)—demonstrated superior strength-to-weight ratios, higher tensile capacities, and improved resistance to environmental degradation compared to conventional materials like reinforced concrete, structural steel, and solid timber. In particular, FRPs exhibited exceptional corrosion resistance and moisture tolerance, making them ideal for applications in harsh or marine environments. Steel–concrete composite beams showed enhanced stiffness and load-carrying capacity, while CLT provided favorable seismic performance and sustainability benefits. Conventional materials, on the other hand, remain advantageous in terms of widespread availability, well-established construction practices, and predictable long-term behavior. Reinforced concrete continues to excel in compressive strength and cost-effectiveness for mass construction, while structural steel offers reliable ductility and recyclability. However, these benefits are offset by vulnerabilities such as corrosion in steel structures, cracking in concrete, and higher maintenance needs over extended service lives. The life cycle assessment results further highlighted the environmental advantages of certain composites. CLT demonstrated the lowest embodied carbon and energy consumption, attributable to its renewable nature and carbon sequestration capacity. FRPs, despite their manufacturing energy intensity, offered extended service life and reduced maintenance requirements, which translated to lower long-term environmental burdens. In contrast, conventional reinforced concrete and steel had higher overall life cycle emissions due to energy-intensive production processes and shorter maintenance intervals. Economic analysis indicated that while composite materials generally involve higher initial procurement and installation costs, they often yield favorable life cycle cost outcomes when reduced maintenance, longer service life, and improved durability are considered. The economic feasibility of composites is particularly evident in high-performance structures where durability and reduced downtime are critical. Ultimately, this research underscores that neither material category can be universally deemed superior; rather, the choice should be context-specific, guided by structural requirements, environmental conditions, sustainability objectives, and economic constraints. Composite materials are highly suitable for projects demanding lightweight construction, corrosion resistance, and sustainability certifications. Conversely, conventional materials remain a pragmatic choice for projects prioritizing cost efficiency, ease of procurement, and construction familiarity. The findings of this study contribute valuable data to the growing discourse on sustainable and high-performance construction, equipping engineers, architects, and policymakers with evidence-based insights for material selection. Future research should expand to hybrid systems that combine the strengths of both composites and conventional materials, as such integrations may offer optimized performance and sustainability for the evolving demands of the built environment.

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