Advances in Construction Materials and Structural Engineering: A Comprehensive Review

Abstract

This comprehensive review examines recent advances across multiple domains in construction materials and structural engineering. The review synthesizes findings from research on bacterial/microbial concrete and self-healing materials, advanced structural modeling techniques, composite beams and post-tensioning, fatigue and cyclic loading behavior, connections and joints in composite structures, and biophilic design principles. By integrating insights from these diverse yet interconnected fields, the review identifies emerging trends, current challenges, and promising directions for future research and application. Cross-cutting themes of sustainability, technological integration, and interdisciplinary collaboration are highlighted as essential considerations for advancing construction innovation. The review concludes that the integration of biological processes, computational modeling, composite action optimization, life-cycle thinking, and human-centered design approaches collectively point toward a more sustainable, resilient, and efficient built environment.

Keywords: Microbial Concrete, Self-Healing Materials, FEM, Post-Tensioning

1. Introduction

The construction industry is continuously evolving, driven by the need for more sustainable, durable, and efficient structures. Recent advances in materials science, structural engineering, and interdisciplinary approaches have opened new frontiers in construction technology. This mini review synthesizes current research across several innovative domains that are reshaping modern construction practices and structural engineering.

The built environment faces unprecedented challenges in the 21st century, including climate change, resource scarcity, and increasing demands for resilience and sustainability. Traditional construction materials and methods often fall short in addressing these challenges, necessitating innovative approaches that combine advances from multiple disciplines. The convergence of biology, materials science, computational modeling, and structural engineering has created fertile ground for transformative technologies that can significantly enhance the performance, durability, and sustainability of constructed facilities.

This review examines several key areas of innovation in construction materials and structural engineering: bacterial/microbial concrete and self-healing materials, advanced structural modeling techniques, composite beams and post-tensioning methods, fatigue and cyclic loading behavior, connections and joints in composite structures, and biophilic design principles. These diverse yet interconnected domains represent some of the most promising avenues for advancing construction technology and practice.

Bacterial/microbial concrete represents a paradigm shift in how we conceptualize construction materials, moving from static, inert substances to dynamic, responsive systems capable of self-repair. By harnessing the metabolic capabilities of microorganisms, particularly bacteria from the Bacillus genus, researchers have developed concrete formulations that can autonomously heal cracks and damage, potentially extending service life and reducing maintenance requirements.

Complementing these material innovations, advanced structural modeling techniques have revolutionized our ability to predict and optimize structural behavior. From spatial grillage models for laminated glass to multi-scale approaches for asphalt materials, these computational methods enable more accurate simulation of complex phenomena such as crack propagation, nonlinear responses, and failure mechanisms. Such models are essential for designing safer, more efficient structures and for validating the performance of novel materials and systems.

Composite construction, particularly steel-concrete composite beams with post-tensioning, offers significant advantages in terms of structural efficiency, spanning capability, and material optimization. Recent research has focused on understanding the behavior of these systems under various loading conditions, the effects of partial shear connection, and the potential for external post-tensioning as a strengthening technique for existing structures.

The long-term performance of structures under repeated loading fatigue and cyclic loading behavior—remains a critical concern, especially for infrastructure subjected to traffic, wind, or seismic forces. Investigations into the fatigue characteristics of composite beams, the influence of connection details, and strategies for enhancing fatigue resistance provide valuable insights for designing more durable and resilient structures.

Connections and joints often represent the most vulnerable components of structural systems, particularly in composite construction. Research on bolted joints, shear connectors, and innovative connection solutions addresses these critical elements, seeking to enhance their strength, ductility, and reliability under various loading scenarios.

This review aims to provide a comprehensive overview of these diverse yet interconnected domains, highlighting recent advances, current challenges, and future directions. By synthesizing findings from multiple disciplines, we seek to foster a more integrated understanding of construction innovation and to identify promising avenues for future research and application. The following sections delve deeper into each of these areas, examining key studies, methodologies, and outcomes that are shaping the future of construction and structural engineering.

2. Bacterial/Microbial Concrete and Self-healing Materials

The concept of self-healing concrete represents a paradigm shift in construction materials, transitioning from passive materials that degrade over time to active systems capable of autonomous repair. At the core of this innovation is microbially induced calcite precipitation (MICP), a biochemical process where specific bacteria catalyze the formation of calcium carbonate ($CaCO_3$) crystals that can fill cracks and voids in concrete structures.

The primary bacterial species employed in self-healing concrete applications belong to the Bacillus genus, particularly Bacillus subtilis and Bacillus sphaericus. These microorganisms are especially suitable due to their ability to form endospores—dormant structures that can survive in the harsh alkaline environment of concrete for extended periods and become metabolically active when exposed to favorable conditions, such as the presence of water and oxygen in cracks [1]. Many researchers demonstrated that B. subtilis isolated from soil samples could significantly enhance the mechanical properties of cement mortar when added in concentrations of 5-10% by weight[2], [3], [4], [5].

The biochemical pathways involved in MICP typically follow one of several routes. The most common is the ureolytic pathway, where bacteria produce the enzyme urease, which catalyzes the hydrolysis of urea to form carbonate ions and ammonia. In the presence of calcium ions, these carbonate ions precipitate as calcium carbonate. Alternatively, some bacteria utilize metabolic pathways involving organic acids or amino acids, which also result in carbonate precipitation [6], [7], [8]. Other researchers employed Bacillus sphaericus with calcium lactate as a nutrient source, finding that this combination effectively promoted calcite precipitation in concrete with steel fiber reinforcement [9].

The precipitation process typically begins when cracks form in the concrete, exposing the dormant bacterial spores to water. The bacteria then germinate and start their metabolic activities, consuming the provided nutrients (often calcium-based compounds like calcium lactate) and producing carbonate ions. These ions combine with calcium ions present in the concrete matrix to form calcium carbonate crystals that gradually fill the cracks, restoring structural integrity and reducing permeability. Figure 1 shows the healing process for cracks.

Microscopic examination using scanning electron microscopy (SEM) has revealed the formation of dense calcium carbonate deposits within cracks, confirming the effectiveness of the bacterial healing process. The researchers observed high $CaCO_3$ deposits in bacterial concrete samples, with Fourier-transform infrared spectroscopy (FTIR) confirming the presence of carbonate groups at higher concentrations than in control samples[10], [11].

Recent advances in understanding these mechanisms have led to more sophisticated approaches, including the integration of fungi alongside bacteria for enhanced healing capabilities. Many studies suggest that fungi, with their filamentous growth habit (hyphae), can bridge larger cracks than bacteria alone, potentially offering a more robust self-healing strategy for concrete structures[12], [13].

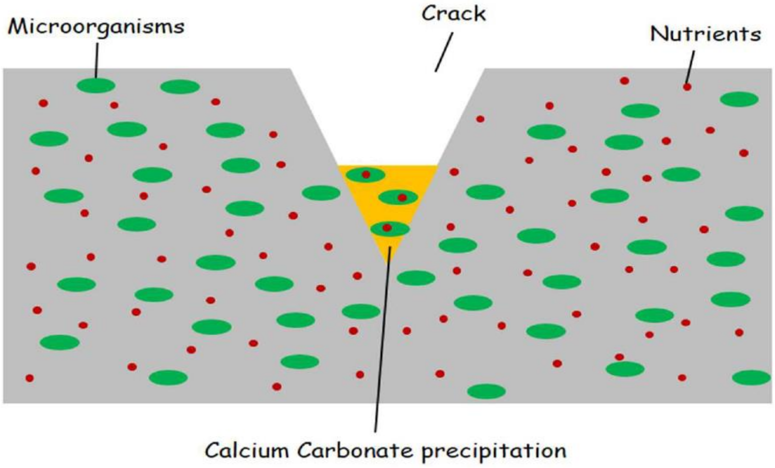

Figure 1. Healing of cracks through calcium carbonate precipitation by microorganisms[14].

2.2 Performance Enhancements

The incorporation of bacteria into concrete formulations has demonstrated significant improvements in various performance metrics, most notably mechanical properties, durability, and crack-healing capabilities.

Mechanical properties show consistent enhancement in bacterial concrete compared to conventional formulations. Studies reported that adding B. subtilis at a 5% concentration increased the compressive strength of cement mortar by significant margins after 28 and 56 days of curing.

Similarly, flexural strength showed improvements, with 5% bacterial concentration providing optimal early strength gains, while 10% concentration yielded superior long-term strength after 56 days. These improvements are attributed to the bacterial precipitation of calcium carbonate, which fills micropores and creates a denser microstructure [4], [5], [6], [7].

Durability in harsh environments represents another significant advantage of bacterial concrete. Previous studies tested specimens cured in both freshwater and magnesium sulfate water solution, finding that bacterial concrete exhibited enhanced resistance to sulfate attack. This improved durability is attributed to the reduced permeability resulting from bacterial calcite precipitation, which creates a more impermeable matrix that restricts the ingress of aggressive agents.

The crack-healing capabilities of bacterial concrete have been extensively documented. Many studies investigated the mechanical properties of Bacillus subtilis self-healing concrete, finding that specimens with bacterial additions could effectively heal cracks up to 0.5 mm wide within 28 days under favorable conditions. The healing efficiency, typically measured as the percentage of crack width reduction or the recovery of mechanical properties, varies depending on bacterial species, concentration, nutrient availability, and environmental conditions [15], [16], [17].

2.3 Current Challenges and Future Directions

Despite the promising results demonstrated in laboratory studies, several challenges must be addressed before bacterial concrete can achieve widespread commercial implementation.

The longevity of bacterial spores in concrete remains a primary concern. The highly alkaline environment of concrete ($pH > 12$) and the physical constraints imposed by the cement matrix can significantly reduce bacterial viability over time. Literature highlight this as a critical challenge, noting that many bacterial species struggle to survive beyond a few months in concrete without protective measures. Various encapsulation techniques have been developed to address this issue, including the use of hydrogels, porous aggregates, and microcapsules to shield bacteria from the harsh concrete environment until needed for healing activities.

Cost implications for large-scale implementation present another significant barrier. The production of bacterial spores, nutrients, and protective carriers adds considerable expense to concrete production. Ramakrishnan (2005) estimate that bacterial concrete can cost 30-50% more than conventional concrete, depending on the specific formulation and encapsulation methods used. This cost premium may be justified for critical infrastructure or structures in aggressive environments but remains prohibitive for routine construction applications [18].

The potential for combined bacterial-fungal approaches represents an emerging direction in self-healing concrete research. Previous studies suggest that integrating fungi alongside bacteria could offer a more robust healing strategy, as fungi can bridge larger cracks through their hyphal growth while bacteria excel at filling smaller voids. This complementary approach could address some of the limitations of purely bacterial systems, particularly for larger cracks that exceed the healing capacity of bacteria alone.

Recent research has also explored post-fire applications of bacterial concrete. A 2025 study published in Nature Scientific Reports investigated self-healing concrete incorporating encapsulated bacteria for post-fire restoration, combining experimental testing with numerical modeling to optimize formulations for this specific application. This represents an important expansion of bacterial concrete technology into specialized applications where conventional repair methods may be inadequate [19].

Future research directions include the development of more resilient bacterial strains through genetic engineering, optimization of nutrient delivery systems, exploration of alternative precipitation pathways, and the integration of bacterial healing with other smart material technologies. Additionally, standardized testing protocols and performance metrics are needed to facilitate comparison between different self-healing concrete formulations and to support the development of design guidelines and specifications for practical applications.

As the technology matures, field trials and long-term performance monitoring will be essential to validate laboratory findings and to demonstrate the effectiveness of bacterial concrete under real-world conditions. Several pilot projects are underway globally, providing valuable data on implementation challenges and performance outcomes that will inform future development and application of this promising technology.

4. Composite Beams and Post-tensioning

4.1 Behavior of Composite Steel-Concrete Beams

Composite steel-concrete beams represent a fundamental structural system widely utilized in both building and bridge construction. These systems leverage the complementary properties of steel and concrete: the high tensile strength of steel and the excellent compressive strength and stiffness of concrete. When properly connected, these materials work together to create structural elements with superior performance characteristics compared to either material used independently.

The load-carrying capacity and deflection characteristics of composite beams depend significantly on the degree of composite action achieved between the steel and concrete components. Researchers investigated the effects of uniform loading on externally post-tensioned composite beams with varying degrees of shear connection. Their study revealed that the load-carrying capacity increases proportionally with the degree of shear connection, with fully composite beams exhibiting the highest strength and stiffness. However, even partial composite action can provide substantial improvements over non-composite behavior, offering a balance between structural performance and economy in shear connector usage [20], [21], [22], [23].

The effects of partial shear connection on composite beam behavior have been extensively studied due to their practical significance. Researchers examined how partial shear connection influences the effectiveness of external post-tensioning as a strengthening technique. Their findings indicated that while higher degrees of shear connection generally yield better performance, there exists an optimal level beyond which additional connectors provide diminishing returns. This optimization potential is particularly relevant for retrofitting applications where adding shear connectors to existing structures may be challenging and costly [22], [24], [25], [26], [27], [28].

Nie et al. provided a comprehensive study on advances in steel-concrete composite structures, noting that partial interaction theory has evolved significantly in recent years. Modern analytical models can now accurately predict the slip between steel and concrete components and its effects on overall structural behavior, enabling more efficient designs that balance performance requirements with material usage and construction complexity[29], [30].

Failure modes and design considerations for composite beams encompass several potential mechanisms. El-Sisi et al. (2023) identified that composite beams may fail through concrete crushing, steel yielding, shear connector failure, or a combination of these modes. The governing failure mechanism depends on the relative strengths of the components and the degree of shear connection. Design approaches must account for these various failure modes to ensure adequate safety margins and ductile behavior under overload conditions.

Long-term performance and durability of composite beams involve considerations beyond immediate strength and stiffness. Creep and shrinkage of concrete can affect the stress distribution and deflection characteristics over time. Additionally, environmental factors such as corrosion of steel components and degradation of the steel-concrete interface can compromise long-term performance. Zona and Ranzi (2023) highlighted the importance of considering these time-dependent effects in both design and assessment of composite structures, particularly for bridges and other infrastructure with long design lives [31], [32].

4.2 External Post-tensioning Techniques

External post-tensioning has emerged as an effective method for strengthening existing composite beams and enhancing the performance of new construction. This technique involves applying tensile forces to external tendons that are anchored to the structure, inducing a compressive force that counteracts applied loads and reduces tensile stresses in critical regions.

Tendon profiles and configurations significantly influence the effectiveness of external post-tensioning. Manty researchers evaluated three different tendon profiles in their study: straight, single-draped, and double-draped configurations. Their results demonstrated that the double-draped profile generally provided the most efficient strengthening effect, as it introduces beneficial moments at both midspan and support regions. However, the optimal profile depends on the specific loading conditions and structural configuration, highlighting the importance of tailored design approaches [26], [33], [34].

Applications in rehabilitation and retrofitting represent a primary use case for external post-tensioning. Investigating the effect of external post-tensioning on steel-concrete composite beams with partial connection, finding that this technique could effectively restore or enhance the capacity of deteriorated or underdesigned structures. The non-invasive nature of external post-tensioning makes it particularly suitable for rehabilitation projects where minimal disruption to existing elements is desired. Design methodologies and optimization for post-tensioned composite beams have evolved to address the complex interactions between post-tensioning forces, shear connection, and applied loads.

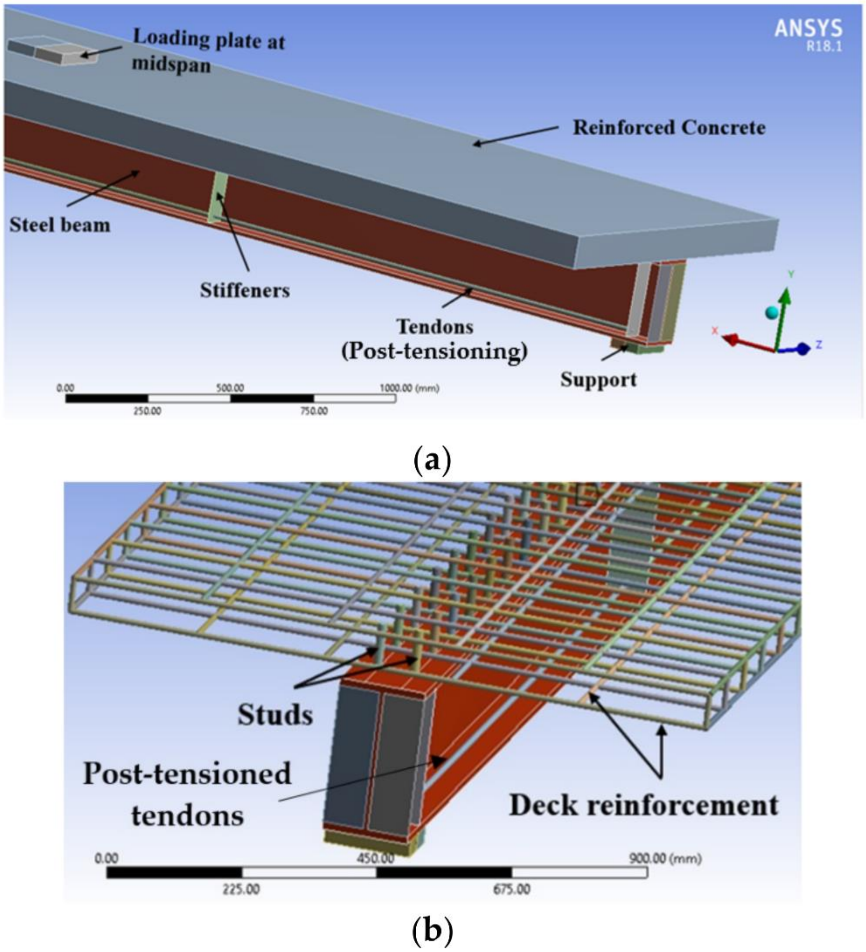

Figure 2. Details of the different components of the post-tensioned composite beam. (a) Longitudinal direction. (b) Transverse direction showing the deck reinforcement.

5. Future Research Directions

The review of current literature across multiple domains reveals several promising directions for future research and development that could significantly advance the state of practice in construction and structural engineering.

Emerging materials and techniques continue to expand the possibilities for structural innovation. The integration of nanomaterials into concrete, the development of bio-based composites, and the exploration of metamaterials with engineered properties represent frontier areas with significant potential. Many studies suggested that the combination of bacterial self-healing with other advanced concrete technologies, such as ultra-high-performance concrete or geopolymer concrete, could create synergistic benefits that address multiple performance objectives simultaneously. Similarly, the development of hybrid structural systems that combine different materials and techniques to leverage their respective advantages offers promising avenues for future exploration.

Interdisciplinary collaboration opportunities are essential for addressing complex challenges that span traditional disciplinary boundaries. The successful development of bacterial concrete, for example, requires expertise from microbiology, materials science, and structural engineering—

disciplines that have historically operated largely independently. Similarly, the integration of biophilic design principles with structural engineering approaches necessitates collaboration between architects, engineers, environmental psychologists, and other specialists. Creating frameworks and platforms that facilitate such interdisciplinary exchange will be crucial for advancing innovation in construction and structural engineering.

Knowledge gaps and research needs identified across the reviewed literature include several common themes. Long-term performance data for innovative materials and systems remains limited, creating uncertainty about durability and life-cycle behavior. Standardized testing protocols and performance metrics for novel approaches such as self-healing concrete are still evolving, making it difficult to compare different solutions or to establish design guidelines. Additionally, the scaling of laboratory-proven technologies to practical field applications often presents unforeseen challenges that require further investigation. Addressing these knowledge gaps through targeted research initiatives will be essential for translating promising innovations into practical applications.

Potential for transformative innovations exists at the intersections of the domains discussed in this review. For example, the integration of self-healing capabilities with smart monitoring systems could create structures that not only detect damage but actively respond to repair it. Similarly, the combination of advanced modeling techniques with digital fabrication technologies could enable highly optimized structures that minimize material usage while maximizing performance. These transformative possibilities highlight the importance of thinking beyond incremental improvements within established domains to explore radical innovations that reimagine how structures are designed, built, and maintained.

6. Conclusions

1. Biological Integration in Construction Materials: The incorporation of bacteria, such as Bacillus subtilis, into concrete offers autonomous self-healing capabilities, enhancing durability and aligning with sustainability goals.
2. Advancements in Structural Modeling: Sophisticated numerical methods, like spatial grillage models for laminated glass, enable accurate predictions of complex structural behaviors, facilitating safer and more efficient designs.
3. Innovations in Composite Beam Technologies: Research into partial shear connections and external post-tensioning has improved our understanding of composite beam performance, leading to more durable and sustainable structural solutions.
4. Emphasis on Fatigue and Cyclic Loading Behavior: Studies on the fatigue behavior of composite beams under cyclic loading conditions have provided insights into enhancing long-term structural performance.
5. Sustainability and Interdisciplinary Collaboration: Integrating life-cycle assessment, digital technologies, and interdisciplinary approaches is crucial for developing sustainable, resilient, and human-centered built environments.

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