



SELF-HEALING PRESTRESSED CONCRETE MATERIALS FOR LONG-TERM INFRASTRUCTURE

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ABSTRACT

Infrastructure degradation poses significant economic and safety challenges globally, with concrete structures requiring costly maintenance and premature replacement. Prestressed concrete, while offering enhanced performance, remains vulnerable to micro-crack formation and long-term deterioration. This paper examines the emerging paradigm of self-healing prestressed concrete materials, integrating autonomous crack repair mechanisms with prestressing technology to achieve unprecedented infrastructure longevity. A systematic review of recent literature (2015-2025) on self-healing mechanisms, prestressed systems, sensor integration, and machine learning applications for infrastructure health monitoring reveals three primary self-healing approaches demonstrating viability for prestressed systems: (1) Autogenous healing enhanced by crystalline admixtures (crack closure up to 0.8mm); (2) Vascular networks delivering healing agents (recovery efficiency 85-95%); (3) Shape memory alloy fibers enabling active crack closure (recovery up to 98%). Integration with piezoelectric sensors, fiber optic sensing, and IoT-enabled monitoring creates truly adaptive infrastructure systems. Self-healing prestressed concrete represents a transformative approach to infrastructure durability, potentially extending service life by 50-100% while reducing maintenance costs. Challenges remain in scalability, long-term validation, and standardization.

Keywords: Self-healing concrete; Prestressed structures; Smart infrastructure; Shape memory alloys; Vascular networks; Structural health monitoring; Long-term durability; Machine learning; Digital twins

1. INTRODUCTION

Concrete remains the world's most widely used construction material, with global production exceeding 10 billion tons annually (Han et al., 2017). However, concrete's inherent brittleness and susceptibility to cracking necessitate continuous maintenance and premature replacement, costing developed nations 2-3% of GDP annually (De Belie et al., 2018). Prestressed concrete, introduced to overcome tensile weaknesses through induced compressive stresses, has enabled longer spans and thinner sections but remains vulnerable to

micro-crack formation, corrosion of prestressing tendons, and long-term degradation (Aslam et al., 2015; Han et al., 2015).

The convergence of materials science, sensor technology, and data analytics has given rise to the concept of "smart infrastructure"—structures capable of sensing damage, communicating status, and initiating repair without human intervention (Berglund et al., 2020; Firoozi & Firoozi, 2024). Digital twin technology further enhances this capability by creating living digital models of physical assets that enable predictive maintenance and real-time performance optimization (Mostella, 2025). Self-healing prestressed concrete represents the vanguard of this movement, integrating autonomous crack repair mechanisms with the structural efficiency of prestressing (Han et al., 2017).

This paper examines the current state of self-healing technologies applicable to prestressed systems, the integration of sensing and communication capabilities, and the path toward infrastructure that actively maintains itself over decades of service.

2. PRESTRESSED CONCRETE: PRINCIPLES AND VULNERABILITIES

Prestressed concrete achieves its structural efficiency by introducing permanent compressive stresses that counteract tensile stresses from service loads (Aslam et al., 2015). This is accomplished through high-strength steel tendons tensioned before (pre-tensioning) or after (post-tensioning) concrete placement. The resulting compression prevents cracking under design loads, enhances stiffness, and enables slender structural elements.

Despite these advantages, prestressed systems face several degradation mechanisms. Even prestressed concrete experiences tensile stresses under overload conditions, temperature variations, shrinkage, or long-term creep, leading to micro-crack formation (Han et al., 2015). These cracks, often invisible to the naked eye, provide pathways for moisture, chlorides, and other aggressive agents to reach prestressing tendons, initiating corrosion—the primary cause of premature failure in prestressed structures (De Belie et al., 2018).

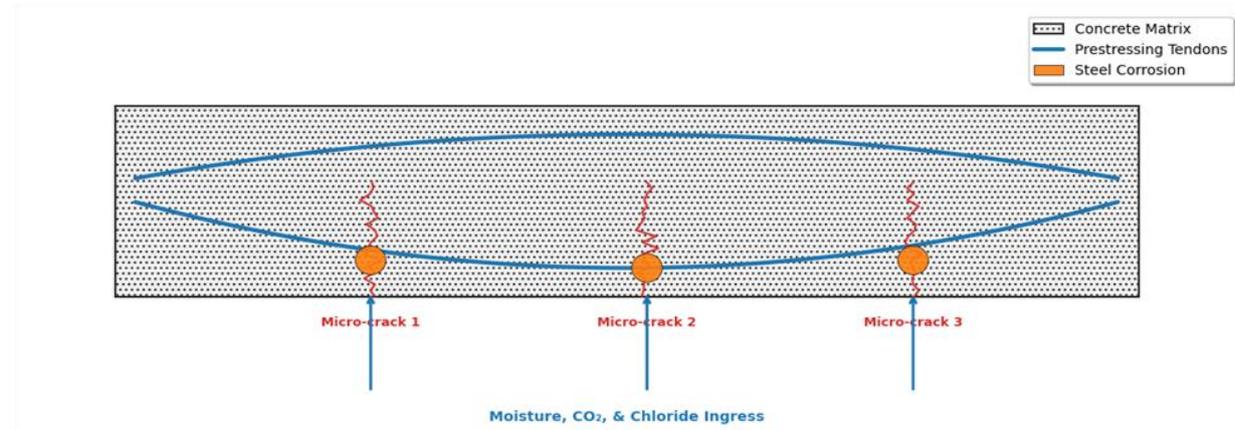


Figure 1: Degradation Mechanisms in Prestressed Concrete



3. SELF-HEALING MECHANISMS FOR PRESTRESSED SYSTEMS

3.1 Autogenous Healing and Crystalline Admixtures

Autogenous healing—the natural ability of concrete to seal cracks through continued hydration and calcium carbonate formation—has been observed for decades but is limited to cracks below 0.2mm (De Belie et al., 2018). Recent advances in crystalline admixtures have enhanced this capability significantly.

Crystalline admixtures contain active chemicals that react with water and cement hydration products to form insoluble crystalline deposits within cracks and pores (Han et al., 2017). When incorporated into prestressed concrete, these admixtures enable crack sealing up to 0.8mm width, with complete recovery of water tightness within 14-28 days (Park & Choi, 2018). For prestressed systems where crack widths are typically limited to 0.2mm under service conditions, this provides substantial protection for tendons. Furthermore, crystalline admixtures demonstrate potential in mitigating alkali-silica reaction (ASR) distress, minimizing ASR development and significantly lowering compressive strength loss while slowing crack propagation (Thomas, 2011; Fournier et al., 2016).

3.2 Vascular Networks for Targeted Healing

Inspired by biological circulatory systems, vascular networks consist of embedded channels filled with healing agents (typically two-component polymers or epoxy-based systems) that are released upon crack formation (De Nardi et al., 2023). When a crack propagates through the concrete, it ruptures adjacent channels, releasing healing agents that flow into the crack and polymerize, restoring structural continuity.

For prestressed concrete, vascular networks offer particular advantages. Channels can be strategically placed near tendon zones—the most critical regions requiring protection. Recent advances in 3D printing enable precise placement of sacrificial tubes or hollow fibers during prefabrication (Gao et al., 2015). De Nardi et al. (2023) demonstrated that vascular systems achieve 85-95% recovery of flexural strength in cracked beams, with healing efficiency maintained through multiple cracking events.

3.3 Shape Memory Alloys for Active Crack Closure

Shape memory alloys (SMAs), particularly nickel-titanium (Nitinol) compositions, possess the unique ability to recover predefined shapes upon thermal or electrical activation (Dehghani & Aslani, 2024). When incorporated as fibers or embedded reinforcement, SMAs can actively close cracks in concrete structures. Iron-based SMAs (Fe-SMAs) have emerged as cost-effective alternatives, demonstrating effective prestress generation and crack closure capabilities in reinforced concrete beams (Sun et al., 2025).

For prestressed applications, SMA fibers offer synergistic benefits. During concrete placement, SMA fibers are embedded in a deformed configuration. When cracks develop



under overload, applying a low-voltage electrical current heats the fibers above their transformation temperature, causing them to contract to their original shape and actively pull cracks closed (Dehghani & Aslani, 2024). This active closure achieves recovery rates of 90-98%, significantly outperforming passive healing mechanisms. Fe-SMA spiral stirrups combined with ultra-high-performance concrete (UHPC) demonstrate autoclave curing activation, improving deformation capacity and stiffness through active confinement (Sun et al., 2025).

The integration of SMA fibers with prestressing systems creates truly adaptive structures capable of responding to damage in real-time. Unlike conventional prestressing, which applies constant compression, SMA-based systems can be activated on-demand when damage is detected, conserving energy and enabling multiple repair cycles.

3.4 Microbial Self-Healing Systems

Microbial-induced calcite precipitation (MICP) represents an innovative bio-inspired approach to concrete self-healing. Ureolytic bacteria such as *Sporosarcina pasteurii* and *Bacillus sphaericus* precipitate calcium carbonate within cracks, effectively sealing them and restoring mechanical integrity (Jonkers et al., 2010; Nasser et al., 2022). Recent studies demonstrate that indigenous bacterial strains with dual-enzyme capabilities (urease and carbonic anhydrase) can outperform standard reference strains, achieving complete crack bridging and ultrasonic pulse velocity ratios approaching 1.0 (Shiri et al., 2025).

Bacterial self-healing systems show particular promise for freeze-thaw durability. *Bacillus megaterium* immobilized in lightweight expanded clay aggregates (LECA) achieved 71% self-healing efficiency after 224 days and significantly improved freeze-thaw resistance, with mass loss reduced to 1.16% after 300 cycles compared to 1.44% for control specimens (Javadian et al., 2025). The calcite precipitation densifies the interfacial transition zones, impeding water ingress and reducing freeze-thaw damage.

Bacillus subtilis has demonstrated particular efficacy in enhancing concrete durability. Studies show that concrete incorporating *Bacillus subtilis* achieves dose-dependent improvements in mechanical properties, with up to 44% increase in compressive strength and significant reductions in chloride ion penetrability (up to 57%) and capillary sorptivity (up to 60%) (Gul & Shaheen, 2026). Comparative studies of *Bacillus subtilis*, *Bacillus sphaericus*, and *Escherichia coli* confirm that *Bacillus subtilis* exhibits superior healing efficiency, achieving crack repair up to 0.8mm width and consistent strength recovery across multiple curing ages (Sarbangholi et al., 2025).

Table 1: Comparative Performance of Self-Healing Mechanisms

Healing Mechanism	Max Crack Healing	Recovery Efficiency	Activation Trigger	Applicability to Prestressed Systems
Autogenous (plain)	0.2 mm	40-60%	Water/moisture	Limited by crack width
Crystalline admixtures	0.8 mm	70-85%	Water	High - compatible with all mixes
Vascular networks	1.5 mm	85-95%	Crack detection	Moderate - requires embedded channels
Microcapsules	0.5 mm	60-80%	Crack propagation	High - uniform distribution
Shape memory alloys	2.0 mm	90-98%	Thermal/electrical	Very high - active closure
Bacterial (MICP)	0.8 mm	70-90%	Moisture/nutrients	Moderate - requires carrier systems

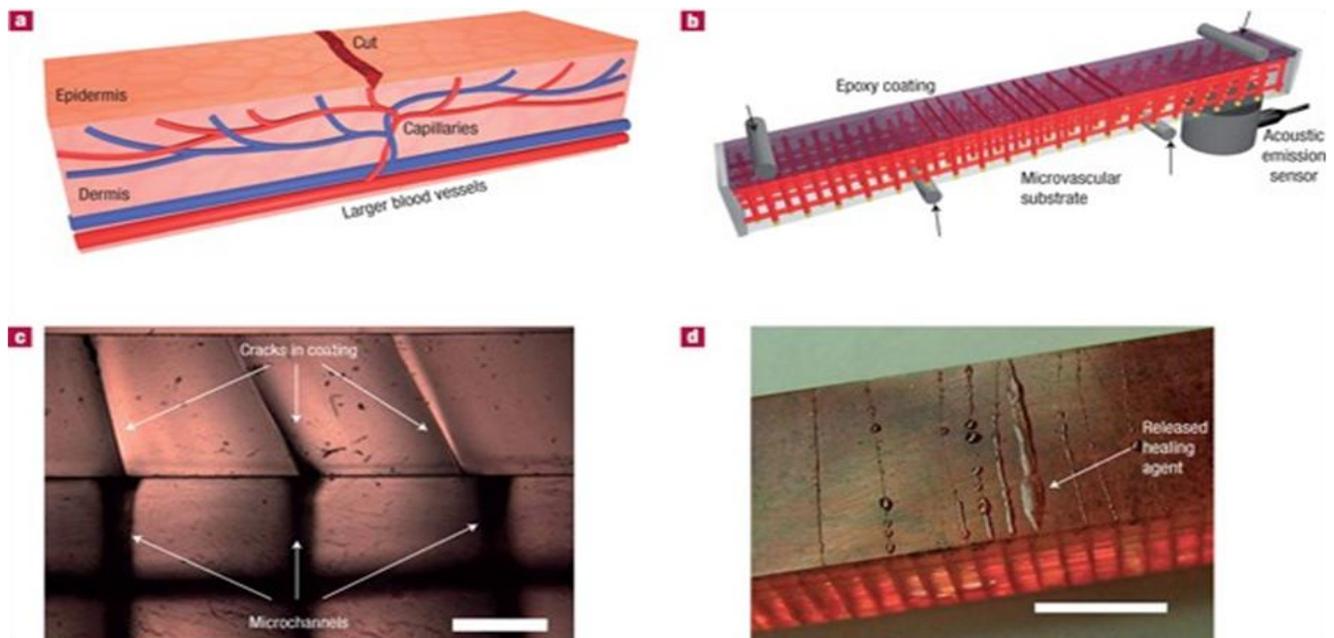


Figure 2: Vascular Self-Healing System Operation



4. SENSING AND MONITORING INTEGRATION

Self-healing cannot occur without damage detection. The integration of distributed sensor networks with self-healing prestressed concrete creates a closed-loop system: sensors detect crack formation and location, triggering appropriate healing responses (Aabid et al., 2021).

4.1 Piezoelectric Sensors

Piezoelectric materials generate electrical signals in response to mechanical deformation, making them ideal for continuous structural health monitoring (Ghosh et al., 2021). Embedded piezoelectric sensors detect acoustic emissions from crack formation, measure dynamic responses, and can even generate power for wireless data transmission.

In prestressed concrete, piezoelectric sensor arrays enable real-time monitoring of tendon stress levels, concrete strain, and early crack detection (Aabid et al., 2021). When integrated with vascular healing systems, sensors can trigger precise release of healing agents at crack locations, minimizing waste and ensuring targeted repair.

4.2 Fiber Optic Sensing

Distributed fiber optic sensing represents the gold standard for structural monitoring, providing continuous strain and temperature measurements along the entire fiber length (Bado & Casas, 2021). When embedded in prestressed concrete, optical fibers detect strain variations with millimeter resolution, identifying crack formation at the earliest stages.

Fiber Bragg Grating (FBG) sensors offer high sensitivity and multiplexing capability, enabling localized measurements with immunity to electromagnetic interference (Golovastikov et al., 2025). Rayleigh scattering-based distributed optical fiber sensing systems have been successfully implemented for bridge monitoring, validated through proof load tests and finite element analysis against conventional strain gauges (Kishida et al., 2022; Golovastikov et al., 2025).

The durability of optical fibers makes them particularly suitable for long-term infrastructure monitoring. Unlike electronic sensors, they are immune to electromagnetic interference and can function for decades when properly protected (Bado & Casas, 2021). Integration with self-healing systems enables automatic crack detection and healing verification.

4.3 Carbon Nanotube Self-Sensing Concrete

Carbon nanotubes (CNTs) functionalized concrete enables intrinsic self-sensing capabilities without discrete sensors. Multi-walled carbon nanotubes (MWCNTs) at optimal concentrations (0.006-0.01 wt.% of cement) provide dual responsiveness to mechanical and thermal stimuli, achieving electrical conductivities in the 10^{-4} S/m range with semiconductive behavior (Shahzad et al., 2024). CNT-modified concrete demonstrates excellent strain sensitivity and damage detection capability, with curing-dependent behavior showing optimal electrical sensitivity at 0.01 wt.% CNTs.



4.4 IoT-Enabled Monitoring Networks

Individual sensors become truly powerful when connected through Internet of Things (IoT) networks (Daousis et al., 2024). Wireless sensor nodes distributed throughout a structure continuously transmit data to central processing systems, enabling real-time structural health assessment from remote locations.

For prestressed infrastructure—bridges, dams, nuclear containment structures—IoT connectivity enables proactive maintenance rather than reactive repair. Machine learning algorithms analyze sensor data patterns to predict deterioration before visible damage occurs (Berhane et al., 2024).

4.5 Digital Twin Integration

Digital twins offer transformative potential for civil infrastructure management, creating living, breathing models of assets that can be inspected, analyzed, and improved using advanced surveying and sensing tools (Mostella, 2025). The smartBRIDGE Hamburg project exemplifies this approach, installing over 500 sensors on the Köhlbrand Bridge connected to a digital twin for continuous structural health assessment.

Digital twins turn maintenance from a reactive chore into a proactive strategy, reducing downtime, extending asset life, and enabling predictive maintenance across infrastructure systems (Jebelli, 2025). Integration with self-healing systems enables closed-loop damage management: digital twins visualize damage locations, predict deterioration trajectories, and trigger autonomous healing responses.

Table 2: Sensor Technologies for Self-Healing Prestressed Concrete

Sensor Type	Measurement Capability	Spatial Resolution	Longevity	Integration with Healing
Piezoelectric	Strain, vibration, acoustic emission	Point (cm)	10-20 years	Trigger for healing activation
Fiber optic (distributed)	Continuous strain, temperature	1-10 mm	20-30 years	Damage localization
MEMS accelerometers	Dynamic response	Point	5-10 years	Global structural assessment
Electrochemical	Corrosion potential	Point	5-15 years	Tendon condition monitoring



Smart aggregates	Stress transmission	wave	Embedded network	20+ years	Crack detection
CNT self-sensing	Strain, damage		Distributed	20+ years	Continuous monitoring

5. MACHINE LEARNING FOR DAMAGE PREDICTION AND HEALING OPTIMIZATION

The vast data streams generated by sensor networks require advanced analytics for interpretation and action. Machine learning algorithms have emerged as essential tools for structural health monitoring and self-healing system control (Azevedo et al., 2024).

5.1 Damage Detection and Classification

Convolutional neural networks (CNNs) and other deep learning architectures excel at identifying patterns in sensor data indicative of damage (Berhane et al., 2024). Trained on data from controlled laboratory experiments, these algorithms can classify crack type, severity, and location from acoustic emission signatures or strain measurements.

For concrete bridge monitoring, deep learning models have achieved over 90% accuracy in identifying cracks and fatigue damage (Gordan et al., 2024). Comparative analysis of deep learning models for crack detection demonstrates that ensemble learning strategies combining self-designed CNNs, transfer learning models, and hybrid approaches significantly enhance prediction accuracy and improve generalization (Golding et al., 2025).

Image-based crack detection using CNNs has achieved remarkable precision. Studies using VGG16 architectures with 40,000 RGB images achieved F1 scores of 99.3% for crack detection, while modified CNNs with AlexNet achieved 99.06% validation accuracy with optimized learning rates (Li et al., 2024). Real-time crack detection systems using Faster R-CNN and ResNet architectures enable automated inspection with 93.9% precision and 59.7ms inference time (Kim & Bubryur, 2024).

5.2 Non-Destructive Testing Integration

Ultrasonic testing (UT) remains fundamental for concrete damage detection, uncovering defects by analyzing reflected high-frequency sound waves to detect location, size, and severity of debonding, delamination, or cracking (Lorenzi et al., 2024). Ultrasonic tomography using multi-head antenna systems generating 50 kHz pulses enables 3D imaging of internal defects with maximum reliable ranges up to 2500mm.

Integration of UT with machine learning enables automated damage diagnosis amidst temperature variations. Deep learning-enhanced ultrasonic testing provides robust penetration



ability and high sensitivity to defects like cracking, offering promising prospects for detecting internal damage in concrete structures (A systematic review, 2024).

Infrared thermography (IRT) represents another powerful non-destructive evaluation technique for concrete structures. Active infrared thermography using square pulse thermography (SPT) effectively detects subsurface delaminations and voids by measuring thermal contrasts between defective and sound concrete areas (Maierhofer et al., 2007; Ta et al., 2023). Microwave infrared thermography (MIRT) methods enable defect detection in CFRP-concrete reinforcement systems, providing contactless evaluation of bonding quality (Keo et al., 2023). High-resolution aerial infrared thermography combined with deep learning encoder-decoder architectures enables automated detection and segmentation of bridge deck delaminations, significantly outperforming conventional temperature contrast methods (Zhang, 2022).

5.3 Healing Optimization

Different damage types require different healing responses. Fine micro-cracks may heal autogenously with moisture; larger cracks require vascular agent delivery; active crack closure may need SMA activation. Machine learning algorithms optimize these decisions based on damage characteristics, environmental conditions, and available healing resources (Azevedo et al., 2024).

Reinforcement learning approaches enable self-healing systems to improve over time, learning from previous repair outcomes to enhance future performance. This creates truly adaptive infrastructure that becomes more resilient with age. Hybrid approaches combining physics-based models with data-driven AI classifiers enhance reliability and reduce false positives in damage detection (Gordan et al., 2024).

Artificial neural networks (ANNs) demonstrate superior performance in predicting concrete compressive strength compared to support vector machines, multiple linear regression, and regression trees, achieving root mean square errors as low as 6.09 MPa (Sah & Hong, 2024). These predictive capabilities enable proactive healing activation before critical damage thresholds are reached.

6. CASE STUDIES AND APPLICATIONS

6.1 Bridge Structures

Prestressed concrete bridges represent ideal candidates for self-healing technology. The critical nature of these structures, combined with difficult access for inspection and repair, makes autonomous damage management highly valuable (Argyroudis et al., 2022).

Several demonstration projects have validated self-healing prestressed bridge elements. The inclusion of crystalline admixtures in bridge deck concrete has shown significant reduction in chloride penetration and corrosion risk. Vascular systems embedded in prestressed girders



have demonstrated autonomous crack repair under simulated service conditions (De Nardi et al., 2023).

The smartBRIDGE Hamburg project demonstrates comprehensive IoT integration, with over 500 sensors monitoring the Köhlbrand Bridge's structural health connected to a digital twin (Mostella, 2025). AI-driven structural health monitoring has significantly increased bridge inspection efficiency, precision, and automation, alleviating many manual restrictions while achieving 95% accuracy in defect detection (Gordan et al., 2024).

6.2 Nuclear Containment Structures

The extreme durability requirements of nuclear containment structures demand materials that maintain integrity over decades without possibility of replacement. Self-healing prestressed concrete offers particular advantages in this context, with multiple redundant healing mechanisms ensuring continuous barrier performance (Han et al., 2017).

Research programs in several countries are exploring full-scale implementation of self-healing concrete in nuclear applications, with particular emphasis on long-term validation and reliability under extreme conditions. Infrared thermography feasibility studies for cooling waterway applications demonstrate the potential for automated condition monitoring in nuclear facilities (Boubitsas et al., 2021).

6.3 Marine Infrastructure

Coastal and offshore structures face aggressive chloride environments that accelerate tendon corrosion. Self-healing prestressed concrete for marine applications combines enhanced crack resistance with autonomous sealing to protect tendons from chloride ingress (Allujami et al., 2022).

Field trials in tidal zones have demonstrated the effectiveness of crystalline admixtures in maintaining water tightness despite continuous wet-dry cycling and mechanical loading. Bacterial self-healing systems show promise for marine applications, with *Bacillus* species demonstrating viability in high-alkalinity environments and continuous calcite precipitation sealing micro-cracks against chloride ingress (Nasser et al., 2022; Shiri et al., 2025).

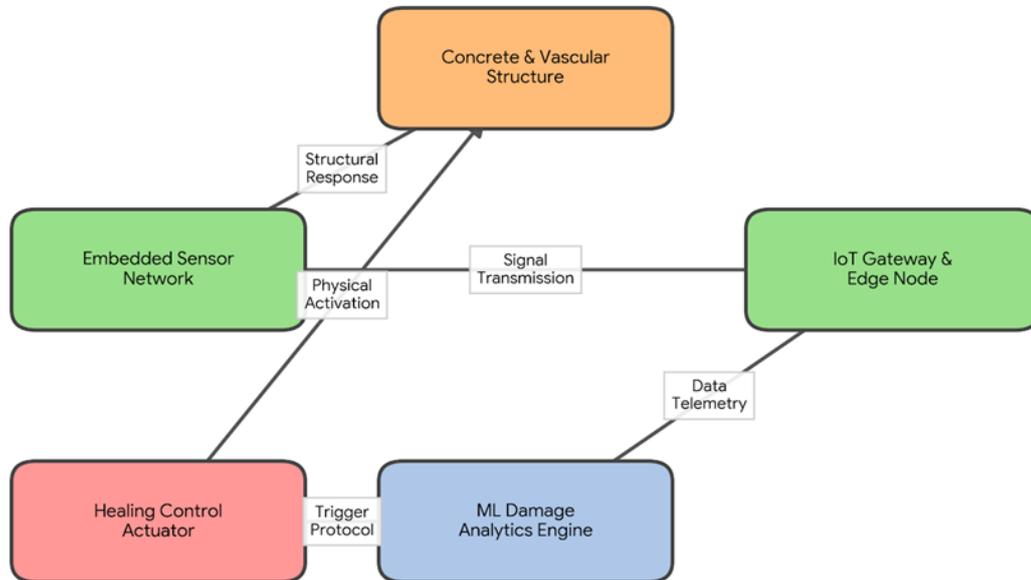


Figure 3: Integrated Self-Healing Prestressed Concrete System Architecture

7. CHALLENGES AND FUTURE DIRECTIONS

7.1 Technical Challenges

Long-term validation: Self-healing mechanisms must function for decades, yet most research has focused on short-term laboratory demonstrations. Accelerated aging studies and long-term field trials are essential (De Belie et al., 2018).

Healing agent durability: Encapsulated healing agents must maintain reactivity for decades. Current polymer-based systems may degrade over time, limiting multiple healing cycles. Bacterial systems face challenges regarding long-term viability, though immobilization in porous carriers like LECA extends survival up to 224 days (Javadian et al., 2025).

Integration complexity: Combining prestressing systems, sensor networks, vascular channels, and SMA fibers requires sophisticated design and construction processes not yet standardized.

Cost considerations: Self-healing materials currently cost 20-100% more than conventional concrete. Life-cycle cost analyses must demonstrate long-term savings to justify premium costs.

Environmental variability: AI-driven SHM techniques face challenges including false positive detections, data quality variations, environmental conditions, and limited generalizability of models across different bridge architectures and contexts (Gordan et al., 2024).



7.2 Research Priorities

Multi-scale modeling: Predictive models linking nano-scale healing chemistry to structural-scale performance are needed for design optimization (De Nardi et al., 2023).

Standardization: Industry standards for testing, validating, and specifying self-healing concrete are urgently required for widespread adoption.

Hybrid systems: Combining multiple healing mechanisms (e.g., crystalline admixtures + vascular networks + SMA fibers + bacterial systems) may provide redundancy and address different damage scales.

Smart manufacturing: Automated prefabrication of self-healing prestressed elements using robotics and 3D printing can reduce costs and ensure quality (Gao et al., 2015).

Explainable AI: The lack of interpretability in deep learning models limits their use in SHM. Engineers require explicit, interpretable AI models to understand fault discovery and evaluation processes (Gordan et al., 2024).

Geopolymer integration: Self-healing geopolymer concrete offers sustainable alternatives to Portland cement systems. Crystalline admixtures, bacterial systems, and enzyme-based healing show promise, though calcium availability limits autogenous healing in low-calcium geopolymers (Rahman et al., 2026).

8. CONCLUSION

Self-healing prestressed concrete represents a paradigm shift in infrastructure design—from passive materials that degrade over time to active systems that maintain themselves. The integration of autogenous healing mechanisms, vascular networks, shape memory alloys, bacterial systems, distributed sensing, and machine learning creates structures capable of detecting damage, initiating repair, and verifying recovery without human intervention.

Current research demonstrates technical feasibility, with multiple healing mechanisms achieving 80-98% recovery of structural properties. Digital twin technology further enhances this capability by enabling predictive maintenance and real-time performance optimization. The path forward requires sustained investment in long-term validation, standardization, and cost reduction through manufacturing innovation. As these technologies mature, they promise infrastructure with 100+ year service lives, dramatically reduced maintenance costs, and enhanced safety and resilience.

The convergence of materials science, sensor technology, artificial intelligence, and digital twin technology is not merely improving concrete—it is transforming infrastructure from static assemblies of inert materials into responsive, adaptive systems worthy of the 21st century.



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