ReACT-SHM:
Responsive Autonomous Concrete Technology for Structural Health Monitoring

PRESENT TECHNOLOGY

Civil infrastructure is constantly exposed to forces that slowly degrade materials over time, including repeated traffic loading, wind, thermal expansion and contraction, freeze–thaw cycles, corrosion of steel reinforcement, and extreme events such as storms or earthquakes. These stressors can initiate small defects that grow gradually and often remain invisible until damage becomes severe, which is why monitoring infrastructure has become increasingly important. In the United States, deferred maintenance for roads and bridges has been estimated at nearly $105 billion as of 2023, demonstrating how large the repair burden can become when deterioration accumulates over time (Pew, 2025). Broader public asset maintenance backlogs are often described as reaching a trillion-dollar scale, reflecting the long-term financial consequences of delayed repair and replacement (Volcker Alliance, 2025).

Structural health monitoring systems (SHMS) use sensor networks to monitor the condition of a structure by measuring the physical responses (strain, vibration, and displacement) of a structure over time (Farrar & Worden, 2007). In this paper, we use SHMS to refer to structural health monitoring systems, and SHM to refer to the broader field of structural health monitoring. The goal of SHMS is to detect any damage or distress that may occur in a structural system during its service life and to identify the earliest indications of damage based on changes in the structural behaviour of the structure, as opposed to waiting for the structure to fail visibly (Farrar & Worden, 2007). SHM has been successfully implemented on a wide range of structures, including bridges, buildings, and aerospace vehicles, in order to enhance safety, decrease maintenance costs, and extend the lifespan of structures (Farrar & Worden, 2007).

A prominent real-world example of SHM deployment is the Stonecutters Bridge in Hong Kong, which has been described as having a long-term SHM system with roughly 1,505 sensors, making it one of the most heavily instrumented bridges reported in the literature (Dong et al., 2010). This type of deployment demonstrates how SHM systems are used in practice to continuously track structural response in large, safety-critical infrastructure rather than relying only on periodic manual inspection (Dong et al., 2010). Fiber Bragg grating sensors provide highly accurate measurements and are commonly used in SHMS since they are not influenced by electromagnetic interference (Yassin et al., 2024). With the ability to embed the Fiber Bragg grating sensors directly in the infrastructure, it is possible to measure structural strain under true environmental conditions over long periods of time (Mieloszyk & Ostachowicz, 2017). Evidence obtained from actual field tests suggests that FBG-based systems are effective in monitoring stress changes associated with large civil engineering projects (Mieloszyk & Ostachowicz, 2017). As shown in **Figure 1**, high-frequency elastic waves are generated by the formation and growth of microcracks in materials, with increased stress resulting in increased acoustic emissions (Ghadarah & Ayre, 2023). Damage can be quantified with acoustic emission monitoring through a signal box before macroscopic failure occurs (Ghadarah & Ayre, 2023). Thus, acoustic emission monitoring enables continuous, non-destructive determination of structural integrity during stress accumulation, before macroscopic failure occurs (Ghadarah & Ayre, 2023). Despite these advances, most SHM systems remain limited to

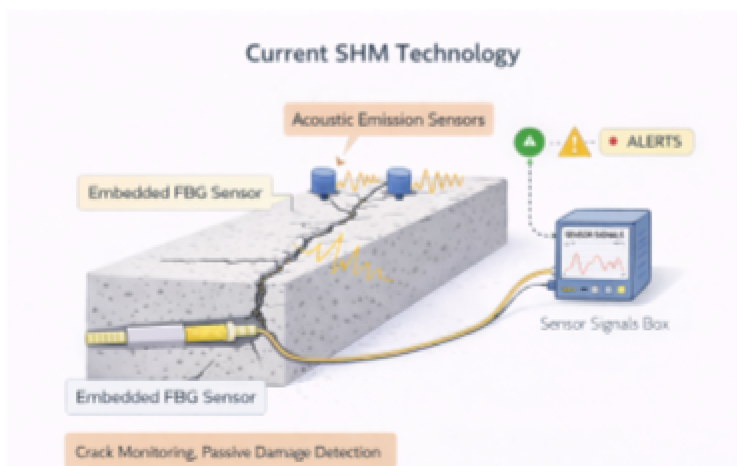

Figure 1. Conventional Structural Health Monitoring (SHM) Technologies for Crack Detection. Outlines an outdated, present measure of structural health monitoring which focuses on continuous protocols that have many negative downsides. Created by students researchers, Biorender, 2026.

damage detection. Data interpretation and corrective actions require human intervention, which can delay repairs, increase costs, and necessitate precautionary measures such as load restrictions or temporary closures (Farrar, Dervilis, & Worden, 2025; UGPTI, 2016).

HISTORY

During the period from the 17th century to the beginning of the 18th century, considerable advancement was made in both the fields of mechanics and elasticity. This advancement led to the foundations of what would later develop into the mathematical model of structural stress analysis (Miller, 2025). In 1638, Galileo Galilei published Two New Sciences, in which he was one of the first authors to investigate aspects related to the strength of materials and beam bending (Miller, 2025). The second author to investigate material properties, Robert Hooke, published Hooke’s Law in 1678, which describes the relationship between the amount of stress applied to a material and the resulting deformation or change in shape of that material (Britannica Editors, 2025). In 1757, Leonhard Euler published his work on the theory of buckling columns, which provided engineers with a method to predict the instability of a structural member (Britannica Editors, n.d.). Thus, all three of these important advancements provided engineers with the ability to mathematically model and predict failure in materials.

From the 1930s to the 1950s, direct monitoring of structural stresses became possible through the application of electrical-resistance strain gauges, which enabled in-situ strain measurements (Britannica Editors, 2009). The 1980s to 1990s saw the development of vibration-based techniques to detect structural failures through changes in dynamic responses (Doebling et al., 1996). These vibration-based approaches helped establish the idea that damage can be inferred from shifts in modal properties such as natural frequencies and mode shapes. By the early 2000s, these methods evolved into formal structural health monitoring (SHM) systems that incorporated sensor networks and automated data analysis (Farrar & Worden, 2007). Several changes made this evolution possible. Sensor networks expanded monitoring from a small number of measurement points to many distributed sensors that could capture multiple structural responses at once, improving coverage and enabling more reliable detection of subtle changes (Chen et al., 2017). At the same time, advances in embedded computing, digital data acquisition, and communications made long-term monitoring practical by allowing large volumes of sensor data to be collected and processed more continuously. The progression from early theoretical foundations in mechanics to modern sensor-based monitoring technologies is summarized in **Figure 2**, which illustrates the historical evolution of structural health monitoring from analytical stress models to embedded, data-driven sensing systems.

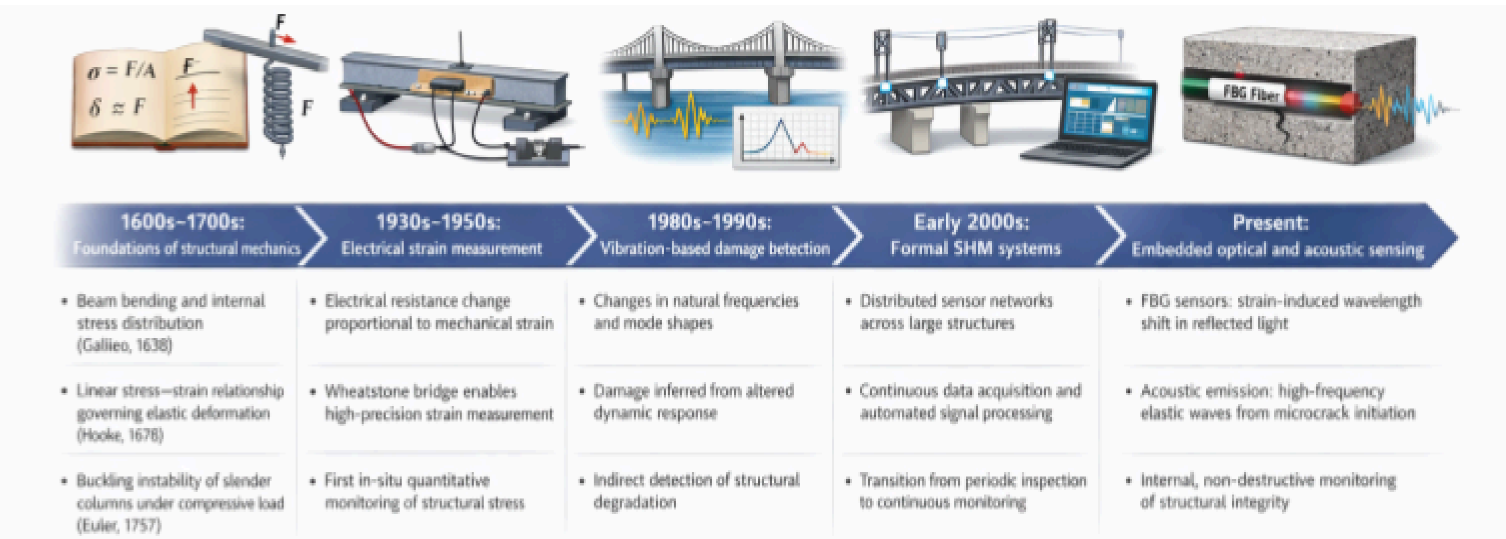

Figure 2: Evolution of Structural Health Monitoring (SHM) from theoretical foundations to advanced sensing. The timeline traces the progression from early mechanical principles (Hooke's and Euler's laws) through the development of electrical strain gauges and vibration-based diagnostics to modern, continuous monitoring systems. Current methodologies emphasize embedded technologies, such as Fiber Bragg Grating (FBG) sensors and acoustic emission monitoring, for real-time, non-destructive assessment of structural integrity. Created by student researchers, Biorender, 2026.

FUTURE TECHNOLOGY:

Over the next ten years, our team envisions structural health monitoring systems advancing beyond passive sensing to active, self-healing infrastructure. Future systems will integrate conventional sensor networks, such as embedded Fiber Bragg Grating (FBG) sensors and acoustic emission monitoring, with intelligent nanoscale agents capable of operating within structural materials like concrete. In this system, macroscale sensor networks and nanoscale agents would operate in a hierarchical feedback architecture rather than as independent components. Embedded FBG sensors and acoustic emission sensors would continuously monitor global strain fields, vibration signatures, and microcrack activity across the structure. When these sensors detect localized anomalies, such as abnormal strain gradients or elevated acoustic emission rates, the data would be processed by onboard or edge-computing units to identify regions of elevated damage risk. These regions would then serve as target zones for nanoscale response, allowing information to flow from the structural scale to the material scale in a controlled manner. A conceptual illustration of this hierarchical sensing and response framework is shown in **Figure 3,** which depicts an embedded nanotechnology system integrating Fiber Bragg Grating (FBG) sensing with localized release of reinforcing compounds near developing microcracks. These nanobots would function in highly alkaline and mechanically constrained environments, continuously monitoring stress, strain, and microcrack formation from within the material itself.

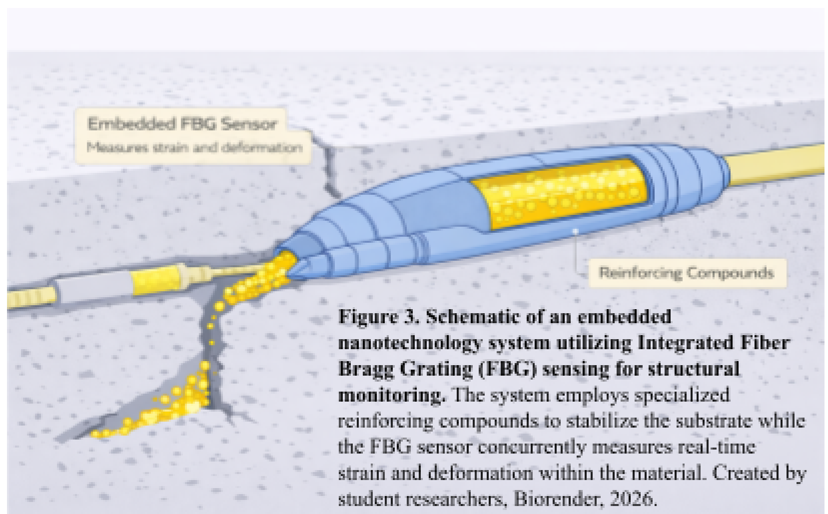

Figure 3. Schematic of an embedded nanotechnology system utilizing Integrated Fiber Bragg Grating (FBG) sensing for structural monitoring. The system employs specialized reinforcing compounds to stabilize the substrate while the FBG sensor concurrently measures real-time strain and deformation within the material. Created by student researchers, Biorender, 2026.

By detecting early-stage damage through localized stress gradients, electric fields, and piezoelectric effects generated during microcrack initiation, the system would enable real-time assessment of structural integrity. At the nanoscale, damage detection would rely on material-specific transduction mechanisms rather than direct replication of macroscale sensing. Microcrack formation in cementitious materials is known to produce localized stress concentrations, charge separation at crack tips, and transient electric fields due to bond rupture and piezoelectric effects in certain mineral phases.

Nanoscale agents composed of conductive or semiconductive materials could respond to these localized electrical and mechanical perturbations through measurable changes in resistance, polarization state, or surface charge distribution. By tuning nanobot material properties and surface functionalization, these agents could be designed to preferentially respond to damage-induced signals rather than background mechanical noise, helping them distinguish early damage signatures from normal operational loading in a heterogeneous concrete matrix. Ultimately, this approach would allow infrastructure to autonomously respond to damage rather than merely report it, significantly improving durability, safety, and lifespan. In this context, autonomous response refers specifically to localized material reinforcement rather than large-scale reconstruction or chemical healing. The proposed system envisions nanoscale agents that release or activate reinforcing compounds, such as mineral precursors or binding agents, near developing microcracks and high-stress zones. This response would not reverse-cure concrete to an earlier thermodynamic state, but instead slow crack propagation and redistribute stress concentrations, reducing the likelihood that small defects evolve into structurally critical failures.

The scientific principles underlying this technology include solid mechanics, elastic wave propagation, photonic sensing, nanoscale electromechanics, and energy harvesting. FBG sensors rely on wavelength shifts governed by Hooke's law to provide precise strain measurements, while acoustic emission monitoring captures high-frequency elastic waves produced by microcrack growth. While these principles operate at the macroscale, they inform nanoscale behavior by identifying the physical processes associated with damage initiation. At nanometer length scales, direct optical sensing is not feasible, and acoustic wavelengths are much larger than individual nanoparticles. As a result, nanoscale agents must rely on alternative transduction mechanisms, such as electromechanical coupling, surface charge variation, or localized conductivity changes, that arise from the same underlying physical phenomena detected macroscopically by FBG and acoustic emission sensors. In this way, macroscale monitoring guides where nanoscale sensing is required, while nanoscale agents detect damage-related signals through physics that remain valid at smaller length scales. At the nanoscale, future breakthroughs are needed to develop durable materials that can withstand long-term exposure to compressive forces and chemical degradation in concrete. Additional advances in nanoscale sensing are needed so nanobots can distinguish between normal operational loads and early damage signatures. Together, these developments would transform structural health monitoring into an intelligent, autonomous system capable of both damage detection and active mitigation throughout a structure's service life.

REQUIRED BREAKTHROUGHS

One breakthrough required for this technology is the development of controllable and durable nanobots capable of long-term operation within concrete. Concrete presents a highly alkaline (often pH > 12) and mechanically harsh environment that can degrade most nanoscale materials through chemical attack, ion exchange, compressive stress, and micro-scale abrasion (Farrar & Worden, 2007). To withstand these conditions, nanobots would need to be constructed from chemically inert materials such as ceramic nanoparticles, carbon-based allotropes, or protected composite structures. Although some materials demonstrate partial resistance in laboratory settings, no existing nanoscale systems are known to maintain autonomous functionality for decades within cured concrete under sustained load (Farrar, Dervilis, & Worden, 2025).

A second breakthrough involves enabling nanobots to accurately detect stress gradients and electric fields generated during microcrack initiation. While crack formation produces localized electrical and piezoelectric effects, current sensing technologies are largely limited to larger scales or controlled environments (Ghadarah & Ayre, 2023). Extending these mechanisms to the nanoscale within opaque, heterogeneous materials remains challenging due to signal-to-noise limitations and long-term stability concerns, requiring advances in selective nanoscale sensing (Yassin et al., 2024).

A third breakthrough concerns controlled nanoscale mobility and targeted reinforcement delivery. Although chemotaxis, magnetic guidance, and electrokinetic transport have been demonstrated in laboratory settings, these approaches are difficult to implement within dense cementitious materials. Future developments must adapt these mechanisms to confined pore networks and enable precise release of reinforcing agents to reduce stress concentrations without introducing new weaknesses (Doebling et al., 1996). Another critical limitation is nanoscale energy harvesting. Nanobots would rely on piezoelectric, acoustic, or electrical energy generated during microcrack formation, yet current nanoscale harvesters produce power several orders of magnitude below the nanowatt-level requirements for sensing and actuation (Ghadarah & Ayre, 2023). Bridging this gap will require substantial improvements in energy conversion efficiency and nanoscale storage for long-term autonomous operation (Farrar, Dervilis, & Worden, 2025).

To investigate these challenges, a proposed study would embed chemically stable, stress-responsive nanoparticles into concrete specimens. Controlled loading would induce localized microcracking, while acoustic emission, microstrain, and electrical measurements would assess crack propagation and stress redistribution. Performance would be evaluated by comparing crack growth rates and strain concentration factors between nanoparticle-enhanced and control samples (Ghadarah & Ayre, 2023; Yassin et al., 2024). The technological gap addressed by these required breakthroughs is illustrated in **Figure 4**, which contrasts current passive damage detection approaches with a proposed transition toward active, nanotechnology-enabled damage mitigation and improved structural integrity.

Figure 4. Evolution of Structural Health Monitoring from passive sensing to nanotechnology-enabled autonomous repair. The diagram illustrates a paradigm shift where embedded nanobots transition infrastructure from simple damage detection to active, real-time reinforcement of microcracks. This breakthrough enables self-repairing infrastructure, effectively preventing closures and extending the overall lifespan of structural assets. Created by student researchers, Biorender, 2026.

DESIGN PROCESS

To develop our proposed future structural health monitoring system, our team evaluated multiple design approaches that could realistically be implemented within the next ten years. Our objective was to identify a solution that not only detects structural damage early but also limits damage progression before major failure occurs. After comparing several alternatives, we selected an integrated design combining embedded Fiber Bragg Grating (FBG) sensors, acoustic emission monitoring, and stress-responsive nanoscale agents to enable targeted in-material mitigation.

One alternative involved autonomous external robotic inspection systems, such as drones or mobile ground robots equipped with cameras and surface-scanning sensors. Although this approach could increase inspection frequency and reduce human risk, it is limited to surface-visible damage and lacks continuous internal monitoring. Many critical failures originate as internal microcracks and stress concentrations that remain undetectable until deterioration becomes severe. We rejected this design because it cannot detect early internal damage or respond in real time. A second alternative was passive self-healing concrete using microcapsules or bio-based mineralization. While this method offers limited autonomous repair, it lacks precise sensing and adaptive control. Healing typically occurs only after cracks form and is constrained by finite healing agents, and the system cannot distinguish between normal loading and early damage signatures. We rejected this approach because it provides repair without intelligent detection. Our final design improves upon this by coupling continuous sensing with stress-responsive nanoscale agents. A third alternative involved AI-driven monitoring systems that analyze sensor data to predict failure and alert engineers. Although prediction accuracy can improve, these systems still rely on delayed human intervention for repairs. We rejected this approach because it improves awareness without improving resilience. Our submitted design reduces reliance on delayed maintenance by enabling autonomous, in-material mitigation that slows damage progression before repairs are scheduled. The alternative approaches considered during this design process, along with their primary limitations, are summarized in **Figure 5**, which contrasts external robotic inspection, passive self-healing concrete, and AI-only prediction systems with the proposed integrated sensing and mitigation approach.

Figure 5. Comparative analysis of alternative structural health monitoring and repair strategies. The figure outlines the limitations of current approaches, specifically highlighting the superficial nature of robotic inspections, the lack of active control in passive self-healing materials, and the absence of autonomous response in AI-driven predictive systems. Created by student researchers, Biorender, 2026.

CONSEQUENCES

The widespread adoption of autonomous structural health monitoring systems with embedded sensing and nanoscale mitigation would have significant societal consequences. One major positive consequence would be improved public safety. Earlier detection of internal damage and continuous mitigation could reduce the risk of sudden infrastructure failures, protecting lives and minimizing disruptions to transportation and essential services. By addressing damage before it escalates, structures would become more reliable over time. Another positive consequence would be reduced long-term maintenance costs and increased infrastructure lifespan. Although the initial cost of embedding advanced sensors and nanoscale systems may be high, extending the service life of bridges and buildings could lower the frequency of major repairs and emergency interventions. This shift toward proactive maintenance could allow governments to allocate resources more efficiently and improve infrastructure planning.

The technology could also support environmental sustainability. Longer-lasting structures would reduce the need for demolition and reconstruction, lowering material consumption and carbon emissions associated with cement production and large-scale construction. Fewer repairs would also mean less disruption to surrounding ecosystems and communities. However, this technology could also introduce challenges. Higher upfront costs may limit early adoption and widen disparities between well-funded regions and under-resourced communities. There are also uncertainties regarding the long-term environmental impact of embedded nanomaterials, particularly during demolition or recycling. Addressing these risks would require careful regulation, long-term testing, and continued human oversight to ensure safe and equitable implementation.

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