# From Microcracks to Multimillion-Dollar Fractures:

# The Case for Self-Healing Polymers in Modern Engineering Applications

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## ABSTRACT.

**The integration of self-healing polymers into systems capable of autonomously repairing damage, ranges from concrete infrastructure to advanced composites used in turbine blades, aircraft wings, and other high-performance materials such as those designed for space exploration. This application has emerged as a promising eco-friendly strategy to enhance durability, reduce maintenance, and extend longevity. These polymers are formulated as hydrogels, encapsulated healing agents, or hybrid systems incorporating nanoparticles, to seal cracks and restore mechanical integrity when activated by environmental stress such as moisture or temperature. Thus, a theoretical exploration of 'self-healing' materials evolved into a practical engineering toolkit that can address damage across diverse structural contexts. Emerging evidence implicates polymer chemistry, network dynamics, and environmental triggers as primary determinants of autonomous healing, supported by a growing body of studies on domestic, industrial, and aerospace materials systems. While the fundamental mechanisms governing crack sealing and moisture-triggered swelling in many polymer systems are well established, their durability, scalability, and reliability across varied operational environments remains insufficiently understood. To address this critical knowledge gap, this article synthesizes current insights into self-healing polymers and related hybrid systems, examines their applications from residential and community infrastructure to sophisticated industrial and aerospace environments, and highlights cost–benefit considerations that will shape their potential for widespread adoption.**

## INTRODUCTION.

Self-healing polymers are becoming an important class of engineering materials as they can autonomously repair microcracks, restore strength, and prevent early-stage damage from turning into major structural failures (1). Their healing behavior stems from several mechanisms, including reversible covalent bonds, supramolecular interactions, microcapsule-based healing agents, vascular delivery networks, and biopolymer-driven swelling responses (1,3,5,41,55). These systems are now being integrated into concrete, automotive coatings, aerospace composites, electronics, and biomedical devices, where they improve longevity under mechanical, thermal, and environmental stress conditions (5,10,21,32,33). Hybrid designs that combine polymers with nanoparticles, biopolymers, or dual-mode healing strategies and utilize machine learning strategies offer even greater reliability and multi-cycle repair (2,10,14). Because these materials reduce repeated maintenance, extend service life, and improve safety, they represent a promising direction for creating more resilient and eco-friendly infrastructure and technology.

## SELF-HEALING POLYMERS.

**Intrinsic Self-healing Polymers**. They derive their healing ability *from* ***reversible interactions within the polymer network itself***, eliminating the need for external healing agents (1). They could be dynamic ***covalent*** polymers that allow multiple healing under stimuli such as heat, light, and pH: examples of polymers with reversible covalent bonds are: Diels–Alder networks, imine exchange, disulfide exchange, while others may have hydrogen bonds, ionic interactions, metal–ligand coordination, or π–π stacking. Another group is the elastomers which heal rapidly at room temperatures and display ***non-covalent*** supramolecular interactions with multiple healing cycles, and common motifs such as ionic or hydrogen-bonded networks, host–guest complexes, or metal–ligand assemblies (6,55). Hydrogels are a major class within intrinsic systems, and recent studies highlight their ability to self-repair microfractures, respond to moisture or temperature, and maintain structural integrity across repeated healing cycles. Intrinsic systems are attractive for structural and aerospace applications because they enable multiple healing events without compromising the bulk matrix (5). However, they face challenges related to mechanical strength, environmental sensitivity, and the need to balance polymer mobility with durability—limitations emphasized across several polymer-focused studies (5).

**Extrinsic Self-healing Systems**. They rely on ***externally stored healing agents*** (1)**.** Microcapsules containing healing agents (e.g., DCPD, epoxy monomers) rupture upon cracking and initiate polymerization, typically applied in epoxy composites, coatings, and cementitious materials (1,3), while microvascular networks release reactive monomers or adhesives when a crack forms and enable multiple healing cycles, and restore structural continuity (1,3,4). These systems have been widely applied in cementitious materials, where encapsulated sodium silicate, epoxy monomers, or superabsorbent polymers (SAPs) can seal cracks and reduce permeability (61). In aerospace composites, extrinsic systems enable localized repair of delamination or matrix cracking by supplying polymerizable resins on demand (3,4). While extrinsic systems offer high healing efficiency and tunable chemistry, they are constrained by finite healing capacity, dispersion challenges, and the need for precise control over capsule or network architecture (1).

**Biopolymers.** Biopolymers form a distinct and rapidly expanding category of self-healing materials due to their sustainability, environmental compatibility, and inherent chemical functionality. These materials have at least five classes that possess abundant reactive groups that enable reversible crosslinking, moisture-triggered swelling, and autonomous crack closure. The first group are ***polysaccharide***-based biopolymers as follows: chitosan is derived from chitin and is excellent for film-forming, antimicrobial, and forms reversible ionic crosslinks; alginate forms ionically crosslinked hydrogels with strong moisture-triggered healing; cellulose and its carboxymethyl and hydroxypropyl derivatives provide viscosity control, water retention, and hydrogen-bond-based healing; starch and its modified subtypes swell and used in hybrid hydrogels and are biodegradable; and finally, dextran forms reversible networks and blends well with synthetic polymers (7). The second group are ***protein***-based biopolymers which offer tunable mechanical properties and reversible bonding, and are as follows: gelatin which is widely used in hydrogels and coatings; collagen has strong hydrogen bonding and is used in biomedical self-healing materials; soy protein isolate which forms crosslinked networks and used in sustainable coatings and adhesives; and finally, silk fibroin provides high mechanical strength and self-assembly behavior (7). The third group are the ***lignin***- and ***phenolic***-based biopolymers that provide stiffness, UV resistance, and chemical reactivity wherein lignin has abundant aromatic groups that enable crosslinking and reinforcement in hybrid systems while tannins are polyphenolic compounds that can form reversible hydrogen-bonded networks (7). The fourth group are ***microbial* and *bio*-derived** polymers are produced by bacteria or fermentation processes and are polyhydroxyalkanoates that are biodegradable polyesters with tunable mechanical properties; bacterial cellulose with extremely strong nanofibrillar network; excellent for hydrogels and composites; and gellan gum which forms ionically crosslinked hydrogels similar to alginate (62). The fifth group are the ***bio-inspired/bio-mimetic*** polymers are not directly extracted from nature but inspired by biological chemistry, and include mussel-inspired catechol polymers (e.g., polydopamine) that have strong adhesion and reversible bonding, as well as elastin-like polypeptides that are thermo-responsive and capable of autonomous healing (9).

In cementitious systems, biopolymers can enhance water retention, promote microbial-induced calcite precipitation, and improve crack sealing efficiency (61). In coatings and flexible electronics, biopolymer networks provide self-repair under mild conditions without toxic reagents. Their biodegradability and low environmental impact make them attractive for infrastructure, packaging, biomedical devices, and soft robotics. However, biopolymers often require reinforcement—via nanoparticles, synthetic polymers, or crosslinkers—to achieve the mechanical robustness needed for structural applications. As a result, many of the most effective biopolymer systems appear within **hybrid** self-healing frameworks.

**Self-healing Hybrid Composites.** These systems represent one of the most advanced directions in self-healing materials research, integrating multiple healing mechanisms to enhance durability, responsiveness, and multi-cycle repair across structural, civil, and aerospace applications. Polymer–nanoparticle hybrids leverage fillers such as graphene oxide, silica, nanoclay, and carbon nanotubes to reinforce matrices, accelerate healing kinetics, and enable thermal or electrical activation, as highlighted in recent reviews of smart self-healing composites (10). Dual-mode systems that combine intrinsic polymer networks with extrinsic microcapsules—such as multicavity microcapsules encapsulating resin and hardener—demonstrate improved crack arrest and autonomous repair under repeated loading (3,4). Vascular network hybrids, which embed microchannels or hollow fibers within thermoset or fiber-reinforced matrices, enable continuous delivery of healing agents and mimic biological vasculature, supporting multi-cycle healing in high-performance composites (12). Biopolymer-based hybrids incorporating alginate, cellulose, lignin, or chitosan further expand the design space by offering sustainable, swelling-based healing mechanisms and compatibility with natural–synthetic reinforcement strategies (13). In concrete, hybrid systems combining SAPs, biopolymers, and nano-silica promote both physical crack sealing and chemical healing through enhanced C–S–H formation. In aerospace composites, nanoparticle-reinforced polymer networks enable heat-triggered healing, improved fatigue resistance, and multifunctional behavior such as damage sensing. Hybrid systems offer the most versatile healing strategies but require deeper understanding of polymer–filler interactions, long-term reliability, and scalability (14). Collectively, these hybrid architectures illustrate the convergence of materials chemistry, polymer physics, and structural engineering in the development of next-generation self-healing polymer composites.

## MATERIAL ENGINEERING APPLICATIONS.

**Infrastructure.** Microscopic damage in water-resistant air barrier membranes of buildings during application, and over time, can lead to significant thermal bridging and material failure. Self-healing elastomers polymers prolong the membranes' lifespan by retaining their original mechanical function, shape, and size during and after installation, in response to temperature and light changes. An example is the laminated Polyguard 400 Air and Moisture Barrier Membrane for moisture and air barrier in roofings, exterior wall cavity and doors and windows. These membranes are made of rubberized asphalt waterproofing element bonded to a robust cross-laminated polyethylene film surface (16). Concrete has innate self-healing properties, wherein fissures mend via hydration of clinker minerals or carbonation of calcium hydroxide, and minor cracks heal in the presence of water. Self-healing or self-repairing concrete was invented by the microbiologist professor Henk Jonkers, at Delft University of Technology, Netherlands, with the addition of bacillus (17). Pooja and Tarannum compared natural healing (autogenic) with engineered systems (autonomous), including polymer capsules and moisture-responsive gels. They found that autonomous systems significantly outperform autogenic healing, especially in dry environments (15).

While concrete cracks commonly occur due to the low tensile strength of the concrete mix, they reduce the durability due to seepage of dangerous liquids and gases, which in turn affect the reinforced steel within. When specific materials (e.g., urea–formaldehyde microcapsules (20–70 μm in diameter) filled with epoxy resin and gelatin microcapsules (125–297 μm in diameter) filled with acrylic resin are utilized (63) or microcapsules or coated pellets and granules or microrganisms) containing repairing solutions are dispersed into the concrete mix (18). Again, the type of integration could be varied as polymer-infused concrete mix, surface coating, embedded capsules or layered between standard concrete layers. Ghazy et al. reviewed advanced self-healing strategies such as microcapsules and vascular networks. They emphasized the environmental benefits of polymer-based healing, including reduced cement usage and enhanced resistance to chloride and sulfate attack (19). Studies on polyvinyl alcohol-borax hydrogels show their ability to form reversible cross-linked networks that respond to moisture and temperature. These gels are ideal for surface coatings or embedded healing agents in concrete structures (20). Self-healing concrete resists high pressure and temperature, reducing failure risks in geothermal and oil wells. Healing polymers reduce maintenance costs and extend lifespan in homesteads, sidewalks, driveways, bridges, and roads. Self-healing polymer allows enhanced durability under extreme conditions specifically in nuclear and hydropower facilities. Smart Concrete Skins pose as surface coatings that seal microcracks and protect against corrosion (21).

**Nanomaterials** are a powerful frontier in enhancing **self-healing concrete**, offering unique properties that traditional additives cannot match. Crack Bridging and Sealing: Nanoparticles like nano-silica, nano-clay, and carbon nanotubes (CNTs) can physically bridge microcracks. They improve the density and cohesion of the cement matrix, making it easier for healing agents (like your polymer gel) to seal cracks. Snoeck et al. reported that combining superabsorbent polymers with nano-silica improved healing in cement paste by up to 80% (22). Catalytic Healing: Some nanomaterials function as catalysts, accelerating chemical reactions that promote healing. For example, nano-iron oxides can trigger hydration reactions that fill cracks with new cementitious material. Moisture Sensitivity: Nanomaterials can be engineered to respond to moisture, swelling or activating healing agents when water enters a crack. This complements your polymer gel's moisture-triggered healing mechanism. Improved Mechanical Properties: Nanomaterials increase compressive strength, flexural strength, and durability. They reduce porosity and improve resistance to chloride and sulfate attack—key for infrastructure longevity. Studies emphasize that the synergy between nanomaterials and polymer gels in autonomous healing systems (23). Kotov's group demonstrated that supramolecular nanocomposites can autonomously repair mechanical damage through reversible nanoparticle–polymer interactions, offering a model for next-generation self-healing hybrid materials with structural-level performance (29).

**Automotive Innovations.** Self-healing technologies have been significantly adopted in the automotive industry, where durability, aesthetics, and safety standards are critical drivers of performance (24). Exterior coatings are one of the earliest commercial successes: scratch-repairing clear coats have been used by major carmakers including Nissan, Infiniti EX, Lexus and Mercedes-Benz, whose premium lines incorporate self-healing top-coat technologies. Self-healing tires are another major pathbreaker, wherein the systems automatically seal punctures through embedded elastomeric or gel-based healing agents, offered by leading tire manufacturers, including Michelin, Continental, and Pirelli, and are used by Tesla, Mercedes, and Audi. Paint protection films (PPF) have also become widely used across the automotive sector. These heat-activated, self-healing polyurethane wraps protect vehicle exteriors from scratches, abrasions, and environmental damage are used by Tesla, BMW, Porsche, and Toyota, which offer self-healing films produced by companies like 3M, XPEL, and STEK. Beyond surface protection, self-healing structural composites are emerging for chassis and body-panel applications. Microcrack-healing carbon-fiber-reinforced polymers (CFRPs) are used by BMW, Audi, and GM, who have published patents exploring self-healing CFRP and polymer-composite systems. Interior components also benefit from self-healing materials. Arruda et al demonstrated that mechanochemically active polymer networks can autonomously reform bonds after mechanical damage, providing a model for high-strength self-healing elastomers suitable for structural, automotive, and protective-coating applications (57). Scuff-healing elastomers are increasingly used in dashboards, trims, and soft-touch surfaces, with Hyundai, Kia, Toyota, and Ford holding patents on self-healing interior polymers and coatings. Finally, self-healing adhesives and sealants—designed to repair microfractures and maintain structural integrity—represent another important category. The automotive industry is a leading end-use sector for these materials, with Volkswagen, GM, and Ford actively patenting self-repairing bonding systems for body structures (25,26).

**Next-generation Aerospace Systems.** Self-healing materials have become a strategic focus across aerospace agencies, defense laboratories, and industry partners, with research spanning structural composites, coatings, electronics, and thermal protection systems. Early sentinel work by NASA (27), the Air Force Research Laboratory (28), and White, Sottos, and colleagues (3) demonstrated autonomic healing in polymer composites, establishing the rationale for damage-tolerant aerospace structures. Strano's group established microvascular self-healing systems that circulate reactive monomers through embedded channels, enabling repeated, autonomous repair in polymer composites under structural loading (4). These concepts now extend to spacecraft and micrometeoroid-debris protection, where the European Space Agency (30) and NASA Glenn Research Center (31) have advanced self-healing polymers for spacecraft skins and load-bearing components. Protective coatings represent another major thrust: Zhang et al (32) and the Office of Naval Research (33) have developed autonomic corrosion-resistant and scratch-healing systems for aluminum alloys. Thermal protection systems also benefit from self-healing approaches, with NASA Ames (34) and Sandia National Laboratories (35) exploring ablative and high-temperature polymer systems capable of repairing microcracks during extreme re-entry heating. Adhesive and bonded structures are also evolving, with Kumar et al (36) and Boeing-affiliated research (37) demonstrating healing in epoxy adhesive layers for composite joints. Finally, shape-memory polymer systems developed at NASA Langley (38) program supports morphing structures capable of autonomous reconfiguration and damage recovery, emphasizing the broad and rapidly expanding role of self-healing materials in next-generation aerospace systems.

**Biomedical Applications.** Biomedical engineering began advancing by using materials that autonomously repair mechanical damage, extend device lifetimes, and improve patient outcomes. Reversible polymer networks that used dynamic covalent chemistry, can restore structural integrity in implantable parts, reducing the need for repeated surgeries (39). Self-healing hydrogels capable of repairing tears under physiological conditions, supported applications in wound dressings, drug-delivery matrices, and soft-tissue scaffolds (40). Injectable self-healing hydrogels support tissue regeneration by providing adaptable, cell-friendly environments (40). In wearable and implantable bioelectronics, stretchable and biocompatible self-healing elastomers maintain electrical performance after damage, supporting artificial skin and continuous-monitoring devices (41). The bio-resorbable orthopedic screws—typically made from polylactic acid (PLA), polyglycolic acid (PGA), or PLGA blends—gradually dissolve after stabilizing fractured bone, eliminating the need for ‘removal-surgery.’ While documented clinical effectiveness exist, constant polymer-engineering studies continue to improve their mechanical strength and degradation profiles (42). Together, these technologies highlight the growing role of self-healing and bio-resorbable polymers in next-generation biomedical devices and regenerative therapies.

**Wearable Technology and Smart Textiles.** Wearable technology and smart textiles are rapidly reshaping personalized healthcare, human–machine interaction, and continuous physiological monitoring through materials that integrate sensing, actuation, and adaptive response. Early studies demonstrated how conductive fibers, flexible sensors, and embedded microelectronics could transform fabrics into responsive interfaces for motion tracking, temperature regulation, and biometric monitoring (43). Later advances in electronic textiles propose stretchable, washable architectures that maintain performance under mechanical deformation, enabling applications ranging from athletic performance analytics to medical diagnostics (44). Studies on self-powered wearable sensors—particularly triboelectric and piezoelectric textiles—has enabled energy-harvesting garments capable of powering low-voltage electronics (45). Smart therapeutic textiles have also emerged, with developments in drug-releasing fabrics, pressure-sensing bandages, and temperature-adaptive materials that support wound healing and chronic-care management (45). Together, these innovations position wearable and textile-integrated electronics as foundational technologies for next-generation health monitoring, assistive devices, and adaptive clothing systems.

**Electronics and Device Longevity.** Electronics that incorporate self-healing polymers are redefining device longevity by enabling circuits, encapsulants, and dielectric layers to autonomously repair damage caused by mechanical stress, thermal cycling, or electrical breakdown (46). Early studies showed that microencapsulated healing agents could restore conductivity in fractured circuits, laying the foundation for resilient electronic architectures. Studies have developed stretchable, biocompatible self-healing conductors that maintain electrical performance after repeated deformation, supporting applications in wearable sensors and soft robotics (41,55). In dielectric materials, self-healing insulating layers that recover after dielectric failure, significantly extending the operational lifetime of flexible and high-voltage devices (47). More recent studies demonstrate polymer networks capable of repairing microcracks at room temperature, improving reliability in next-generation flexible displays and energy-storage systems (48). Together, these findings show that self-healing polymers can dramatically enhance the longevity and safety of modern electronic devices.

## REAL-WORLD ISSUES AND ECONOMIC BENEFITS.

Self-healing polymers are eco-friendly as they extend the longevity, reduce the need for repair and replacement, and lower carbon footprint due to reduced manufacturing and disposal. Self-healing polymers are key toward waste reduction, resource efficiency, and more sustainable material lifecycles, in addition to achieving a higher cost-to-benefit ratio. Several studies have demonstrated that self-healing systems can reduce lifecycle material consumption by up to 50-75% by preventing crack propagation and delaying replacement cycles (2,3,5,64,65). In electronics, self-healing conductive pathways are reported to extend device lifespan by maintaining electrical continuity after repeated mechanical stress (4,54).

Recent U.S. infrastructure failures built within the past 25 years show how environmental factors and material degradation can undermine even modern construction—demonstrating massive losses without self-healing polymers. The FIU pedestrian bridge in Miami, (built 2018; cost ~$14 million), collapsed soon after installation, leading to ~$100 million in demolition, legal, and reconstruction expenses (49). The Fern Hollow Bridge in Pittsburgh, (rebuilt early 2000s), collapsed in 2022 due to corrosion and drainage-related deterioration weakened its steel legs; the replacement bridge cost: ~$25 million, far higher than the cost of preventive maintenance (50). The Hard Rock Hotel in New Orleans, (built 2019, cost ~$85 million), partially collapsed needing a multi-year demolition and stabilization effort (cost: tens of millions) (51). Further, runways at Denver International Airport, (built: 1995-early 2000s), required multi-million-dollar repairs due to freeze–thaw cracking (52), while basements and driveways built in the 2000s across cold-weather and clay-rich regions cost homeowners $20,000–$80,000 for basements and $8,000–$20,000 for driveways (53,54). These examples show how cracks, moisture intrusion, and cyclic environmental stress can be incur losses and self-healing polymers can mitigate this by autonomously repairing microcracks, sealing corrosion pathways, and extending the service life of both large-scale and residential infrastructure. Self-healing polymers typically increase initial material costs by 15–35% in applications such as concrete driveways, basement slabs, and protective coatings, but labor costs remain the same. Studies show that these systems can autonomously repair microcracks, slow corrosion, and reduce maintenance interventions by up to

75%, extending service life enough to avoid full replacements that cost tens of thousands of dollars.

Self-healing polymers save money in transportation systems as they prevent small cracks, coating damage, and electrical failures from worsening into expensive repairs: in automobiles, they can eliminate $2,000–$10,000 in recurring paint, composite, and sensor-related repairs (10,24-26,56), and in aircraft they reduce composite-skin and delamination maintenance that reaches hundreds of thousands of dollars (60). By autonomously restoring 60–90% of lost mechanical strength or conductivity, these materials significantly cut preventive maintenance by ~40% in composite-rich aerospace structures and extend longevity.

## CONCLUSIONS.

Self-healing polymers are gaining importance due to their ability to repair microcracks and restore mechanical or electrical function before the damage spreads, which improves the longevity of materials used in infrastructure, vehicles, and advanced technologies. By relying on reversible chemical bonds, encapsulated healing agents, or hybrid polymer–nanoparticle systems, these materials can respond to environmental stress factors in ways that traditional materials cannot. As research continues to improve their strength, reliability, and long-term performance, self-healing polymers have the potential to make future buildings, transportation systems, and devices more resilient and cost-efficient through their entire lifespan.

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