

Incorporating Active Healing and Feedback in Structural Systems (Technical Brief)

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ABSTRACT

Self-sealing or self-healing materials can be found in many applications, including automotive and aerospace, and remain a topic for current research. The nature of these materials allows damage to be repaired autonomously. This can improve safety and reliability, but also pose challenges for structural health monitoring and prognostics. One goal of structural health monitoring is to monitor the accumulation of minor damage and degradation in order to predict and prevent catastrophic failure. This task can be made harder by self-healing materials which cover up the clues used for health monitoring and prognostics. Incorporating sensing technology into self-healing materials can improve their performance by adding the capability of damage, detection assessment and location, and feedback on the healing process. Additionally, structural health monitoring is still possible and improved by the coupling of sensing and healing systems. To illustrate the benefit of a coupled system a laboratory scale test bed was created. A thermal healing polymer embedded with resistive heating wires acts as the self-healing material. Sensing duties are performed using an impedance, capacitance, and resistance testing device and an PC. As damage occurs to the polymer it is detected, located, and characterized. Based on the sensor output, a repair is made and subsequently monitored to ensure completeness. This proof-of-concept prototype has the potential to be expanded and improved with alternative sensor options, self-healing materials, and system architecture.

1. INTRODUCTION

The capacity for self healing is ubiquitous in nature and has been present in man made objects and structures

for centuries. Primary examples dating back to antiquity are wood boats, wet cooperage wood barrels, and wood pipelines. The method of sealing is to construct the vessel wall out of wood slats using snug, but not watertight, joints and seams. Water causes the wood to swell and seals the leaks. Modern self-sealing vessels and materials began to appear with the development of rubber and petroleum-based solvents. Many unvulcanized and partially-vulcanized rubbers will swell in the presence of petroleum-based solvents. An early patent (ca. 1896) by Mercier developed a self-healing material that could seal through-wall punctures. The material used layers of unvulcanized rubber, mesh fabric and petroleum jelly. Upon being pierced, the petroleum jelly would intermingle with the unvulcanized rubber and cause the rubber to swell and seal the hole (Mercier, 1896). The technology of self-sealing fluid vessels progressed with the development of modern high-performance vehicles and other systems, such as space suits (Schwartz, 1970).

The development of self-sealing or self-healing materials remains a topic of current research. Similar to the strategy in the 1896 Mercier patent, several recent self-healing strategies are based on a catalyst housed within a material and released upon localized damage (Dry, 2003) ,(White, 2001). Similar approaches used self healing fiber reinforced plastics (FRP) based on hollow fibers containing epoxy resin or hardener embedded in the FRP matrix. Upon damage the fibers are ruptured and leech their contents, which then combine to strengthen or repair damaged areas (Trask, 2006). In addition to developing self-healing systems, much research has been dedicated to developing the materials to facilitate self-healing. One such effort focused on developing a stress sensitive catalyst which could be applicable for self healing applications because it causes polymerization or cross linking of reactive polymers (Piermattei, 2009). Other approaches rely on the surrounding environment for self healing. One example is

cementitious composites utilizing moisture to heal microcracks with the formation of calcium carbonate (Yang, 2009). There are similar advances in coatings, such as a urethane coating capable of self-healing upon exposure to ultraviolet light (Ghosh, 2009). Self-healing is also benefiting from nanotechnology developments. Simulations have shown that nanoparticles embedded in reactive polymer agents could suppress crack formation and growth (Lee, 2004).

2. SMART-HEALING

The phrase “biology inspired” and term “biomimetic” appear frequently in self-healing literature. The brief history and review of recent advances in self-sealing and self-healing describe healing capabilities that are actually only a portion of those present in a complex biological self-healing system. There are potential complications arising from the passive, autonomous nature of these materials. Self-healing materials could allow minor damage to persist unnoticed until it develops into larger more dangerous problems.

2.1 From Self-Healing to Smart-Healing

To realize fully the potential for improved lifespan, fault tolerance, and safety, self-healing materials should be integrated into a structural health monitoring and prognostic system. This would be analogous to the role of the central nervous system in biological organisms, where the location and scale of injury is represented by the source and level of pain. The central nervous system also acts as a feedback mechanism to monitor healing, as pain subsides normal activity may be resumed. This same logic and methodology should be applied to self-healing materials. A smart-healing material or structure would be capable of detecting and locating damage and a scale-sensitive response. As damage occurs it would be detected, located, and analyzed. Minor damage would be healed immediately and autonomously by the self-healing material but also logged for further inspection during routine maintenance. Moderate to major damage would result in reduced work load, scheduling prompt inspection and maintenance, or removal from service entirely and immediate maintenance.

2.2 Developing a Smart-Healing System

The success of a smart-healing system depends on its ability to 1) detect damage, 2) locate damage, 3) assess damage, 4) determine an appropriate course of action, 5) implement action plan, and 6) continue to monitor and terminate healing process as needed. Various methods and technologies are available for each of these steps, including several techniques that can accomplish several tasks simultaneously. The first three tasks of a smart-healing system – damage detection, location, and assessment – are sufficiently related that they can be accomplished using one sensor and signal processing algorithms. One approach is to monitor the electrical properties of the self healing material, resistance, capacitance, and inductance. Inductance, capacitance, and resistance (LCR) meters combined with data acquisition

hardware, and signal processing algorithms are capable of detecting subtle changes in the electrical properties of the self-healing material. Baseline values for the LCR properties are acquired in a controlled test and used for comparison of future readings. These same properties are constantly monitored during testing to look for changes associated with incurred damage. Responses to damage include: relying on the autonomous healing properties of specialized self-healing outlined above, activating an assisted healing process combining self or assisted healing and a reduced workload until maintenance can be performed, or immediate removal from service. After an action plan is carried out a feedback system would monitor the healing process and adjust the action plan accordingly.

3. SMART-HEALING PROTOTYPE

A goal of this project was to develop a proof-of-concept smart-sealing system, see Figure 1. The healing material for this demonstration was a thin layer of thermal healing polymer embedded with resistive heating wires. This material is not self healing in that an external stimulus is required. A more appropriate term for the polymer and heating wire combination could be ‘active-healing.’ The resistance wires were arranged in a grid pattern and wired such that each node could be electrically isolated. The ability to isolate nodes for sensing and healing is key. The reduced area allows more accurate damage detection, a node to associate with the damage and therefore location, and the ability to heal specific location.

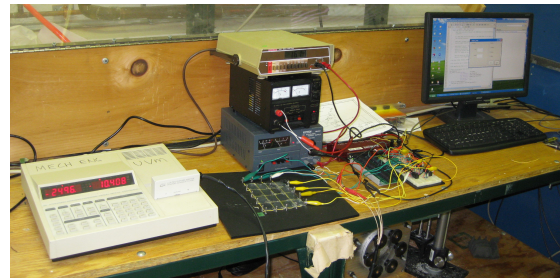


Figure 1: Smart-Healing Prototype

Healing was accomplished by flowing the appropriate current through resistance wire to heat the damaged section of a material, causing a temporary phase change to fill in the damaged area, Figure 2. A Stanford Research Systems SR715 LCR meter was used to determine the electrical properties of the polymer-resistance wire combo. Data were collected and analyzed using MATLAB. Observed values are compared with a dataset obtained by inducing damage under controlled conditions. Based on both the location and scale of damage, one of several predetermined plans of action was selected. For the proof-of-concept demonstrations the action plans consisted of heating of resistance wire and a warning message. The heating of the polymer produces a distinct change in

the inductance value of the node, which is used to determine when the polymer is sufficiently heated for healing and when it has cooled to the normal state, see Figure 3. Communication with the LCR meter and control of the self-healing material was done using a USB-based digital I/O board (LabJack UE-9).

The entire system, comprised of active-healing polymer and wire array, sensing, logic, and autonomous repair capability may be better described as a smart-healing system, to differentiate from the passive self-healing materials described above.

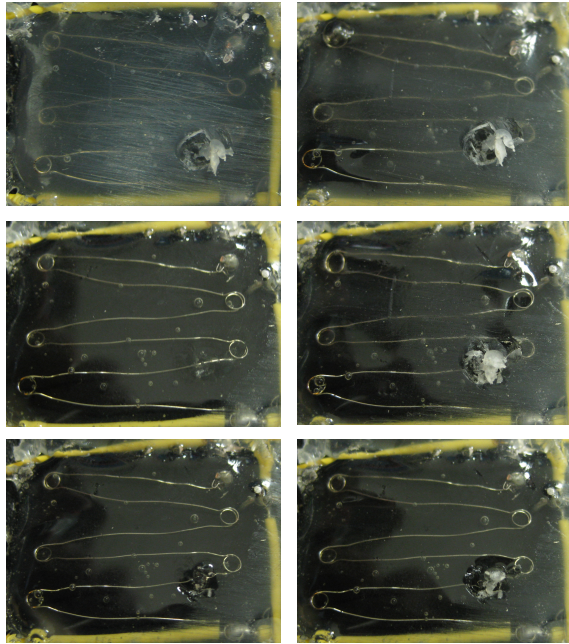


Figure 2: Sequence of Thermal Healing Polymer, clockwise from top left

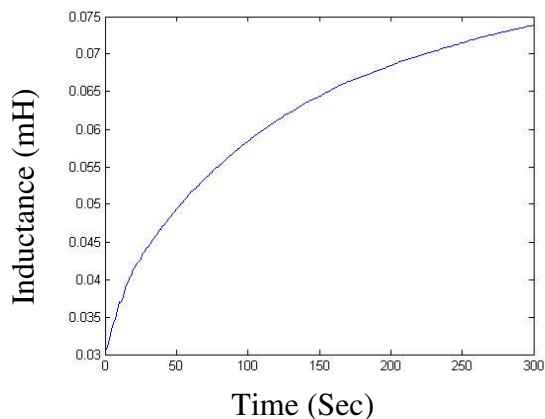


Figure 3: Change in Inductance Associated with Phase of Thermal Healing Polymer

4. CONCLUSIONS

The ability to perform prompt and autonomous repairs would greatly improve structural health monitoring but the integration of the two requires an entirely new system. This technical brief presents the goals and requirements for a smart-healing system and a proof-of-concept prototype. While effective in a controlled setting, the prototype is far from ready for real world use. Fortunately the field of self-healing materials is rapidly expanding as is sensor design and implementation for structural health monitoring. Future work includes evaluation of alternative healing strategies such as replacing the thermal healing polymer and resistance wire with a UV curing resin and appropriate light source or the use of robotics. Alternative sensing systems include acoustic emissions and ultrasound systems.

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