SHM

NDT

Self-Sensing Materials for Nondestructive Evaluation

by Simon Laflamme and Filippo Ubertini

Self-sensing materials are materials engineered to transduce deformations into measurable or observable changes; for example, as resistance and capacitance changes. Such capability can be leveraged to automate the nondestructive evaluation of structural components, also known as structural health monitoring. —John Z. Chen, Technical Editor

Recent advances in materials science and engineering have enabled the fabrication of structural materials with enhanced functionalities. One of those functionalities is the ability to self-sense, where the material is engineered to transduce deformations into measurable or observable changes. Such self-sensing capabilities can be leveraged to automate the nondestructive evaluation (NDE) of structural components, also known as structural health monitoring (SHM). This paper provides a tutorial on self-sensing materials that can be used for NDE, with a particular focus on those based on resistance and capacitance measurement principles. The electromechanical principles used in fabricating self-sensing materials are reviewed for both resistance- and capacitance-based self-sensing materials. Next, two example materials are discussed in more detail: a self-sensing concrete based on electrical resistance and a self-sensing carbon fiber reinforced polymer (CFRP) based on electrical capacitance. The paper concludes with an example of a system-level application consisting of a masonry building equipped with smart bricks, with a focus on linking signals to damage discovery and condition assessment.

Introduction

The field of NDE is typically concerned with the inspection of materials through noninvasive methods. Its process often necessitates highly trained inspectors and can be costly and expensive to conduct. In addition, NDE is inherently conducted on a time or breakdown basis, which means that defects can be difficult to detect at the exact moment they occur or when they become structurally important. The NDE process can be automated, which is known as SHM, where materials or components can be continuously monitored, enabling real-time condition assessment. However, SHM necessitates carefully crafted sensor networks and signal processing algorithms linking sensor data to condition assessment. Furthermore, these sensors must be either installed onto a surface or embedded, which adds technical and economic challenges when deployed at larger scales. A solution is to empower traditional structural materials with self-monitoring functions, termed self-sensing materials.

Self-sensing materials, also known as a specialized type of smart materials, can be created by altering their nano- and microstructures in order to transduce states of interests into measurable or observable changes. For example, a material can be augmented with a piezoelectric behavior in order to transduce mechanical stress into electrical charges, surface-modified with mechanochromic photonic crystals to generate a mechanochromatic response to mechanical strain, or functionalized with electrical properties to transduce mechanical strain into a measurable change in an electrical signal. While these approaches, and others, are excellent strategies to provide a structural material with functionalities enabling SHM, this paper focuses on the last family of electrical approaches due to their high popularity for SHM applications that can be attributed to their scalability, relative ease of implementation, and/or more direct link between signal and damage.

The objective of this paper is to provide a tutorial on self-sensing materials transducing strain, such as those provoked by damage or vibrations, into measurable changes in an electrical signal. For example, an epoxy-based composite can be altered to provide it with a piezoresistive behavior to monitor localized damage. It follows that data acquired from these systems can be leveraged to facilitate the inspection task, and even yield condition-based maintenance capabilities. However, in order to fabricate and apply these materials, it is important to understand their opportunities and limitations. This paper attempts to do so by providing the reader with high-level overviews and discussions of key mechanisms in self-sensing materials. First, the basic electromechanical principles in fabricating these materials are presented. Next, examples of self-sensing materials are reviewed to understand typical sensing functionalities and their associated challenges. Last, an example of a system-level application is discussed, with a focus on linking signals to damage discovery and condition assessment.

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Electromechanical Principles

The most common underlying measurement principle of self-sensing materials is to measure an electrical signal that can be mapped to a change in the material's geometry. For example, the resonant frequency of a material can be measured, and its change would relate to a change in mass or stiffness. Smart sensing skins have been proposed in the form of a patch antenna, which uses an integrated circuit that enables wireless data acquisition. Other, more popular techniques include the use of electrical resistance or capacitance that can also relate to a change in geometry. The idea is to transform the material itself into a resistive- or capacitive-based strain gauge. Examples include smart cementitious materials that leverage the piezoresistive effect of conductive fillers and smart skins fabricated from soft elastomeric capacitors. Other electrical signals can be leveraged, including inductance (such as self-sensing bearings), and admittance (such as self-sensing piezoelectric sensors and actuators). Given the popularity of resistance-based and capacitance-based techniques, likely due to their scalability and ease of implementation

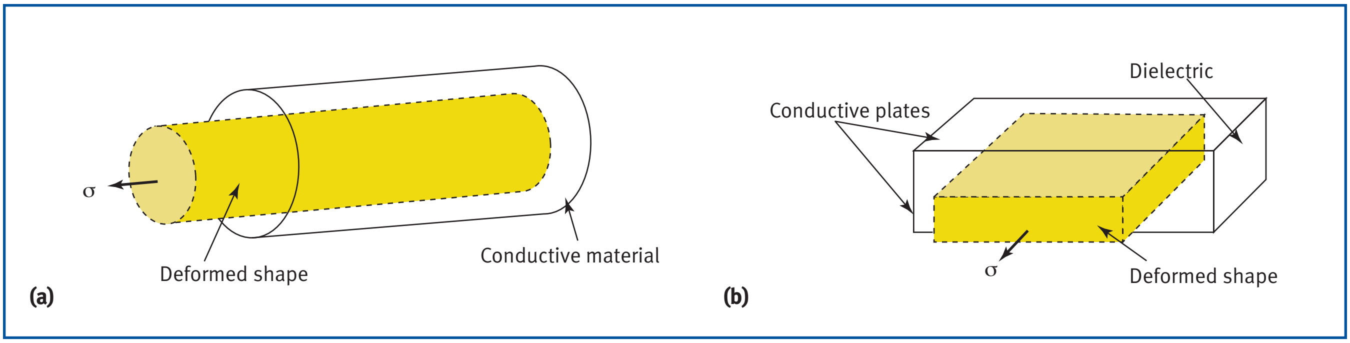

Figure 1. Schematic of: (a) resistive strain gauge; and (b) capacitive strain gauge.

in creating full-scale self-sensing materials, this tutorial paper will focus primarily on these. The subsections that follow explain the electromechanical principles for resistance-based and capacitance-based self-sensing materials.

Resistance-Based Self-Sensing

The principle in creating resistance-based self-sensing materials lies in transforming the structural component of interest into a strain gauge. Consider the component shown in Figure 1a. A stress (σ), here uniaxial, will produce a change in the conductive material's geometry and resistivity, therefore altering the material's resistance. It follows that a measurable change in the material's resistance can be mapped to a deformation or strain. The amplification of the strain by the electrical measurement is typically a constant and is termed the gauge factor, often represented by the Greek letter λ. The gauge factor is an important property of a self-sensing material. The higher the gauge factor, the higher the resolution of the sensor and the lower its sensitivity to electrical noise is. Typical strain gauges are made of metallic materials, and examples of gauge factors for strain gauges include 2.1 for constantan and 3.6 to 4.4 for platinum. It is important to note that the change in resistivity due to mechanical stress is termed the piezoresistive effect. The contribution of the piezoresistive effect to conventional strain gauges is approximately 30% and does not vary significantly with strain.

A challenge in transforming structural materials into strain gauges lies in their very low sensitivity to strain, which makes the measurement principle impractical. A technique is to leverage the piezoresistive effect to significantly boost the gauge factor. This is done by modifying the nano- or microstructure of the material to reach electrical percolation. Electrical percolation can be defined as the material's phase transition zone indicated by a significant change in its electrical conductivity. Such a change in electrical conductivity can be achieved by loading a composite with electrically conductive nano- or microparticles until conductive chains are created, therefore significantly increasing the composite's conductivity (or decreasing its resistivity). Figure 2a illustrates an example of electrical percolation occurring in a cement paste loaded with carbon black (CB) particles. The example is extracted from a previous study (Laflamme et al. 2018), where the sensing properties of a cementitious composite loaded with CB were investigated. The figure shows that as the CB concentration level increases, the resistivity of the composite material slowly decreases until the percolation threshold is reached around 0.96% CB, after which the resistivity suddenly drops and tends to stabilize.

Research suggests that strain sensitivity, and therefore the piezoresistive effect, is the highest around the percolation threshold. The example percolation study presented in Laflamme et al. (2018) also measured the relative change in resistance of the cementitious sensors versus strain as a function of CB loading levels. Figure 2b plots the results at 0.54, 0.71, 0.96, and 1.25% CB. One can observe that the strain sensitivity of each sensor is linear, and that the slope, related to the gauge factor, is significantly steeper for the 0.96% CB sample, which corresponds to the loading level right before electrical percolation occurs. Gauge factors obtained experimentally were $\lambda = 47.3$, 82.5, 178, and 17 for CB loadings of 0.54, 0.71, 0.96, and 1.25%, respectively. These results demonstrate that the gauge factor can be considerably increased by fabricating a conductive composite close to its electrical percolation.

There exist various conductive nano- and microparticles that can be used in creating self-sensing materials. Several studies have analyzed cementitious materials filled with carbon nanoinclusions that include CB particles, carbon fibers, graphene, and carbon nanotubes (CNTs). Generally, there exists an important trade-off between the cost of

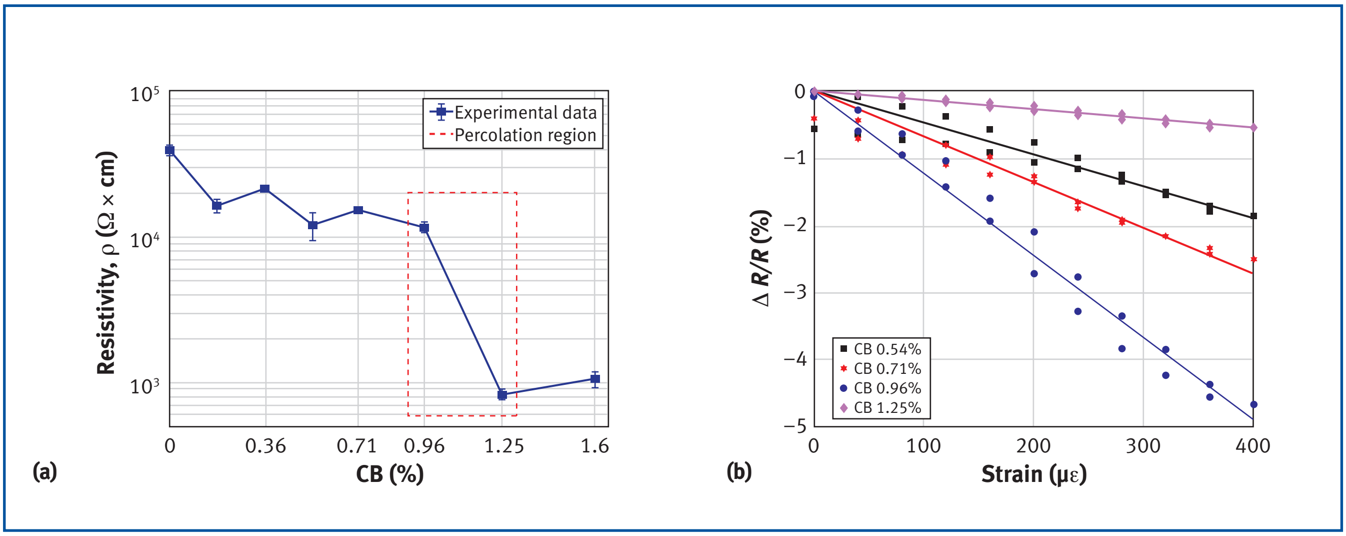

Figure 2. Cement paste experiment: (a) resistivity (ρ) as a function of carbon black (CB) inclusion; and (b) relative change in resistance (Δ*R*/*R*) as a function of strain (ε) (adapted from Laflamme et al. 2018).

the particles and their conductivity and ease of dispersion. For example, CB is very inexpensive and easy to disperse, but its conductivity is very low compared to CNTs, so a higher level of particle loading is required to achieve percolation. Conversely, CNTs are very conductive, but they are hard to disperse and expensive to acquire. However, they are typically required in very small amounts and may yield significantly improved mechanical and electrical properties.

Capacitance-Based Self-Sensing

Self-sensing materials based on electrical capacitance are less popular than those based on electrical resistance, but yet include numerous applications. The measurement principle is analogous to that of the resistive-based systems, where the material is transformed into a strain gauge, but the electromechanical model relies on the measurement of the capacitance. Consider the parallel plate capacitive strain gauge illustrated in Figure 1b, where the conductive plates (electrodes) are along the top and bottom (not shown) of the prism, and the dielectric is sandwiched between the conductive plates. Analogous to the resistance-based technique, stress, here also uniaxial, provokes a change in the material's geometry that can be measured as a change in capacitance. Unlike resistance-based techniques, it is difficult to boost the gauge factor of a capacitance-based strain gauge aside from altering the capacitor material's Poisson's ratio or the configuration of the electrodes (therefore altering the geometry itself).

Instead, one can boost the electrical sensitivity of the material, defined here as the ratio of the measured capacitance to change in strain. An effective solution in increasing the sensitivity is the inclusion of nano- or microparticles in the dielectric to increase the material's relative permittivity. Such an increase in sensitivity is desirable in order to facilitate the measurement process and obtain signals that rapidly rise beyond noise (such as that caused by the inherent capacitance of the connecting cables). Popular choices of particles include barium titanate and titanium dioxide. For example, in a previous study (Saleem et al. 2014), a self-sensing polymer was fabricated using a styrene-ethylene/butylene-styrene (SEBS) to form the dielectric yielding a relative permittivity $e_r = 2.1$, while the inclusion of 15% titanium dioxide at 15 vol% yielded $e_r = 3.8$ (both measurements taken at 100 Hz), representing an 80% increase in sensitivity.

Examples of Self-Sensing Materials

This section discusses two examples of self-sensing materials with the intent to provide the reader with more insights on their electromechanical behaviors and possible applications to NDE. The first one is a resistance-based material consisting of a self-sensing conductive concrete. The second one is a capacitive-based material consisting of a self-sensing carbon fiber reinforced polymer (CFRP).

Self-Sensing Conductive Concrete

Resistance-based self-sensing concretes have been proposed to conduct SHM of concrete structures by leveraging distributed strain-sensing capabilities through the detection and evaluation of cracks and discontinuities in the material by creating smart

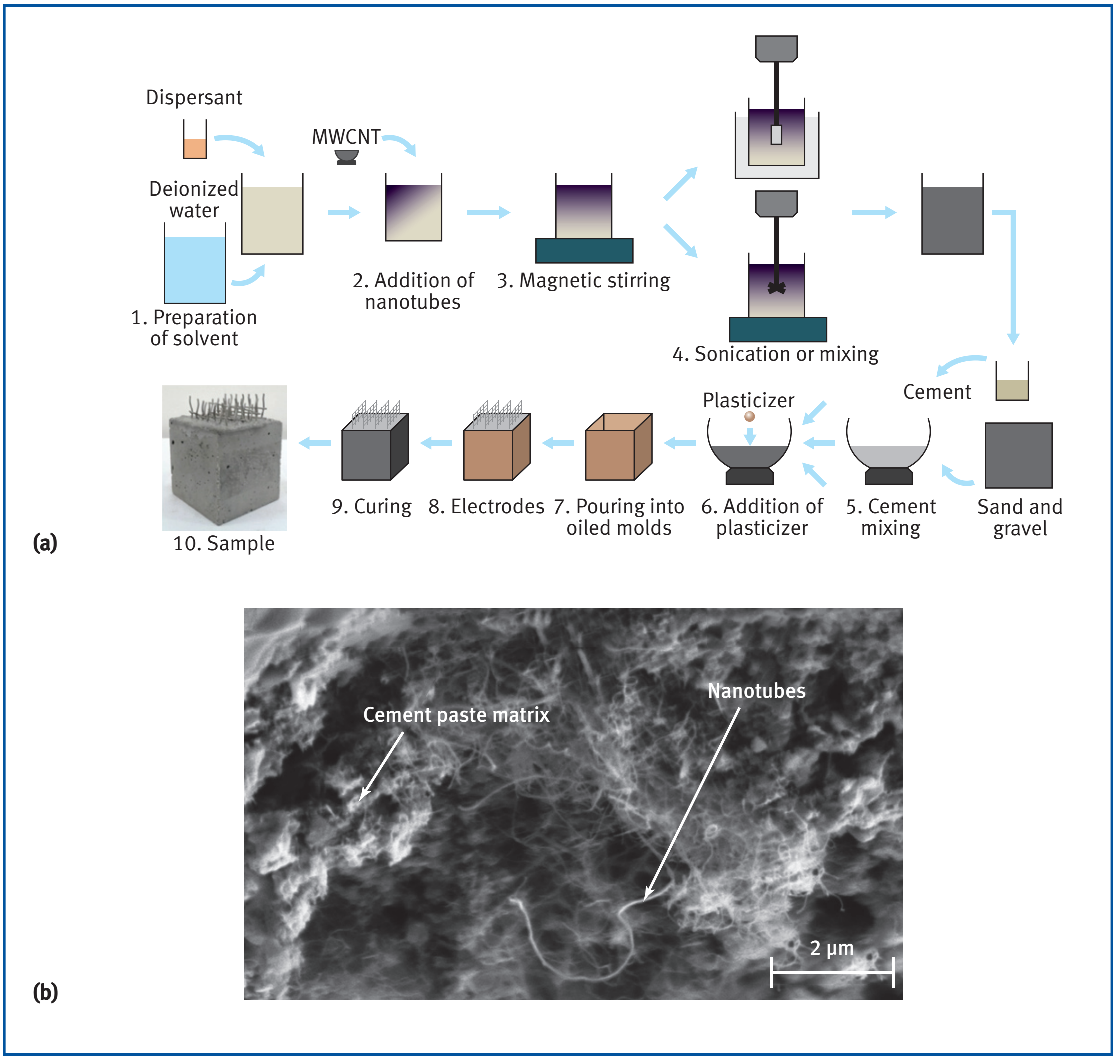

Figure 3. Smart concrete: (a) preparation procedure of smart concrete cube specimens; and (b) typical SEM image of nanotubes within hardened cement paste (adapted from D'Alessandro et al. 2016).

aggregates and through weight-in-motion characterization. Cementitious sensors have the advantage of enhanced durability and lower life-cycle costs compared with existing alternative technologies.

Popular choices of conductive particles to create such smart concretes include multiwalled carbon nanotubes (MWCNTs), with typical dimensions of 10 to 15 nm in diameter and 0.1 to 10 µm in length. These MWCNTs have shown excellent piezoresistive properties with gauge factors that can be in the order of 10^2 to 10^3, owing to their high piezoresistivity, electrical conductivity (up to an order of $10^7 (\Omega m)^{-1}$), and excellent mechanical properties (Young's modulus greater than 1 TPa and tensile strength of approximately 150 GPa). Alternatives to MWCNTs are nano- or microcarbon fibers, graphene nanoplatelets, carbon black, or simple graphite.

Figure 3 shows a typical fabrication process of concretes doped with MWCNTs and the scanning electron microscope (SEM) image of the nanotubes dispersed in the hardened cement matrix. The optimal dispersion of MWCNTs is a particularly delicate task that may require the use of ultrasonication of the nanotubes dispersed in water prior to adding cement and aggregates, and the use of special chemicals that facilitate MWCNTs dispersion. These are called dispersants and their use should be taken with care, as they may impair the conductivity and strain sensitivity of the resulting composite.

Figure 4 illustrates the electromechanical response of self-sensing concretes through a smart concrete cube being tested in an axial compression machine (Figure 3a). The figure shows a time history of the measured strain using commercial strain gauges under

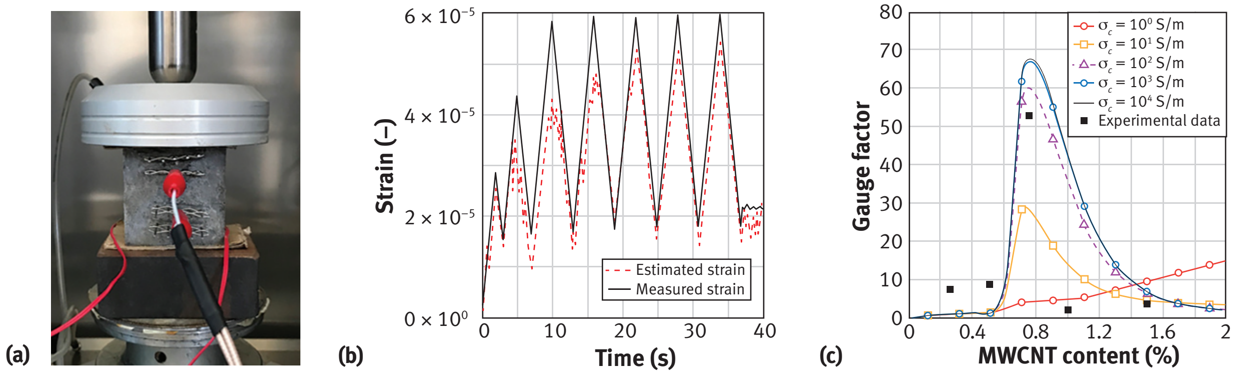

Figure 4. Smart concrete sample being tested under compression load: (a) experimental setup; (b) comparison between measured strain (using strain gauges) and strain estimated from smart concrete's output using a constant gauge factor (adapted from D'Alessandro et al. 2016); (c) analytical and experimental variation of smart concrete gauge factor versus multiwalled carbon nanotubes (MWCNT) content with respect to weight of cement for different values of MWCNT conductivities (adapted from García-Macías et al. 2017).

repeated triangular loadings, compared with the response estimated using an electromechanical model (Figure 3b). The theoretical/experimental prediction of the gauge factor (λ) of concrete cubes is also presented (Figure 3c) as a function of MWCNT weight content with respect to cement for different values of electrical conductivity (σ_c) of the nanotubes. Various mechanisms are responsible for the piezoresistivity of concretes filled with MWCNTs, including: (1) volume expansion and reorientation of MWCNTs; (2) change in conductive network configurations; and (3) change in tunneling resistance. The result of these mechanisms is a gauge factor that highly depends on the amount of MWCNTs contained in the mix, and that is the maximum at the electrical percolation threshold (see Figure 4c) as previously mentioned. The same gauge factor is also highly affected by imperfections in the MWCNTs' dispersion and the presence of bundles and agglomerations.

A particularly notable feature of self-sensing concretes is their ability to work as strain-sensing materials both in the presence of slowly varying and dynamically varying loads, therefore permitting modal identification of the structure. It has been shown that smart concrete block sensors deployed on a simply supported reinforced concrete beam allowed the identification of the natural frequencies of the beam in the range of 0 to 500 Hz, which was validated against traditional accelerometers and strain gauges (Ubertini et al. 2014). This notable sensitivity of the material at relatively high frequencies was illustrated through a phenomenological lumped circuit approach, where it was shown that such sensitivity may be attributable to some small piezoelectricity characterizing the material; that is, the capability of the material to output small changes in voltage under an applied strain. Although negligible at low strain rates, this effect may be dominating the electrical response of the material at relatively high strain rates. It follows that self-sensing concretes can be used to perform several NDE tasks in real time, from static (such as crack detection) to dynamic (such as modal characterization) identification.

Self-Sensing Carbon Fiber Reinforced Polymer

An example of self-sensing materials based on capacitance is self-sensing CFRP. CFRP is widely used to create laminated composites and is used in many engineering fields due to its excellent mechanical properties. Of interest to this example are its applications in civil engineering for the strengthening, rehabilitation, and retrofitting of structures. The process typically consists of adhering CFRP laminates onto concrete surfaces to improve structural service life through enhanced tensile strength and resistance to abrasion and wear. Given the low ductility of CFRP materials, it is often desirable to inspect them for the presence of cracks, which can be done via NDE. In a previous study (Yan et al. 2019), a self-sensing CFRP was proposed to automate that process. As discussed in the study, self-sensing CFRPs based on resistance have been proposed. Nevertheless, the inherent structure of a CFRP laminate lends itself to leveraging the capacitance technique. As shown in Figure 5a,

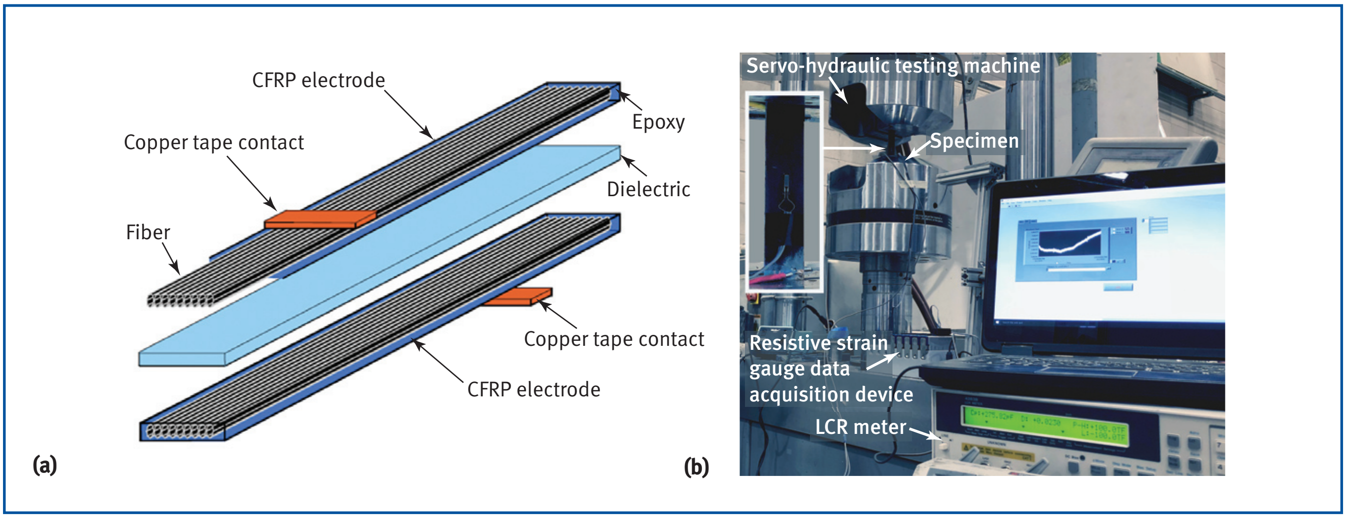

Figure 5. Smart carbon fiber reinforced plastic (CFRP): (a) schematic; and (b) experimental test setup for electromechanical characterization (adapted from Yan et al. 2019).

a capacitor can be made out of a CFRP laminate by leveraging the CFRP for making the electrodes, and an epoxy layer for the dielectric. With that configuration, copper tapes can be used to create a mechanical contact with the data acquisition system.

Yan et al. (2019) used an epoxy filled with titanium dioxide as a dielectric to enhance the material's sensitivity to strain and reduce noise associated with measurements. The self-sensing CFRP was characterized by subjecting specimens to quasi-static tensile tests through a displacement-controlled load at a loading rate of 2 mm/min applied using a servo-hydraulic testing machine with a controller (Figure 5b). Measurements were acquired using an LCR meter, and strain was measured by adhering a resistive strain gauge onto the CRFP.

Figure 6 shows typical results obtained from the characterization. Figure 6a compares the relative capacitance signal of the CFRP with and without (pristine) the inclusion of titanium dioxide in the epoxy, demonstrating that the addition of titanium dioxide significantly improved the stability of the signal. The 5 vol% addition of titanium dioxide also increased the material's relative permittivity by 12% (not observable in the figure). Figure 6b plots the relative capacitance as a function of strain for five

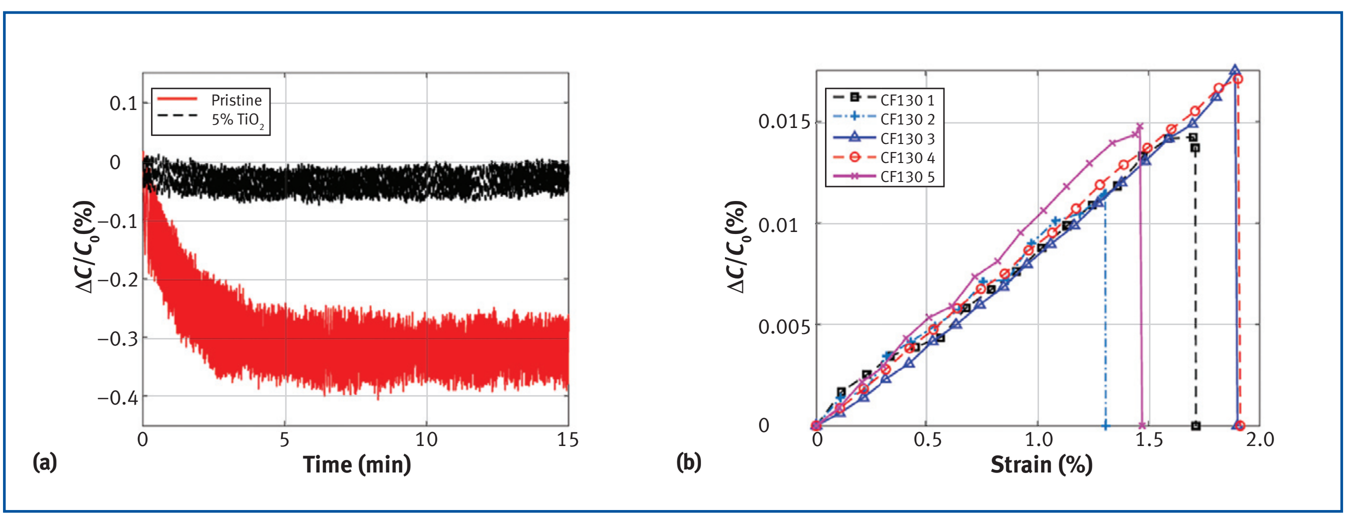

Figure 6. Results of the characterization: (a) signal time series of relative capacitance ($\Delta C/C_0$) for pristine and titanium dioxide-filled dielectric; and (b) relative capacitance versus strain for five self-sensing CFRP samples (adapted from Yan et al. 2019).

specimens (numbered CF130 1–5), exhibiting a linear relationship with respect to strain. The drop at the end of each signal is due to the material failure. Results from the self-sensing CFRP show the promise of the material at automating the NDE process by: (1) reporting strain; and (2) indicating failure of the laminate, both in real time. This can be useful, for instance, for conducting condition-based maintenance of structures after natural disasters or managing inspection operations.

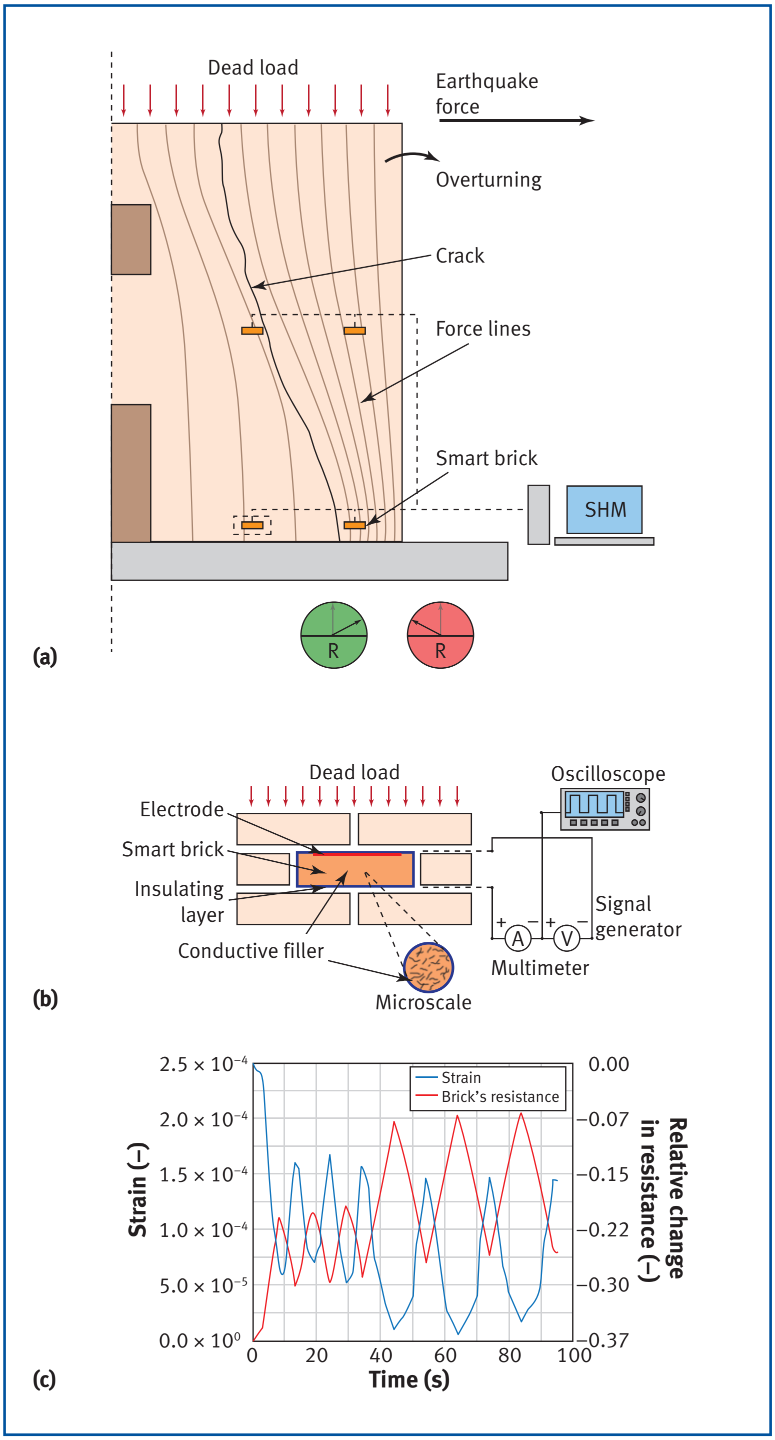

Figure 7. Example of system-level application: (a) conceptual deployment of smart bricks in a masonry building; (b) illustration of strain reading mechanism at the smart brick level; and (c) typical strain sensing response of a smart brick (adapted from Meoni et al. 2019).

An Example of a System-Level Application

Field applications of self-sensing structural materials are still rare and research enabling broad implementations is still progressing. A vision for a self-sensing structure constituted from self-sensing materials is presented in Figure 7a. The example structure is a masonry structure that uses smart clay bricks deployed at strategic locations. The structure can be constructed with either conventional or smart (self-sensing) mortar layers. These bricks can be installed, for example, by swapping out existing bricks or during construction.

Similar to smart concretes, smart bricks are modified fired clay bricks made electrically conductive through the use of suitable inclusions. However, because clay is baked at around 1000 °C, carbon inclusions are unsuitable. A valid alternative is the use of thermally resistant stainless steel microfibers that are first mixed with raw clay and then fired in the oven to form the brick. A convenient way of taking strain readings with smart bricks is the use of horizontal copper plate electrodes attached to a function generator that provides a biphasic voltage signal and a digital multimeter that reads the current circulating through the brick (Figure 7b). As a result of computing the electrical resistance of the brick by dividing voltage by current intensity, and by considering one point reading per period of the biphasic wave, a quite stable time signal is obtained, which can be used to read strain-induced changes in electrical resistance (Figure 7c). Note that the signal is nonlinear as a function of strain at low compressive loads (that is, below 2.5 MPa), but exhibits a more linear behavior at higher compressive loads.

Smart bricks can be used within a structure to identify damage and crack-induced changes in the permanent strain conditions after an event. Particularly, when a damage or a crack forms within an internal or external wall or the facade of a masonry structure (for example, due to the activation of a local failure mechanism after a critical event such as an earthquake), a stress/strain redistribution takes place (see the deviation of force lines after the formation of the crack shown in Figure 7a), so smart bricks will output changes in their electrical resistance that are proportional to local changes in their stress/strain conditions (assuming that the bricks remain in their

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elastic range of deformation). It follows that the temporal comparison of the smart bricks' readings pre- and post-event may yield static damage sensitive features that can be used for decision making. An organic application is for the monitoring of historic structures, where data could be used to conduct fast post-earthquake safety assessments.

In other research (Meoni et al. 2019), a damage-sensitive feature (I) was proposed to quantify damage by comparing the average pre-earthquake and post-earthquake strain conditions induced by permanent loads in a structure, therefore representing a simple metric that is expected to increase with increasing stress/strain redistribution (damage) highlighting, for example, which facade or wall within the building is experiencing the most significant load redistributions. The authors applied the metric to a scaled-down model of a two-story masonry building equipped with eight smart bricks at the base (Figure 8a). The building was subjected to progressive damage induced by a shaking table reproducing earthquakes of increasing severity. The experiments were also reproduced

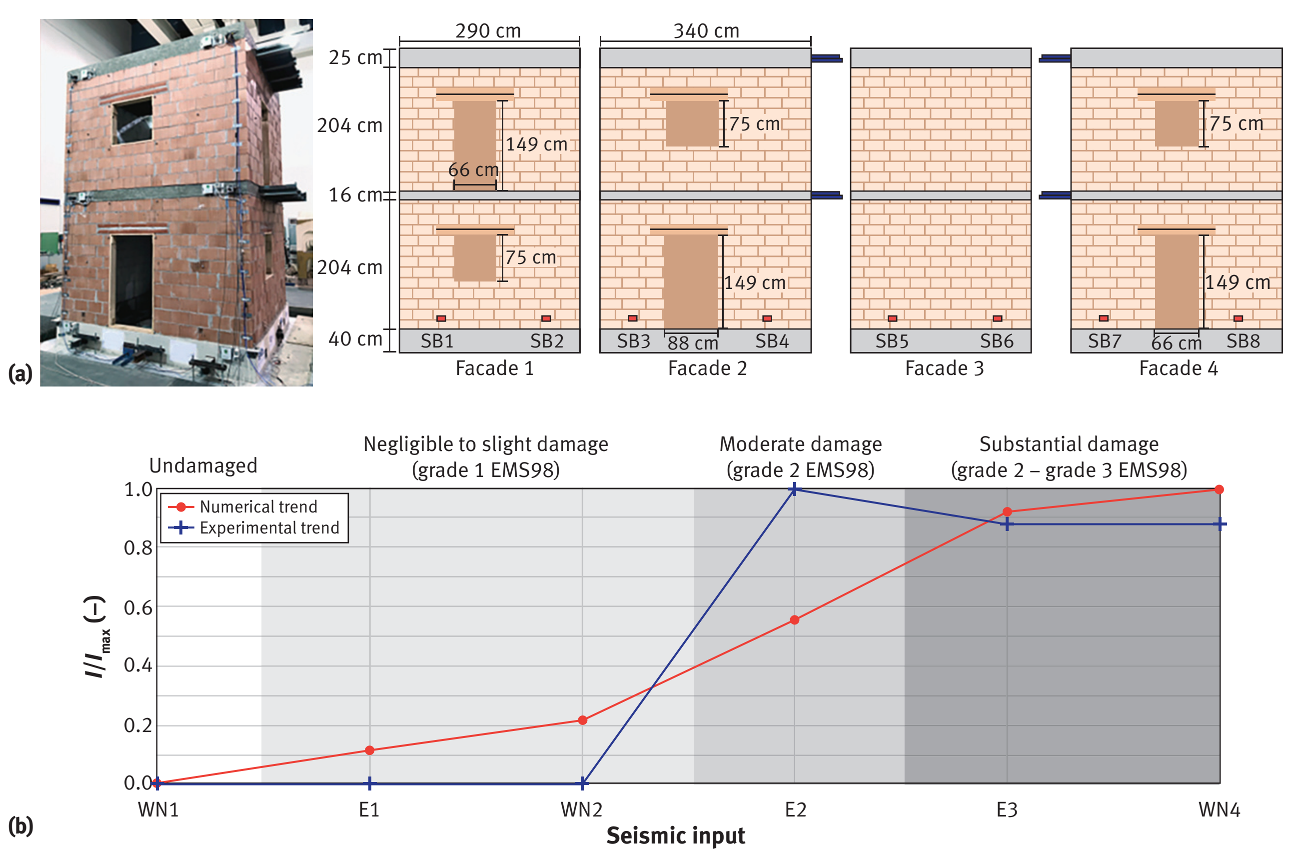

Figure 8. Scaled-down model example: (a) masonry building equipped with smart bricks (labeled SB1–SB8) and subjected to shaking table tests; and (b) experimental versus numerical normalized damage-sensitive features I/I_{max}, with I_{max} being the maximum observed value of I (adapted from Meoni et al. 2019).

through finite element nonlinear simulations. Figure 8b plots the experimental and numerical normalized damage-sensitive features I/I_{max}, with I_{max} being the maximum value of I observed in the whole seismic sequence, where I is obtained using the smart bricks. The metric is plotted against the damage grades observed experimentally on the structure consistent with the European macroseismic scale EMS98. Note that EMS98 classifies damage severity with a grade from 1 to 5, with 5 being the ultimate limit state. The smart brick system is clearly capable of revealing progressive damage conditions significantly before the ultimate limit state conditions are reached (the structure only attained a damage state of between 2 and 3, even after the strongest shaking). This can be useful, for example, in conducting a quick assessment of structural conditions, enabling management of the structural inspection process.

Conclusions

While the vast majority of example applications of self-sensing materials is still at the research level, their promise at automating the NDE process for detecting and quantifying particular conditions is well understood. Further developments and innovations in materials research and signal characterization will empower these materials with great scalability on both an economic and a technical perspective, by decreasing costs associated with large-scale deployments and simplifying the signal-to-decision link. It is foreseen that in the not-so-far future, self-sensing materials will be integrated in many structural systems, therefore contributing to enhancing safety and lifecycle costs through enabling real-time operation and maintenance decisions. ◐

ACKNOWLEDGMENTS

Figure 2a is adapted from Figure 8 in "Smart Concrete for Enhanced NDE," S. Laflamme, D. Eisenmann, F. Ubertini, I. Pinto, and A. DeMoss, *Materials Evaluation*, Vol. 76, No. 10, ©2018 the American Society for Nondestructive Testing. Figure 2b originally appeared as Figure 10 in the same paper.

Figure 3 is adapted from Figures 3 and 5b in A. D'Alessandro, M. Rallini, F. Ubertini, A.L. Materazzi, and J.M. Kenny, "Investigations on Scalable Fabrication Procedures of Self-Sensing Carbon Nanotube Cement-Matrix Composites for SHM Applications," *Cement and Concrete Composites*, Vol. 65, pp. 200–213, ©2016, and is reprinted with permission of Elsevier.

Figure 4 is adapted from Figure 26c in E. Garcia-Macías, A. D'Alessandro, R. Castro-Triguero, D. Pérez-Mira, and F. Ubertini, "Micromechanics Modeling of the Uniaxial Strain-Sensing Property of Carbon Nanotube Cement-Matrix Composites for SHM Applications," *Composite Structures*, Vol. 163, pp. 195–215, ©2017, and is reprinted with permission of Elsevier.

Figures 5 and 6 are adapted from Figures 2a, 3, 4a, and 5b in J. Yan, A. Downey, A. Chen, S. Laflamme, and S. Hassan, "Capacitance-Based Sensor with Layered Carbon-Fiber Reinforced Polymer and Titania-Filled Epoxy," *Composite Structures*, Vol. 227, 111247, ©2019, and are reprinted with permission of Elsevier.

Figures 7 and 8 are adapted from Figures 1, 4a, and 9a in A. Meoni, A. D'Alessandro, N. Cavalagli, M. Gioffré, and F. Ubertini, "Shaking Table Tests on a Masonry Building Monitored Using Smart Bricks: Damage Detection and Localization," *Earthquake Engineering & Structural Dynamics*, Vol. 48, No. 8, pp. 910–928, ©2019, and are reprinted with permission of John Wiley & Sons.

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