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Recent Advances on SHM of Reinforced Concrete and Masonry Structures Enabled by Self-Sensing Structural Materials †

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Abstract: Structural Health Monitoring is aimed at transforming civil structures into self-diagnosing systems able to automatically reveal the occurrence of a fault or a damage after a critical event such as an earthquake. While data science is presently experiencing tremendous advances leading to the availability of powerful tools and algorithms for extracting relevant information by effectively fusing data provided by different types of sensors, one of the main bottlenecks still limiting the development of SHM in the field of civil engineering is the general lack of reliable sensing technologies that are scalable at the large scale. A very promising solution to this large scale challenge would be leveraging the construction materials for strain sensing and direct damage detection. In this direction, the authors have recently proposed smart concretes and smart bricks that are piezoresistive concretes and clay bricks obtained by doping traditional construction materials with conductive nano- or micro-inclusions. These novel multifunctional materials have the ability to provide measurable electrical output under the application of a mechanical load and to provide information useful for damage detection, localization and quantification. The paper introduces both technologies, discusses their potentials, and illustrates their application to paradigmatic structural elements arranged in the laboratory. The presented results contribute to demonstrating the revolutionary impact that smart concretes and smart bricks may have in the near future on SHM of concrete and masonry structures.

Keywords: smart concrete; smart brick; Structural Health Monitoring; earthquake-induced damage detection

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1. Introduction

Structural Health Monitoring (SHM) of civil engineering structures is receiving important attention worldwide and it is likely to be expected that in the near future, many structures that are important from both an economical and societal perspective, such as those belonging to the historic heritage, will be transformed into self-diagnosing systems capable of providing an alarm when there is a fault or damage.

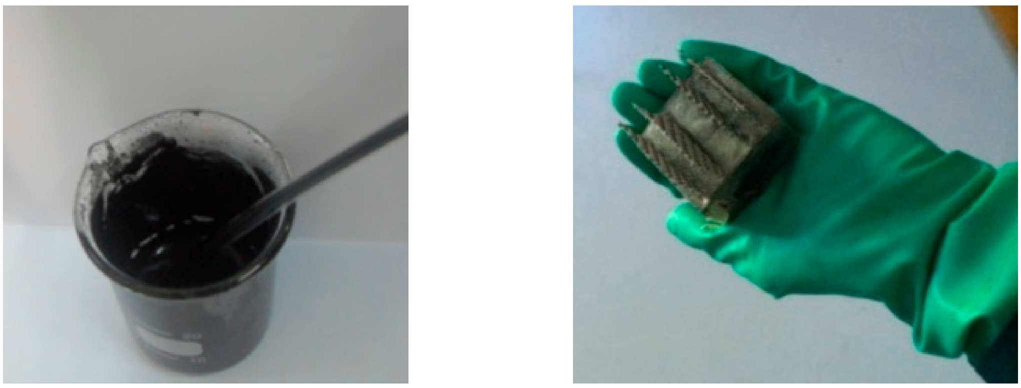
To date, a lot of research efforts are being devoted to the development of suitable SHM algorithms for the detection, localization and quantification of damage in a structure at an early stage, using information provided by sensing systems, including for the of data of different physical natures. While in the past several of these algorithms were based on physical models of the structure under investigation (i.e., physics-driven), research attention in recent years has shifted to unsupervised machine learning approaches that do not require such models (i.e., data-driven) and hybrid alternatives.

Despite this important progress, valuable and effective applications to large structures are still limited, mostly because of a lack of scalability of existing sensing technologies to large-scale. Existing sensing solutions economically (e.g., installation and maintenance costs) and technically (e.g., algorithms for very large spatio-temporal datasets) difficult to deploy at large. For instance, traditional sensors, such as strain gauges and displacement tranducers, are very local in nature, usually require extensive wiring connections, and are very limited in terms of durability in a life-cycle perspective. With at the objective to increase the scalability of SHM solutions, promising solution is the development of self-sensing structural materials that are smart construction materials possessing the multifunctional properties of being strain- and damage-sensitive. In particular, work presented in this paper focuses on smart concretes [1,2] and the more pioneering smart bricks that represent potentially revolutionary solutions towards self-diagnosing concrete and masonry structrues. These materials can be exploited for embedding sensors in a structure having essentially the same durability as the structure being monitored, or for achieving a spatially distributed sensing solution [3]. The rest of the paper is organized as follows. Sections 2 and 3 briefly present both technologies. Section 4 discusses their potentials at SHM applications. Section 5 presents laboratory demonstrations. Finally, Section 6 concludes the paper.

2. Self-sensing structural materials

2.1 Smart Concrete

Smart concrete technology (Figure 1) is based on the incorporation of suitable electrically conductive micro- or nano-inclusions into structural concrete to provide the material with smart strain-sensing and damage-sensing properties. Among the various inclusions that can be used for this purpose, particularly popular are carbon-based ones, such as carbon fibers, carbon black and carbon nanotubes, but other fillers can be used as well, such as metallic fibers and nickel powder.



(**a**) (**b**)

Figure 1. Smart concrete: (**a**) Dispersion of MWCNT in water for preparation of smart concrete; (**b**) Cubic sensor made of smart concrete doped with MWCNT.

The strain sensing property of smart concrete originates from measurable variations in some of its slected electromechanical properties when the material is deformed. In most of the cases, a linear relation between the change in electrical resistance, ΔR, occurring between two electrodes embedded in the material and strain, ε (positive in compression), can be approximated as:

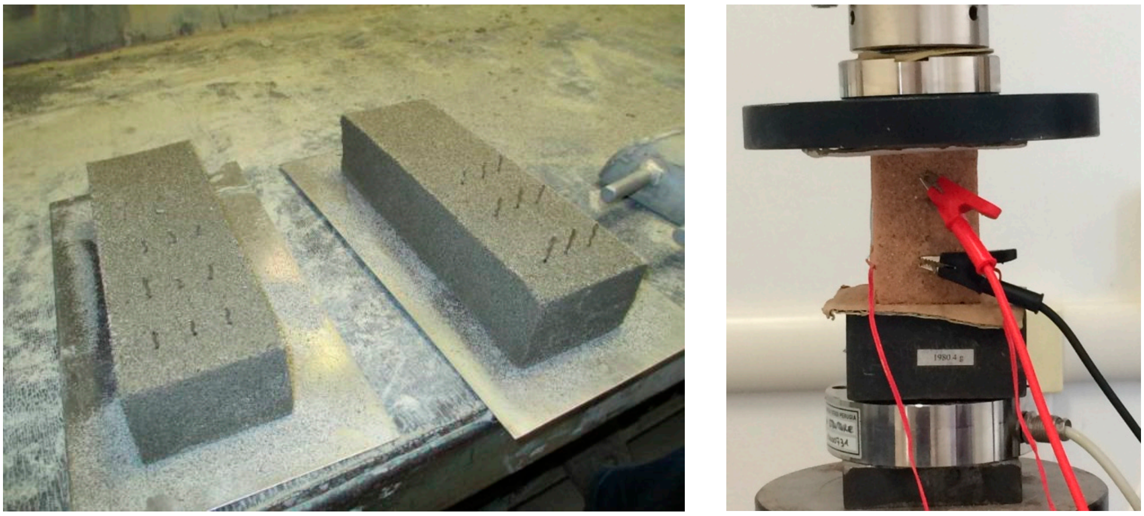
$$\Delta R/R = -\lambda\varepsilon, \quad (1)$$

where λ is the gauge factor of the material.

The electrical conductivity of the material can be exploited for direct damage sensing, whereby a crack induces a sudden change in the local resistivity of the material.

2.2 Smart Bricks

Smart bricks (Figure 2) are nanocomposite clay bricks acting as strain sensors in structural masonry. Similarly to smart concrete, they are obtained by doping traditional clay bricks with suitable conductive or semi-conductive inclusions. However, such inclusions must be able resist the high baking temperatures incurred by the brick during its fabrication process. Among the various possibilities are titanium dioxide (titania) and micro- or macro-fibers made of special metals that resist high-temperatures without oxidating.



(**a**) (**b**)

Figure 2. Smart bricks: (**a**) Preparation of smart bricks doped with conductive inclusions; (**b**) A smart brick after burning being tested in the lab.

2.3 Modeling Strategies

The electromechanical behavior of smart concretes and smart bricks is complex and only partly understood at the fundamental physical and electrochemical levels. The two models presented here are the main approaches that can be followed to establish a mathematical link between the mechanical input (strain) and the electrical response of these materials. The former (Figure 3a) is based on equivalent lumped electrical circuits with strain varying parameters that fit the experimentally measured response of the materials. The latter (Figure 3b) is based on micromechanics homogeneization theory [4], estimating the mechanical and electrical properties based on a well founded mathematical and physical basis, accounting for technical aspects such as amount, type and geometry of inclusions, as well as quality of their dispersion.

3. Potential of Smart Concrete and Smart Brick Technologies

Smart concretes and smart bricks represent multifunctional composite materials providing, at low cost, two of the most performing and widespread structural materials (concrete and masonry) with smart sensing capabilities such as the ability to detect cracks and to self-sense the internal state of strain in a component or system. These novel composites have the potional of transforming civil structures into self-sensing systems, enlarging the sensitive volume to its maximum extent and resulting in cost-effective large-scale deployment of SHM solutions to civil constructions, such as recently constructed and historic buildings, as well as critical infrastructures. These novel technologies can allow a continuous assessment of structural conditions while minimizing costs required for special sensing hardware and related operation and maintenance (e.g., sensor initial and maintenance costs, access to the sensors for inspection purposes, wirings, etc.). Durability issues of traditional sensing technologies are also overcome by smart concrete and smart brick technologies, becuase the developed sensing solutions have essentially the same durability than that of the structure being monitored. Overall, through smart concretes and smart bricks, owners and operators will be able to obtain real-time diagnostic and prognostic data, enabling improved management of maintenance programs and retrofits, preventive conservation, and increased safety.

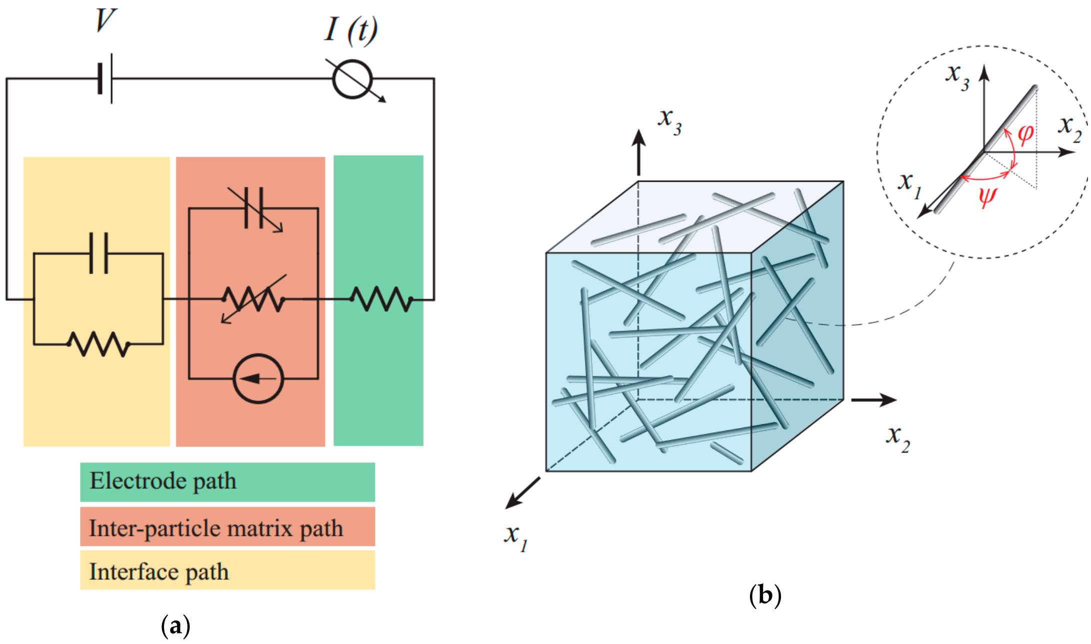


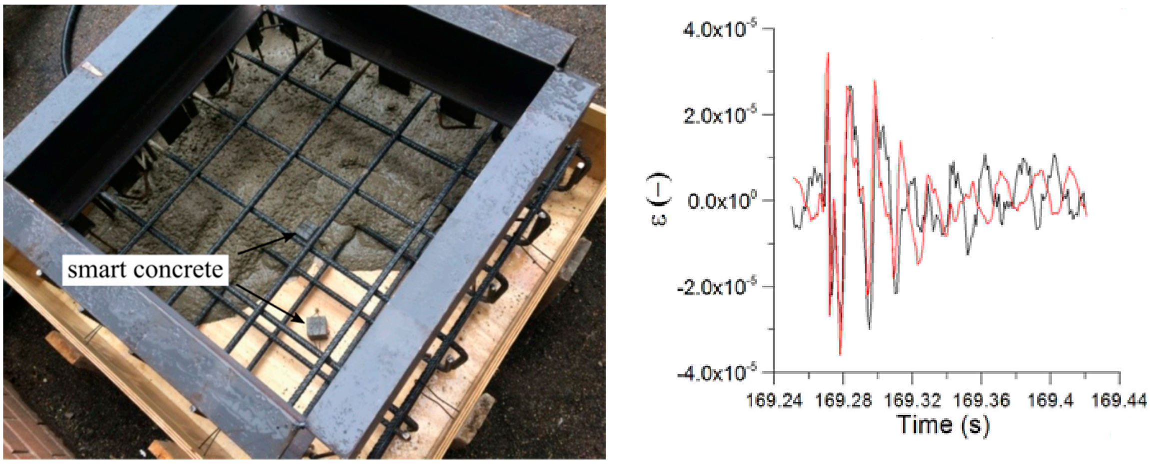
Figure 3. Modeling strategies for self-sensing structural materials: (**a**) Example of a lumped circuit model; (**b**) Sketch of a micromechanics modeling approach.

4. Laboratory Applications and Results

Recently, the authors have conducted extensive laboratory work to optimize the composition and characterize the electromechanical behavior of both smart concretes and smart bricks. In addition, experiments on full-scale structural components have been performed to practically demonstrate the potential of (i) embedded smart concrete sensors for strain sensing in dynamic conditions, (ii) conductive concrete as a means to directly detect cracks in the form of local changes in electrical conductivity and (iii) smart bricks for strain monitoring and damage detection within masonry wall.

Figure 4a shows a reinforced concrete plate fabricated in the laboratory with embedded cubic sensors made of cement paste doped with multiwall carbon nanotubes, and a typical time history of strain estimated by the cubic sensor during a hammer hit test on the beam, compared to the time history of the strain measured at the same location of the sensor by an electric strain gauge.

Figure 5 shows two experiments conducted on structural elements fully casted with cement paste doped with multiwall carbon nanotubes undergoing controlled damage conditions. One experiment is carried out on a reinforced cement paste beam and the other on a reinforced cement paste plate subjected to impact loading at the center. In both cases, a drop in the electrical response measured within two points of the structural elements across a crack is observable which allows direct damage detection and localization.



(**a**) (**b**)

Figure 4. Example application of smart concrete sensors embedded to measure strain in reinforced concrete structures: (**a**) Photo evidence of the embedded sensor during concrete casting; (**b**) Comparison of the output of the smart concrete sensor (black line) and of a traditional strain gauge (red line) during a hammer hit test on a RC beam.

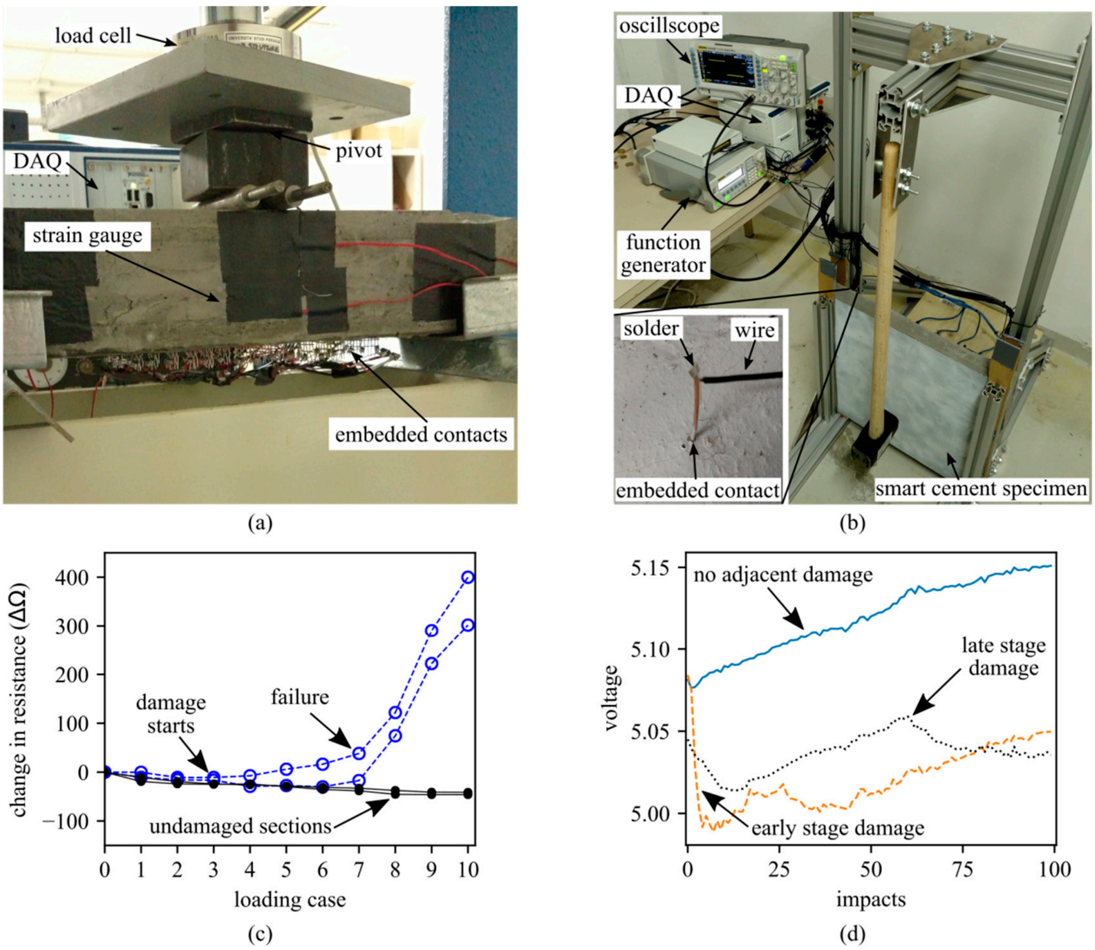


Figure 5. Example laboratory structural elements made of smart concrete for direct damage sensing: (**a**) Photo evidence of a smart concrete beam; (**b**) Photo evidence of a smart concrete plate; (**c**) Smart concrete beam electrical output exhibiting damage; (**b**) Smart concrete plate electrical output exhibiting damage.

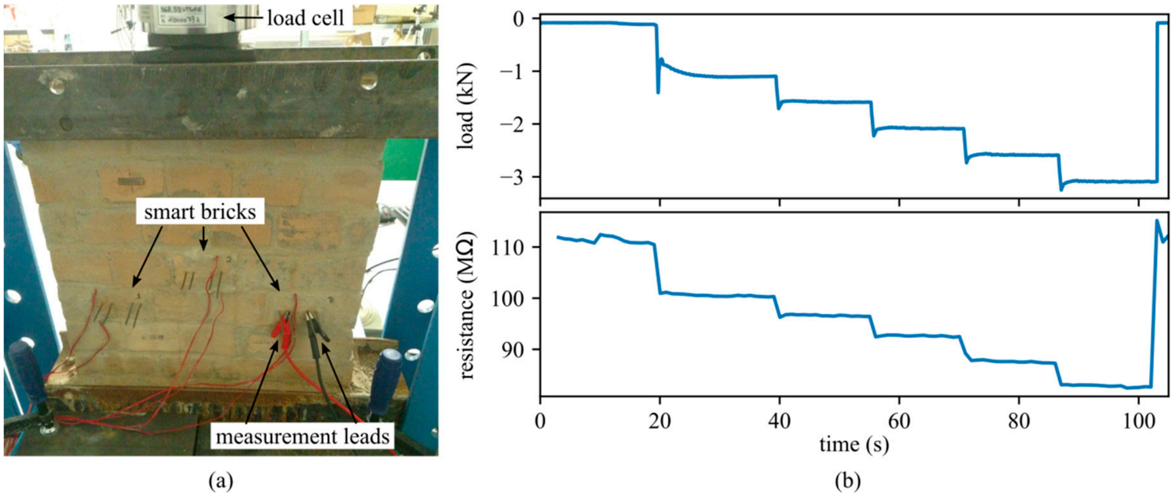


Figure 6. Example application of a smart brick embedded to measure strain in a masonry wall specimen: (**a**) Photo evidence of the smart brick in the wall; (**b**) Output of the smart brick under increasing compression load.

The last experiment considered in this paper, Figure 6, consists of a brick masonry wall with three embedded smart bricks doped with titanium dioxided and subjected to eccentric in-plane compression load. The results clearly highlight that the outuput of the smart bricks follows the expected distribution of the strain allowing compression load monitoring.

5. Conclusions

The results presented in the paper contribute to demonstrating the potential of self-sensing structural materials, namely smart concretes and smart bricks, in improving the current state of development of SHM technologies by overcoming some of the main limitations that impede their large-scale deployment to civil engineering structures.

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Conflicts of Interest: The authors declare no conflict of interest.

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