

Full-scale testing of a masonry building monitored with smart brick sensors[†]

Antonella D'Alessandro^{1*}, Andrea Meoni¹, Enrique García-Macías², Massimiliano Gioffrè¹, Nicola Cavalagli¹ and Filippo Ubertini¹

¹ Department of Civil and Environmental Engineering, University of Perugia, Perugia 06125, Italy; antonella.dalessandro@unipg.it (A.D.); andrea.meoni@unipg.it (A.M.); massimiliano.gioffre@unipg.it (M.G.); nicola.cavalagli@unipg.it (N.C.); filippo.ubertini@unipg.it (F.U.)

² Department of Continuum Mechanics and Structural Analysis, School of Engineering, Universidad de Sevilla, Sevilla 41004, Spain; egarcia28@us.es (E.G.M.)

* Correspondence antonella.dalessandro@unipg.it; Tel.: +39-075-585-3910

† Presented at the 5th International Electronic Conference on Sensors and Applications, 15-30 November 2018.

Received: date; Accepted: date; Published: date

Abstract: The seismic monitoring of masonry structures is especially challenging due to their brittle resistance behavior. A tailored sensing system could, in principle, help to detect and locate cracks and anticipate the risks of local and global collapses, allowing prompt interventions and ensuring users' safety. Unfortunately, off-the-shelf sensors do not meet the criteria that are needed for this purpose, due to their durability issues, costs and extensive maintenance requirements. As a possible solution for earthquake-induced damage detection and localization in masonry structures, the authors have recently introduced the novel sensing technology of "smart bricks", that are clay bricks with self-sensing capabilities, whose electromechanical properties have been already characterized in previous work. The bricks are fabricated by doping traditional clay with conductive stainless steel microfibers, enhancing the electrical sensitivity of the material to strain. If placed at key locations within the structure, this technology permits to detect and locate permanent changes in deformation under dead loading conditions, associated to a change in structural conditions following an earthquake. In this way, a quick post-earthquake assessment of the monitored structure can be achieved, at lower costs and with lower maintenance requirements in comparison to traditional sensors. In this paper, the authors further investigate the electro-mechanical behavior of smart bricks, with a specific attention to the fabrication of the electrodes, and exemplify their application for damage detection and localization in a full-scale shaking table test on a masonry building specimen. Experimental results show that smart bricks' outputs can effectively allow the detection of local permanent changes in deformation following a progressive damage, as also confirmed by a 3D finite element simulation carried out for validation purposes.

Keywords: smart brick sensors; damage detection; structural health monitoring; strain sensitivity; masonry structures; seismic behavior

1. Introduction

The majority of historical buildings worldwide are made of stone or brick masonry and their cultural value makes their maintenance and preservation of pivotal importance for the community. Monitoring technologies can aid the preventive conservation activities by using sensor networks, deployed at critical locations within the building, to identify the behavioral conditions of the structure and their variations caused by cracks or incipient damages due to the degradation of the materials or critical natural events. In particular, masonry structures are quite vulnerable to earthquakes due to their brittle behavior which often results in sudden failures [1, 2]. A tailored

Structural Health Monitoring (SHM) can be useful to recognize such occurrence and increase occupants' safety [3]. To this purposes, several researchers are working at developing low-invasive and effective techniques for evaluating mechanical properties, as well as dynamic signatures, of masonry structures [4]. In order to contribute to this research, the Authors have recently developed a burned clay sensor, called smart brick, with strain-monitoring capabilities and conceived to be inserted within the masonry as a normal clay brick [5, 6]. The smart brick has a clay matrix doped with steel micro fillers which enhance the electrical capabilities of the material. Critical issues arise in the correct quantification and dispersion of the inclusions, in the optimization of the measurement setup, as well as in signal processing aimed at damage detection and localization. In this paper, the authors further investigate the electro-mechanical behavior of smart bricks with respect to previous work, with a specific attention to the fabrication of the electrodes, and exemplify their application for damage detection and localization in a full-scale shaking table test on a masonry building specimen. Experimental results show that smart bricks' outputs can effectively allow the detection of local permanent changes in deformation following a progressive damage, as also confirmed by a 3D finite element simulation carried out for validation purposes.

2. Structural Clay-based Sensors

The smart bricks used for the present research were prepared by mechanically mixing different amounts of fillers – from 0.25% to 2% with respect of the whole weight - into the fresh clay (Fig. 1(a)). The fillers were stainless steel fibers, model R.STAT/S. The resulting composite was poured into prismatic molds, initially sprinkled with sand and then dried (Figs. 1(b-c)). After a thermal cycle of 12 hours up to at 900°C, the samples were instrumented with two different types of electrodes: copper plates or conductive resin with embedded copper strips [7] (Fig. 1(d)). The conductive resin was obtained by adding graphite powder to Araldite 2020 in the percentage of 75% in weight. The smart bricks were prisms with dimensions of 50x50x70 mm³. It is key to note that the deployment of the electrodes is fundamentally different in the two configurations, as copper electrodes lay horizontally, while resin electrodes lay vertically. In the latter case, therefore, spurious strain-sensing effects at the contact interface with the electrodes due to the applied vertical compression should be eliminated.

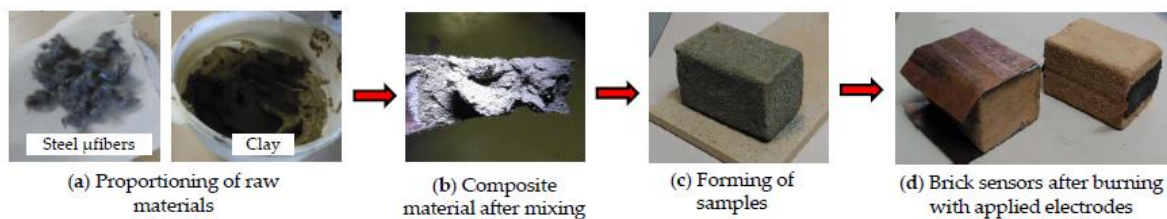


Figure 1. Photographic sketch of the preparation procedure of the brick sensors with steel microfibers

3. Methods

Three different types of tests were carried out to compare the electrical behavior of the smart bricks with different types of electrodes and to investigate their sensing capabilities: electrical tests for investigating conductivity properties, electromechanical tests for the analysis of strain sensitivity and a full-scale test on a masonry small building to demonstrate the potential of the technology for in situ monitoring purposes.

3.1. Electrical tests

Electrical tests were carried out by applying a square wave with 20 V peak-to-peak by using a RIGOL DG1022 function generator. The function had a duty cycle of 50% and a frequency of 1Hz. Electrical measurements were recorded through a DAQ NI PXIe-1073 with a digital multimeter NI PXI-4071 at a sampling frequency of 10 Hz.

Conductivity was achieved through the following equation, considering current measurements taken at the point at 80% of the positive constant part of the current waveform signal:

$$\sigma_t = \frac{l}{A \cdot V / I_t} \quad (1)$$

where, V is the applied constant voltage ($V_{pp}/2$), I_t is the measured current intensity, A is the section of the sample, l the distance between the electrodes and t is the time of the measurement.

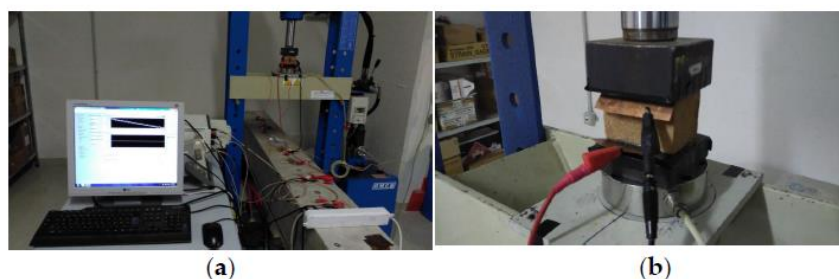


Figure 2. Setup of the electrical and electromechanical tests: (a) data acquisition system; (b) a sample during the tests.



Figure 3. Full-scale tests: (a) placement of the smart brick in the masonry; (b) setup for the electrical measurements; (c) picture of the tested building

3.2. Electromechanical tests

Electromechanical tests were conducted by using the same setup described in Section 3.1. The loading-unloading cycles were applied using a press with a maximum load of 20 tons. Figure 2 shows the electrical setup and a detailed view of a smart brick during the tests.

3.3. Tests on full-scale masonry buildings

The full-scale test was carried out on a masonry building of two floors, built at the ENEA Casaccia Research Center (Fig. 3(c)), with a base of 290 x 340 cm and a height of 490 cm. Eight smart bricks were placed in the bottom parts of the four building's façades (Fig. 3(a)). The masonry structure was subjected to increasing seismic inputs (including white noise inputs (WN_s) and

earthquakes (E_s) through a shaking table. The electrical measurements were recorded after each earthquake input (Fig. 3(b)).

The changes in volumetric strain, for a step, s , of the seismic sequence and for the i -th smart brick, were evaluated with:

$$\Delta \varepsilon_i^s = \frac{1}{GF_i} \frac{R_i^s - R_i^0}{R_i^0} \tag{2}$$

where R_i^s is the electrical resistance measured after the s -step of the seismic sequence, R_i^0 is the value of the electrical resistance for the undamaged condition and GF_i is the estimated gauge factor.

4. Tests and Results

4.1. Electrical tests

Figure 4 shows the comparison of the electrical conductivity measured on the smart bricks with different types of electrodes. The results highlight a consistent behavior, with a percolation like trend, also demonstrating, at the same time, that resin electrodes result in an overall higher conductivity conceivably owing to a reduction of the contact electrical resistance.

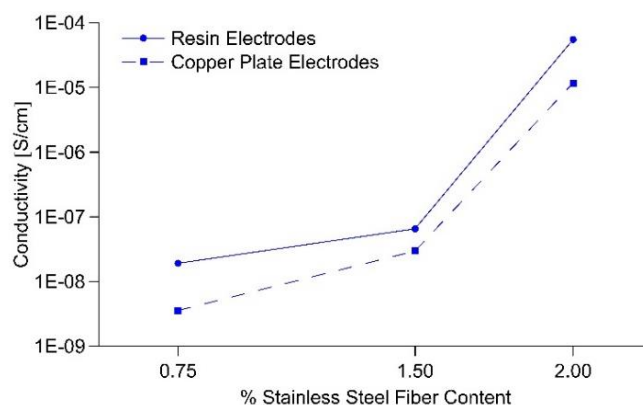


Figure 4. Comparison of electrical tests on samples with plate and resin electrodes.

4.2. Electromechanical tests

Figure 5 shows an example of electromechanical outputs of smart bricks with different types of electrodes and a comparison against the outputs of traditional strain gauges applied on the sensors. A clear correlation between actual strain and electrical outputs of smart bricks can be observed, where it has to be noted that the brick with resin electrodes provides a more linear strain sensing behavior compared to the one with copper plate electrodes. In this case the lower strain sensitivity is due to the different configuration of the electrodes (cfr. Section 2), while the improved quality of the signal is conceivably due to the elimination of spurious effects at the contact interface.

Table 1 summarizes the electrical performance of the smart bricks with different amounts of fillers and instrumented with copper plate electrodes. Although resin electrodes are better performing, in this exploratory study smart bricks with copper plate electrodes were used for the full scale experiment in order to maximize strain sensitivity.

4.3. Tests on full-scale masonry buildings

Experimental results obtained at increasing levels of the white noise and seismic loads were compared to a numerical macro-mechanical FE analysis, using a model characterized by a mesh size of 50 mm. Further details on the numerical simulations are omitted for the sake of brevity but are provided in the slide presentation of the paper.

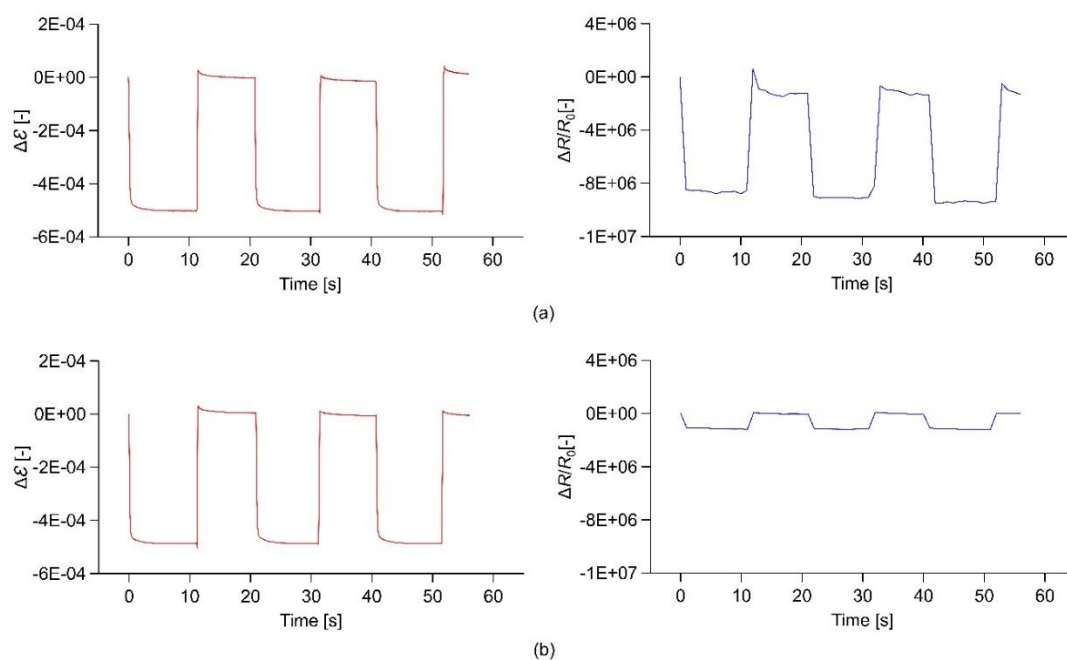


Figure 5. Electromechanical tests of the smart bricks with 0.75% of stainless steel microfibers with: (a) copper plate electrodes; (b) resin electrodes.

Table 1. Initial resistance R_0 , gauge factors GFs and Sensitivity S of smart brick with copper plate electrodes and different amounts of fillers.

Sample	R_0 [Ω]	GF	S [Ω]
0.00%	6,34E+07	181	1,15E+10
0.25%	3,59E+07	496	1,78E+10
0.50%	2,44E+07	219	5,33E+09
0.75%	5,19E+06	464	2,41E+09
1.50%	2,48E+06	1028	2,55E+09
2.00%	3,40E+05	795	2,71E+08

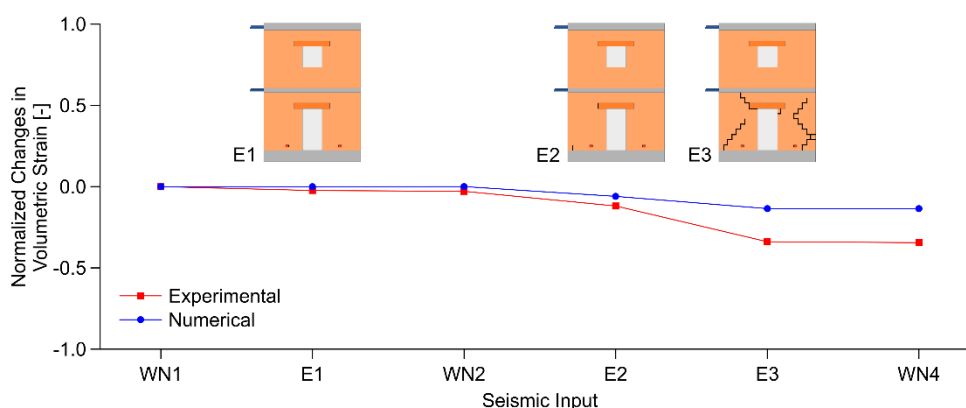


Figure 6. Comparison between normalized changes in volumetric strain from the experimental and numerical measurements for sensors placed on façade 4.

Figure 6 shows an example of comparison between experimental and numerical outputs in terms of volumetric strain under dead load after each step of the experimental sequence: the results appear to be quite correlated and confirm that the smart bricks are capable to provide the trend of change of volumetric strain under dead loads due to changes in structural conditions caused by progressive damage.

5. Conclusions

This paper has presented the results of electrical, electromechanical and full-scale investigations on novel smart bricks doped with stainless-steel microfibers. Different types of electrodes and various amounts of fillers were analyzed in order to assess the self-sensing behavior of the smart sensors. The results showed that vertical resin electrodes are able to reduce the contact resistance affecting electrical measurements and are promising for further application. The smart bricks possess interesting self-monitoring capabilities, demonstrated by their high gauge factors. Full-scale results show that such smart bricks can identify permanent changes in strain under dead loads associated to a progressive damage: this result is particularly valuable for quick assessments of a structural integrity of masonry constructions after important events as earthquakes.

Author Contributions: investigation and data analysis, A.D and A.M.; modeling, A.M., N.C. and E.G.M.; writing—original draft preparation, A.D.; writing—review and editing, A.D. and F.U.; visualization, A.D. and A.M.; supervision, F.U., funding acquisition, F.U. and M.G.

Funding: This research was funded by Italian Ministry of Education, University and Research (MIUR) through the funded Project of Relevant National Interest “SMART-BRICK: Novel strain-sensing nanocomposite clay brick enabling self-monitoring masonry structures (protocol no. 2015MS5L27). The paper was also supported by “Fondazione Cassa di Risparmio di Perugia”, research project “Casa Sicura”, Grant Number 2017.0233.021.

Acknowledgements: The Authors acknowledge Fornaci Briziarelli Marsciano Spa, who provided technical support for the preparation of the smart bricks and for the building of the masonry specimens.

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

References

1. Formisano A., Vaiano G., Fabbrocino F., Milani G. Seismic vulnerability of Italian masonry churches: The case of the Nativity of Blessed Virgin Mary in Stellata of Bondeno. *Journal of Building Engineering* **2018**; *20*: 179–200.
2. De Lorenzis L., DeJong M., Ochsendorf J. Failure of masonry arches under impulse base motion. *Earthq Eng Struct D* **2007**; *36*(14): 2119–2136.
3. Saisi A., Gentile C., Guidobaldi M., Xu M. Dynamic monitoring and seismic response of a historic masonry tower. *Key Eng Mater* **2014**; 628
4. Carpinteri A., Lacidogna G. Damage monitoring of an historical masonry building by the acoustic emission technique. *Mater Struct* **2006**; *39*(2): 161–167.
5. D’Alessandro A, Meoni A, Ubertini F. Stainless Steel Microfibers for Strain-Sensing Smart Clay Bricks. *Journal of Sensors* **2018**; 2018(7431823): 8. <https://doi.org/10.1155/2018/7431823>.
6. Downey A., D’Alessandro A., Ubertini F., Laflamme S., Geiger R. Biphasic DC measurement approach for enhanced measurement stability and multi-channel sampling of self-sensing multi-functional structural materials doped with carbon-based additives. *Smart Mater Struct* **2017**; *26*(065008): 6.
7. Cacciotti R., Jaroslav Valach J., Benjamin Wolf B., Innovative and easy-to-implement moisture monitoring system for brick units. *Constr Build Mater* **2018** *186* 598–614



© 2018 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).