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Strain monitoring in masonry structures using smart bricks

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ABSTRACT

Monitoring a building's structural performance is critical for the identification of incipient damages and the optimization of maintenance programs. The characteristics and spatial deployment of any sensing system plays an essential role in the reliability of the monitored data and, therefore, on the actual capability of the monitoring system to reveal early-stage structural damage. A promising strategy for enhancing the quality of a structural health monitoring system is the use of sensors fabricated using materials exhibiting similar mechanical properties and durability as those of the construction materials. Based on this philosophy, the authors have recently proposed the concept of "smart-bricks" that are nanocomposite clay bricks capable of transducing a change in volumetric strain into a change in a selected electrical property. Such brick-like sensors could be easily placed at critical locations within masonry walls, being an integral part of the structure itself. The sensing is enabled through the dispersion of fillers into the constitutive material. Examples of fillers include titania, carbon-based particles, and metallic microfibers. In this paper, experimental tests are conducted on bricks doped with different types of carbon-based fillers, tested both as standalone sensors and within small wall systems. Results show that mechanical properties as well as the smart brick's strain sensitivity depend on the type of filler used. The capability of the bricks to work as strain monitoring sensors within small masonry specimens is also demonstrated.

Keywords: Smart bricks, Smart materials, Structural Health Monitoring, Self-sensing structural materials, Masonry structures, Clay-based sensors

1. INTRODUCTION

Structural Health Monitoring (SHM) of masonry structures can automate the process of their structural condition assessment after earthquakes in particular for historic and monumental buildings. This automation of their condition assessment allows for the optimization of repair, retrofitting and restoration activities, as well as for the prompt deployment of safety protocols to protect the public during aftershocks^{1,2,3}.

In spite of the important interest that SHM technologies are presently receiving in the literature, successful applications of such technologies in large-scale structures are still limited due to the difficulty of linking measurements to prognosis. In addition, the limitations of existing sensing solutions, mainly related to their small sizes in comparison to the structure being monitored in addition to their short durability and difficult logistics (including power and wiring to data acquisition systems) further complicate large-scale deployments. Of interest are masonry structures, which are difficult to monitor due to inherent complexity in their behavior from the significant material non-linearity, as well as possible failures modes that can occur either locally or globally^{4,5}.

The concept of self-sensing construction materials has emerged in recent years as a potential solution to the current limitations in sensing technologies for SHM of civil infrastructures. In this context, the use of smart concretes for embedded sensing has been of key interest. Smart concretes are multifunctional concretes doped with conductive micro- or nano-inclusions and are able to provide a crack-sensitive and strain-sensitive electrical output⁶⁻¹¹. More recently, the authors have extended this concept to structural masonry by proposing "smart bricks"¹². These are piezoresistive clay bricks that can be inserted at critical locations within a building and provide a localized compressive strain measurement.

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Smart bricks are useful in detecting local and global changes in structural conditions, for instance following an earthquake. This technology is particularly attractive because it has the same durability as that of the construction material. These smart bricks are architecturally compliant and can provide high fidelity strain measurements, since the same structural block is used for measuring strain within the masonry.

Compared to previous work, this paper proposes a fabrication methodology for smart bricks using different carbon-based fillers with a high level of conductivity. After defining the fabrication procedure of the smart bricks and the thermal gravimetric analysis (TGA) of the fillers, laboratory testing is conducted to demonstrate their strain sensing properties for both free-standing and embedded bricks into small walls. The rest of the paper is organized as follows. Section 2 presents the concept of a smart brick, as well as materials and the fabrication process; Section 3 presents the experimental methodology; Section 4 presents and discusses the obtained results and Section 5 concludes the paper.

2. MATERIALS AND FABRICATION PROCESS

2.1 Smart brick concept

The smart brick is a clay brick whose electrical and piezoresistive properties are enhanced through the addition of suitable conductive nano- or micro-fillers to the clay matrix enabling a measurable change in electrical resistance upon an external compression load. It is a new sensing technologies for structural health monitoring of masonry buildings, whereby nano-modified strain-sensing bricks can be used to detect changes in load-paths following the initiation of a damage, by comparing actual strain measurements with baseline data referring to the undamaged structure. Figure 1 illustrates the smart brick concept by showing a single smart brick and a conceptual deployment of smart bricks, placed at key-points in the structure to monitor earthquake effects, such as the formation of cracks in the walls and the activation of local collapse mechanisms such as the overturning of a wall. The single smart brick is equipped with electrodes that can be used to measure the electrical resistance, R_0 , of the brick through a data acquisition system. When loaded with a force F , the electrical resistance undergoes a change, $\Delta R(F)$, as a consequence of a change in geometry. This feature produces the strain sensing property of the brick that can be quantified assuming a linear relationship between the fractional change in electrical resistance outputted by the smart brick, $\Delta R/R_0$, and the applied volumetric strain, ε_v , as follows:

$$\frac{\Delta R}{R_0} = -\lambda \varepsilon_v = -\lambda(\varepsilon_x + \varepsilon_y + \varepsilon_z) \quad (1)$$

where λ is the gauge factor of the brick and ε_x , ε_y , ε_z are the linear strains in three orthogonal directions.

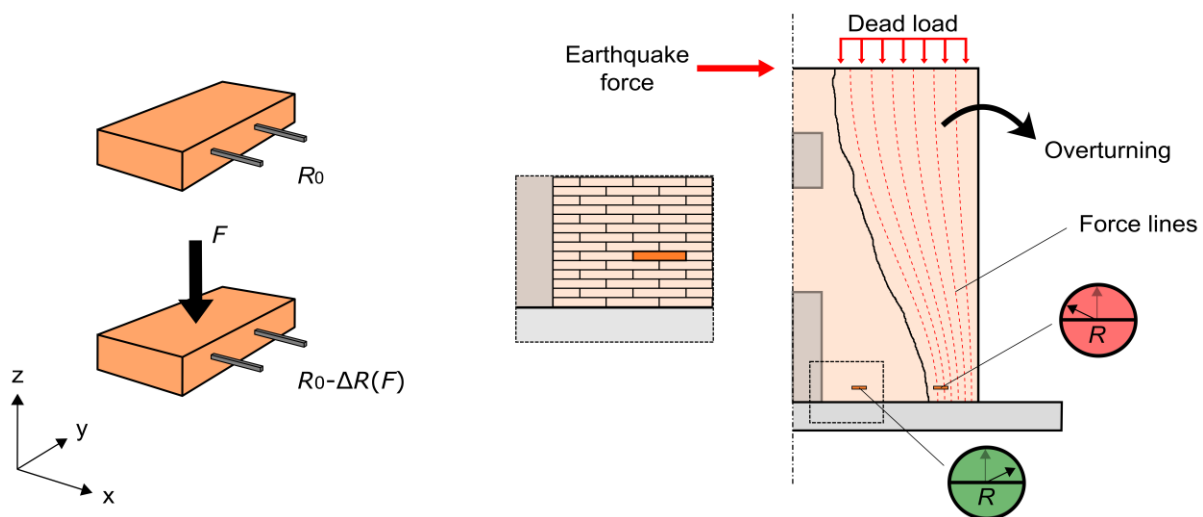


Figure 1. Illustration of the smart brick concept.

2.2 Components and fabrication of carbon-based smart bricks and walls

In this research, neat and nano-modified clay bricks were fabricated according to the mix designs listed in Table 1. Three different carbon-based nanofillers were investigated: Arkema Graphistrength C100 multi-walled carbon nanotubes (MWCNTs), Pyrograf-III PR-19-XT-LHT carbon nanofibers (CNFs), and Cheap Tubes graphene nanoplatelets (GNPs). Figure 2 shows the fabrication procedure for the nanocomposite clay bricks doped with the 0.2% of carbon fillers with respect to the weight of the clay. Carbon-based fillers were dispersed through sonication in a water solution where a physical dispersant Byk 154 was added in order to enhance the dispersion of the fillers (Figure 2a-b). Nanosuspension and clay were mechanically mixed (Figure 2c) and the composite was poured into sanded wood molds of $29 \times 14 \times 7 \text{ cm}^3$ dimensions. Specimens of $7.25 \times 7 \times 7 \text{ cm}^3$ were cut and stainless steel wire electrodes, of 2.2 mm diameter, were inserted in the clay (Figure 2e-f). Samples were dried at a maximum temperature of 90°C and then burned up to 900°C over six hours (Figure 2g).

Three small-scale masonry walls of $29 \times 7 \times 22 \text{ cm}^3$ were constructed, each with a nano-composite brick placed in the centre, according to the setup shown in Figure 3, in order to investigate the behavior of smart bricks inserted into a masonry wall. The specimens were fabricated with three rows of bricks put in place using cement mortar layers of approximately 0.5 cm thickness in both horizontal and vertical directions.

Table 1. Mix designs of the bricks.

| Component | Neat (g) | MWCNTs (g) | CNFs (g) | GNPs (g) |
|-----------|----------|------------|----------|----------|
| Clay | 4800 | 4800 | 4800 | 4800 |
| Water | - | 100 | 120 | 120 |
| Filler | - | 10.5 | 10.5 | 10.5 |
| Byk 154 | - | 10.5 | 10.5 | 10.5 |

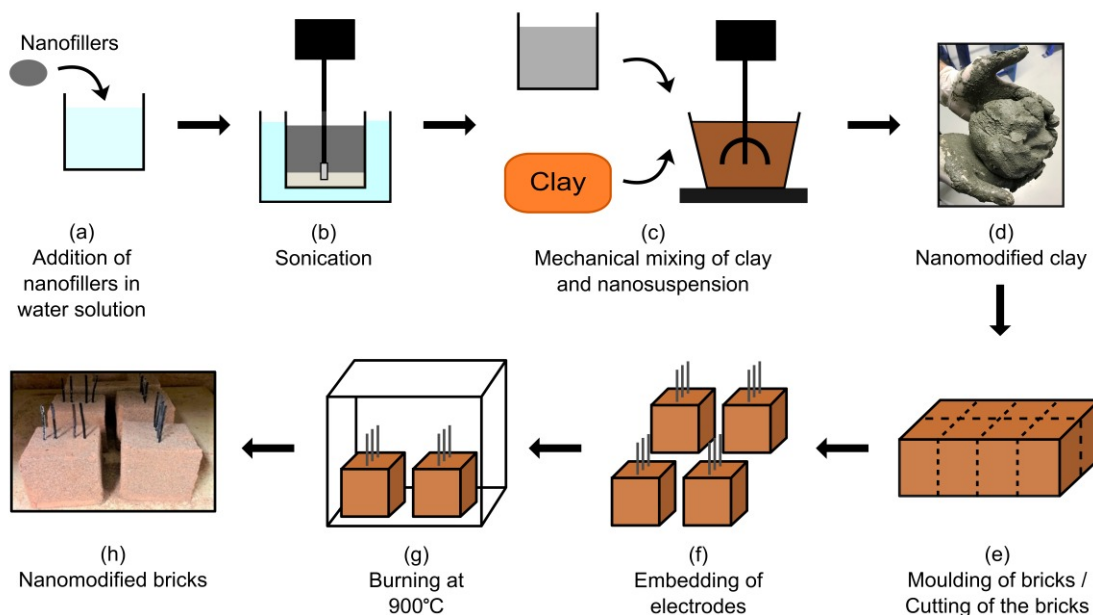


Figure 2. Fabrication procedure of smart bricks doped with carbon-based nanofillers.

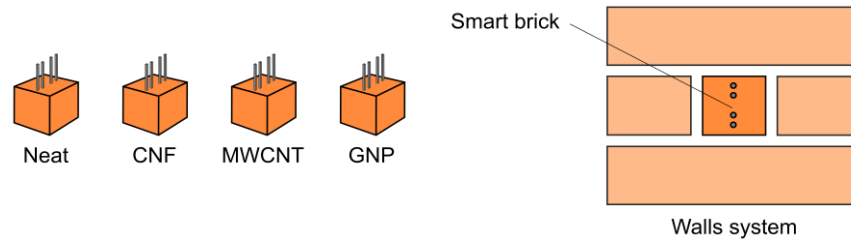


Figure 3. Specimens configuration in small-scale masonry walls.

2.3 Thermogravimetric analysis of the fillers

A thermogravimetric analysis (TGA) was carried out to evaluate the heat resistance of the carbon-based nanofillers used in this work. Weighing operations were performed with an analytical balance, model Sartorius (reading accuracy 0.01 mg), while a muffle furnace was used to heat the fillers. Small known quantities of each material were placed in crucibles, weighed and then heated at 900°C. A second weighing was conducted to determine the weight of the nanofillers after heating. The residual weight percentages were calculated and are reported in Figure 4. The heat resistance of the graphene nanoplatelets is relatively small compared to other carbon nanofillers, where they lost more than 98% of their weight. A much higher heat resistance was observed with CNF and MWCNT. In addition, signs of oxidation of nanoparticles were noted through a simple optical analysis.

It should be emphasized that this test was carried out in non ideal conditions as nanofillers were in direct contact with oxygen and therefore with a greater propensity to oxidize. Within clay, nanofillers are protected and most likely more resistant to heat. This is confirmed by micrographs shown in Figure 5 showing a neat brick and bricks doped with CNFs obtained through the Scanning Electron Microscope (SEM) analysis. CNFs are visible in both pre-burning and post-burning bricks without notable differences owing to the burning phase. However, results from the TGA indicate a possible challenge in using carbon-based fillers for smart bricks.

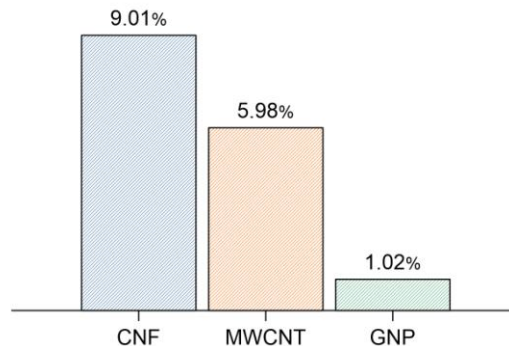


Figure 4. Residual relative weight of the carbon-based fillers after heating at a temperature of 900°C.

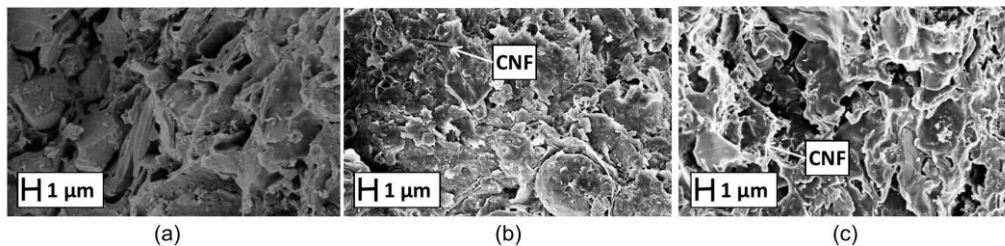


Figure 5. SEM micrographs: (a) post-burning neat brick; (b) pre-burning CNF brick; (c) post-burning CNF brick.

3. EXPERIMENTAL METHODOLOGY

3.1 Electrical tests on bricks

Electrical tests were performed to investigate the influence of different carbon-based nanofillers on the electrical properties of the clay matrices. A biphasic DC two-probe measurement method was adopted to conduct electrical test, thus eliminating the polarization effect that characterizes clay materials¹³. A function generator, model Rigol DG1022a, was used to apply a 1 Hz voltage square wave, ranging from -10 V to 10 V ($20 V_{pp}$, from peak to peak) with duty cycle of 50%, to the external electrodes of the bricks. A digital multimeter, model NI PXI-4071, was used to measure electrical current at a frequency of 10 Hz. The multimeter was hosted within a chassis, model NI PXIe-1071, with embedded controller, model NI PXI-8820. Electrical resistance, R , was calculated according to Ohm's law (2) after 30 s of electrical test:

$$R = \frac{V}{i} \quad (2)$$

where V is the applied voltage, $V = V_{pp}/2$, i is a value of electrical current taken at 80% of the measured total positive signal for each cycle.

3.2 Strain sensing tests on bricks

Electromechanical tests were conducted on the specimens to understand the influence of different carbon nanofillers on the strain-sensing capability of the clay materials. Using an electric-servo test machine (model Advantest 50-C7600 manufactured by Controls with a servo-hydraulic control unit model 50-C 9842) three different load time histories were applied to the samples after a preload of 0.1 kN. These time dependent loadings are: 1) "Step test", where the specimens were subjected to a first load step lasting about 20 seconds with an intensity equal to 1.0 kN followed by the application of four load steps of 0.5 kN held constant for approximately 15 seconds (Figure 6a); 2) "Triangular test", where a linear load of 1.8 kN was applied and released over a 125-second test span (Figure 6b); and 3) "Hold test" where a first load step lasting about 20 seconds with an intensity equal to 1.0 kN was applied to the bricks followed by the application of a second step with a load intensity of 3.0 kN until the end of the test (Figure 6c). The applied compression load was monitored by a 2000 kg load cell model Laumas CL 2000. In order to measure the applied strain, each brick was equipped with two strain gauges, model Kyowa KC-120-120-A1-11M2R, positioned onto opposite faces of each specimen.

The data acquisition system was a chassis NI PXIe-1071, with embedded controller NI PXI-8820, paired with a PXIe-4330 to acquire load cell and strain gauge data and a digital multimeter, model NI PXI-4071, to measure electrical current. Similar to the electrical test, a DC biphasic two probe method was used and a 1 Hz voltage square wave ranging from -10 V to 10 V ($20 V_{pp}$) with duty cycle of 50% was applied to the external electrodes of the samples. Figure 7 shows the described experimental test setup for the electromechanical test on bricks. The strain-sensing property of each sample was evaluated through equation (1) using the Triangular test.

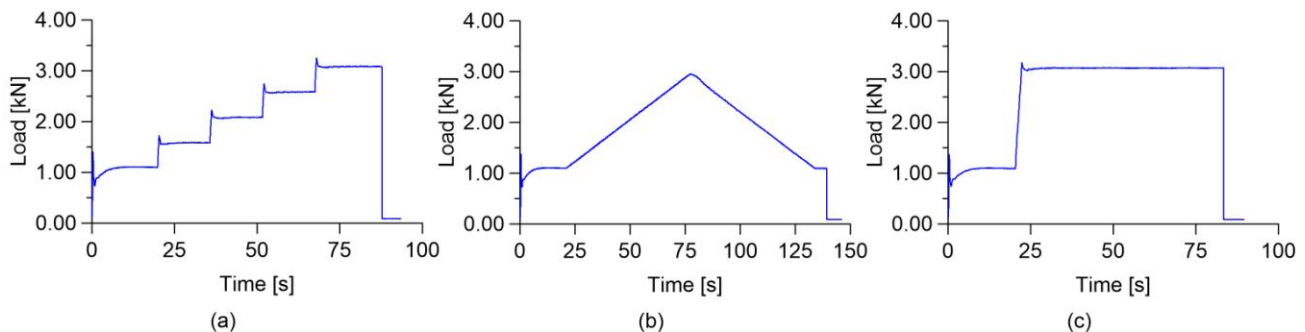


Figure 6. Load histories: (a) "Step test"; (b) "Triangular test"; (c) "Hold test".

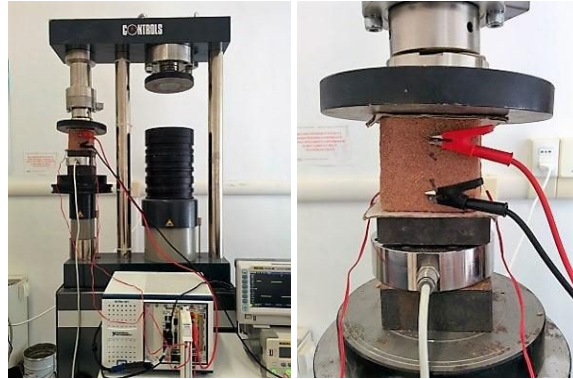


Figure 7. Experimental test setup for electromechanical test on brick.

3.3 Preliminary testing within masonry walls

Preliminary electromechanical tests on small-scale masonry walls were performed to investigate the behavior of the sensors when inserted in a structural configuration. Wood blocks were positioned at the top and the bottom of the walls to act as bearing pads between the wall and two steel beams, used to distribute the applied loading forces during the tests. The specimens were subjected to a cyclical load case, termed “Double triangle test”, applied using an electric-servo test machine, model Advantest 50-C7600 by Controls, equipped with a servo-hydraulic control unit model 50-C 9842. Starting from a preload of 2.5 kN, the load was linearly increased up to 19 kN and released down to approximately 5.0 kN. A second cycle, equal to the first one, completed the electromechanical test (Figure 8).

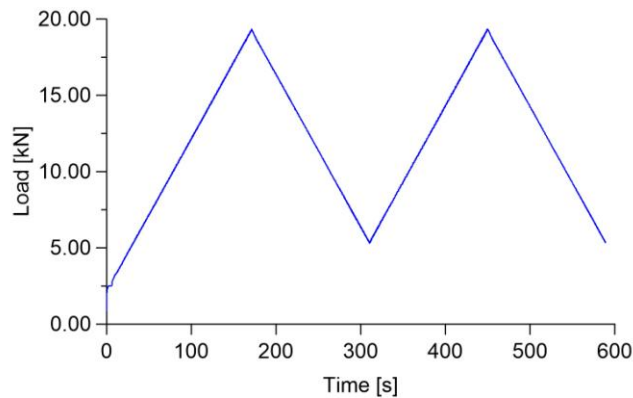


Figure 8. “Double triangle test” load history.

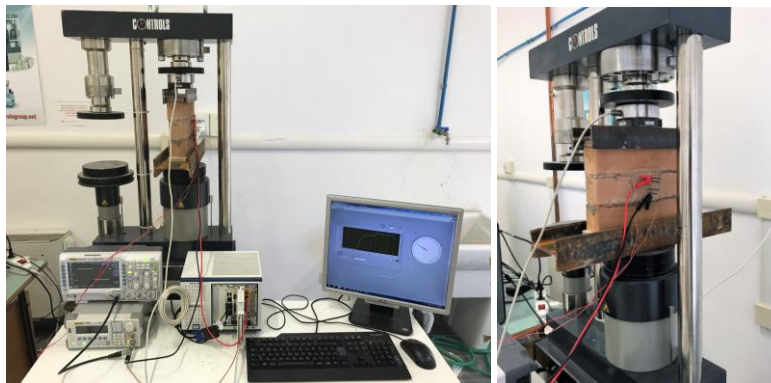


Figure 9. Experimental test setup for electromechanical test on masonry wall.

The DC biphasic two-probe method was used for electrical measurements¹³. A 1 Hz voltage square wave of 20 V_{pp} with a duty cycle of 50% was applied using a function generator, model Rigol DG1022a, to the external electrodes of the smart bricks while current measurements were carried out with a digital multimeter, model NI PXI-4071, mounted in a chassis, model NI PXIe-1071 with embedded controller, model NI PXI-8820. Data provided by a 2000 kg load cell, model Laumas CL 2000, was acquired with a dedicated module, PXIe-4330, also embedded in the chassis. The experimental test setup for electromechanical tests on masonry walls is illustrated in Figure 9.

4. RESULTS AND DISCUSSION

4.1 Electrical tests on bricks

Figure 10 shows the electrical resistance values obtained from electrical tests on specimens. The smart brick doped with MWCNTs exhibited some reduction in its electrical resistance value when compared to the neat brick. Conversely, GNP and CNF bricks are characterized by an increase in electrical resistance that can probably be attributed to the local effects at the electrodes. In particular, the addition of carbon-based nanofillers to the samples should enhance the electrical conductivity of clay, however, oxidation experienced by the electrical contacts and by the nanofillers during the burning phase can counteract this effect.

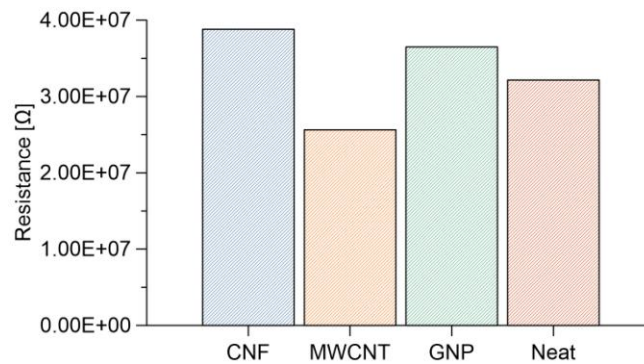


Figure 10. Electrical resistance values obtained from the specimens.

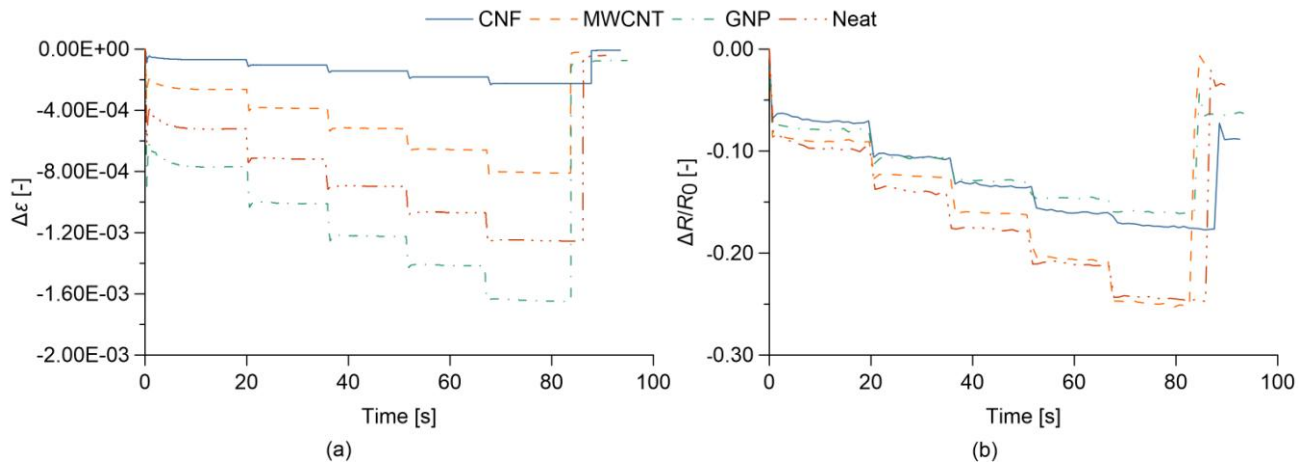


Figure 11. “Step test” load case: (a) Applied strain; (b) Relative change in electrical resistance.

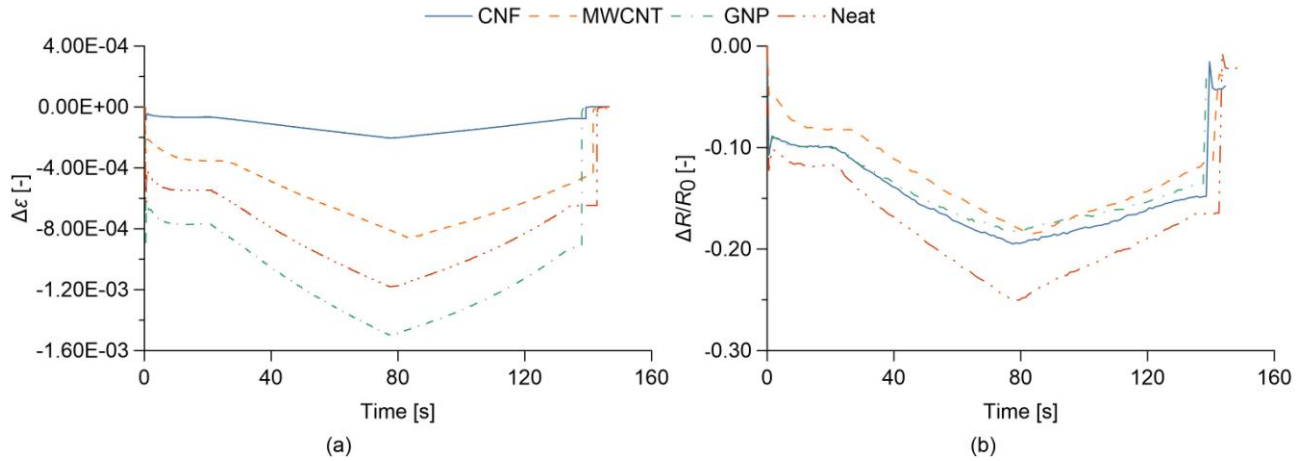


Figure 12. “Triangular test” load case: (a) Applied strain; (b) Relative change in electrical resistance.

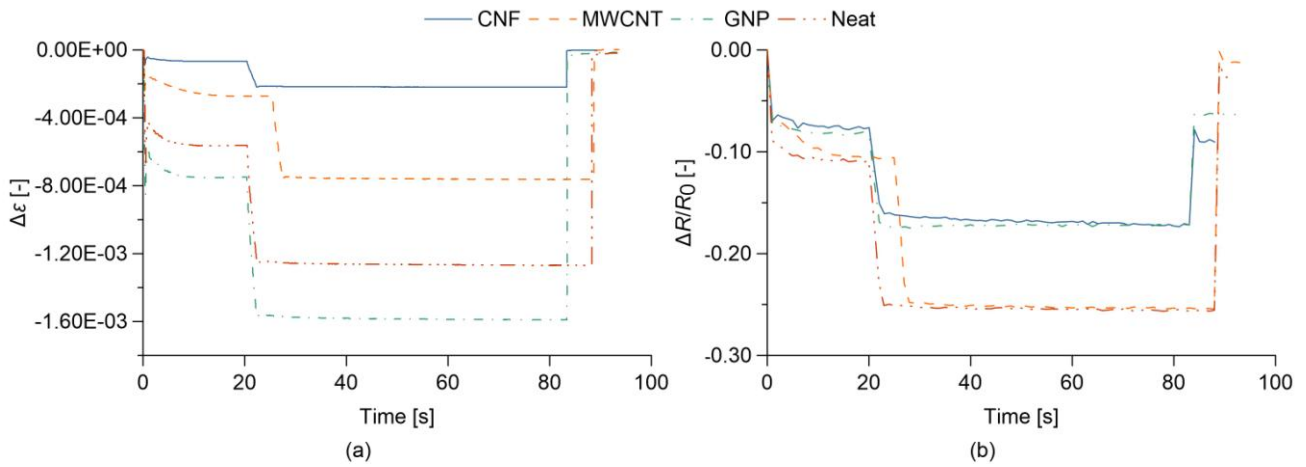


Figure 13. “Hold test” load case: (a) Applied strain; (b) Relative change in electrical resistance.

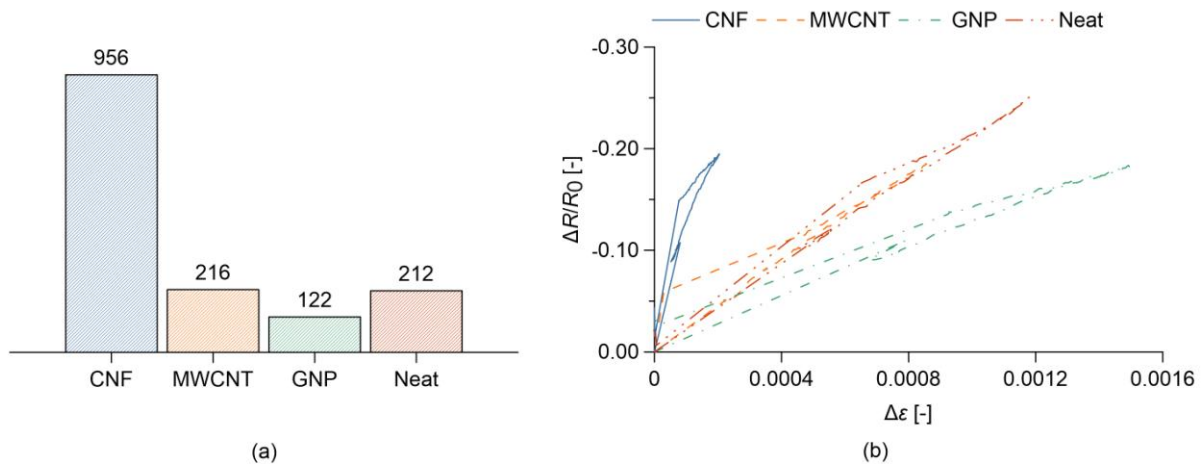


Figure 14. Results obtained from electromechanical tests carried out applying the “Triangular test” load case: (a) Gauge factor values; (b) Relative change in electrical resistance versus applied strain.

4.2 Strain sensing tests on bricks

Results obtained from electromechanical tests are shown in Figures 11-13. Nano-modified and neat specimens have exhibited a clear piezoresistive behavior under the application of different load cases. The neat brick is characterized by a noticeable variation of the relative change in electrical resistance over every load histories, but the CNF brick shows an enhanced strain-sensing capability, owing to the presence of the nano-inclusions. This is particularly observable in Figure 14(a), showing values of the gauge factor of the different specimens obtained from the "Triangular test" load case. Strain sensing responses of the investigated brick specimens appear to be remarkably linear, as shown in Figure 14(b). Noticeable is that CNFs increase the stiffness of the bricks. The reason why CNFs outperform other types of carbon-based nanofillers is related to their higher thermal resistance as shown by TGA analysis.

4.3 Preliminary testing within masonry walls

Figure 15 shows electrical resistance outputs obtained during the electromechanical tests on masonry walls. Sensors inserted into the walls are not isolated from mortar layers and from other bricks that constitute the wall. Similarly to what was also found in past research by the authors, the measured electrical outputs are influenced by the propagation of the electrical current flow through the other components of the walls¹². On the other hand, smart bricks have demonstrated a noticeable sensitivity of their fractional change in electrical resistance under application of the compression load. The results confirm that smart bricks can suitable strain sensors for SHM of masonry structures. From the results, it should also be noted that the smart brick doped with CNFs is the one that exhibits the best recovery of the initial electrical resistance after unloading of the wall.

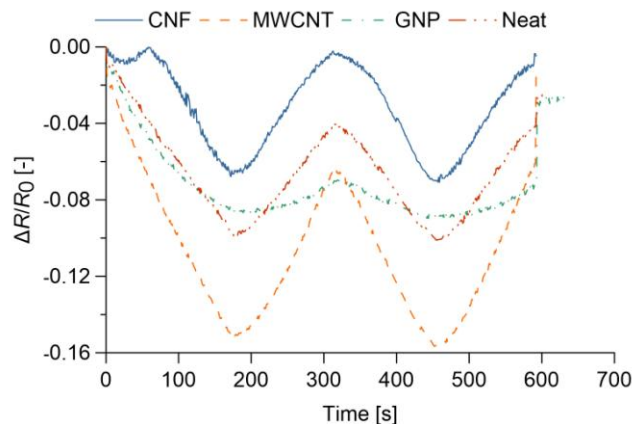


Figure 15. Relative change in electrical resistance versus time for wall specimens subjected to double triangular compression loading.

5. CONCLUSION

The paper investigated the influence of different carbon-based nanofillers on electrical and piezoresistive properties of smart clay bricks, a new class of smart strain sensors for SHM of masonry structures. The fabrication procedure of nano-modified smart bricks has been described and results obtained from TGA and SEM analysis of the fillers discussed. Carbon nanofillers are seen to be quite sensitive to the high temperature, which is reached during the burning phase of the clay bricks. CNFs have demonstrated the best heat resistance when compared to MWCNTs and GNPs.

An improvement in electrical properties has been noticed in the clay brick doped with MWCNTs while the CNF specimen has demonstrated a notable strain-sensing capability compared to the other samples. The worst results in term of TGA analysis, electrical and electromechanical properties were obtained with bricks doped with GNP.

The second part of the paper has been devoted to presenting results of preliminary testing of smart bricks inserted within masonry walls subjected to compressive loading, therefore simulating structural embedment. The obtained results confirm that smart bricks are a highly promising new-sensing technology suitable for SHM of masonry structures.

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