Continuous and embedded solutions for SHM of concrete structures using changing electrical potential in self-sensing cement-based composites

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ABSTRACT

Full Abstract

Interest in the concept of self-sensing structural materials has grown in recent years due to its potential to enable continuous low-cost monitoring of next-generation smart-structures. The development of cement-based smart sensors appears particularly well suited for monitoring applications due to their numerous possible field applications, their ease of use and long-term stability. Additionally, cement-based sensors offer a unique opportunity for structural health monitoring of civil structures because of their compatibility with new or existing infrastructure. Particularly, the addition of conductive carbon nanofillers into a cementitious matrix provides a self-sensing structural material with piezoresistive characteristics sensitive to deformations. The strain-sensing ability is achieved by correlating the external loads with the variation of specific electrical parameters, such as the electrical resistance or impedance. Selection of the correct electrical parameter for measurement to correlate with features of interest is required for the condition assessment task. In this paper, we investigate the potential of using altering electrical potential in cement-based materials doped with carbon nanotubes to measure strain and detect damage in concrete structures. Experimental validation is conducted on small-scale specimens including a steel-reinforced beam of conductive cement paste. Comparisons are made with constant electrical potential and current methods commonly found in the literature. Experimental results demonstrate the ability of the changing electrical potential at detecting features important for assessing the condition of a structure.

Keywords: Carbon nanotubes, Smart cement, Sensor network, Composites damage detection, Structural health monitoring, Sensors, Smart sensors, Smart Structures.

1. INTRODUCTION

Self-sensing structural materials are defined as materials capable of monitoring their own mechanical conditions[1] while maintaining their structural functionality. Self-sensing structural materials have received considerable research interest for their potential use for structural health monitoring (SHM).[2] In particular, various carbon-based self-sensing structural materials have demonstrated damage detecting[3] and strain-sensing[4] ability through the use of impedance and resistance measurements. However, an inherent time-based drift in the materials' measured electrical output caused by material polarization is present when monitoring the self-sensing material. This work introduces a biphasic DC measurement approach that is well suited for self-sensing materials and eliminates the inherent sensor drift found in carbon-based self-sensing materials.

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The focus is on the use of carbon-doped cement composites as self-sensing structural materials. These materials have been demonstrated for strain-sensing,[4] damage detection,[3] and a combination of both. Numerous carbon-based fillers and additives for cement composites have been proposed in recent years, as extensively documented in the literature.[1,5–7] Self-sensing cement-based structural materials offer the benefit of easily binding with the monitored structure in embedded applications as they possess material characteristics similar to the structure being monitored. Fabrication often consists of doping carbon-based fillers into the cementitious materials through the use of surfactants.[2,8] Various carbon-based fillers have been mixed with cementitious materials, including carbon fibers,[3,9] carbon black,[10,11] and more recently multi-walled carbon nanotubes (MWCNTs).[8,12] Cement composites doped with MWCNTs offer great potential as self-sensing structural materials due to their excellent electrical and mechanical properties.[13] They have been employed in the fabrication of many strain sensing composite materials. A cement composite, previously developed by some of the authors,[4,8] will be used throughout this work as a self-sensing structural material. The strain-sensing piezoresistivity property of this class of materials has been shown to be caused by the pull-out of fibers passing through microcracks.[2,9]

The majority of research efforts into self-sensing cement composites have used direct current (DC) for the extraction of various electrical parameters (e.g. voltage, resistance or conductivity), The prevalent use of DC measurements techniques is due to its ease of use and relatively low cost of electrical test equipment.[14] DC measurements can be taken using either a two-probe or a four-probe configuration, where a two-probe configuration uses two probes to both source current and measure voltage. In comparison, a four-probe configuration uses separate pairs of current-carrying and voltage-sensing probes. The four-probe method can provide more accurate results as it bypasses the resistance of the measurement cables and the contact resistance at the signal/sample interface.[15] In carbon-doped materials, the contact resistance between the carbon doped material and the metal electrodes can be substantial.[16,17]

DC measurement approaches have shown useful for laboratory characterization of cement composites doped with carbon additives. However, they tend to induce an inherent time-based drift in the material's measured electrical output. This electrical drift represents itself as an increase in the resistance from the beginning of the measurement, as noted in the work of many authors.[4,8,16,18–24] This drift is most commonly attributed to material polarization.[23,25] In addition, it has been proposed that changes in materials dielectric constant[21,26] and the direct piezoelectric effect[27] also contribute to source the drift. Many researchers have attempted to mitigate the materials drift through delaying measurements until the drift levels out,[4,27,28] particularly for use in dynamic measurements.[4] However, this technique may be less suitable for static measurements or SHM where resistance measurements need to be compared over time such as for the inspection of civil infrastructure post natural disaster.

Alternating current (AC) measurement techniques have been proposed as a solution to the obstacle of time-based sensor drift, owing to a continuous electrical charging and discharging of the sample. However, published research using various AC measurement techniques demonstrate that they are not immune to drift.[12,14,21,24] The simultaneous sampling of multi-sectioned self-sensing materials is challenging, because LCR meters do not allow for the simultaneous sampling of multi-sectioned self-sensing materials. For example, the use of multiple LCR meters for simultaneously monitoring multiple adjacent sections of a carbon-doped concrete beam will cause a high level of signal crosstalk due to interactions between the different LCR sensing currents. Furthermore, traditional AC parameters such as reactance, impedance and phase angle require the use of expensive electronic equipment in comparison to DC techniques[14] and may require the use of fast sampling digitizers and processors to obtain and calculate measurement values.[29] This increases the costs associated with the deployment of a real-time SHM system using self-sensing structural material. Due to the challenges in obtaining simultaneous multi-channel measurements with traditional AC test equipment and the time-bases drift present in traditional DC measurements caused by material polarization, the introduction of a measurement technique specifically formulated for monitoring of multi-sectioned carbon-based self-sensing materials is required to empower cement-based self-sensing structures.

The main focus of this work is the introduction of an electrical measurement approach that highly reduces the effect of drift found in carbon-doped cement composites. The proposed method allows for the simultaneous measurement of independent sections of a self-sensing structural element to be compared over time without continuous measurements. The proposed measurement method is developed around the theory that the drift present in carbon-based cement composites is an intrinsic material property that develops from the polarization effect due to the dielectric characteristics of the material. This material polarization is considered to be fully dependent on the direction of sensing current flow as the self-sensing material is itself not intrinsically polarized. Therefore, we propose that the action of taking measurements is itself the cause of material polarization and, therefore, the cause of the material's resistance drift. Reversing the effect of the polarization can be achieved by reversing the direction of the sensing current flow.

The proposed biphasic DC measurement approach provides consistent and stable long-term results by continuously changing the polarity of the electrical potential across the self-sensing material. Continuously changing the polarization of the electrical potential charges and discharges the self-sensing material. Material sensing is provided by a periodic measure/discharge square wave, where DC measurements are made during the "measure" region of the square wave. Material depolarization is obtained through reversing the applied current during the "discharge" region of the periodic signal. The discharging the self-sensing material between measurement cycles results in the material polarization being repeatable for all measurement cycles, therefore, providing a constant measurement over time. The proposed biphasic DC measurement approach presented here can be implemented in either a two-probe or four-probe method. The self-sensing materials resistance can be calculated using the total current draw of the material, taken as the voltage drop across a resistor connected in series with the material. These resistance values can thereafter be used to correlate sensor signals to the variation of element strain or the detection of material defects and damages. This DC measurement approach allows for the simultaneous, multi-channel resistance-based monitoring of different sections of a self-sensing structural element through multiple voltage measurements while only requiring a single current source.

The proposed approach shows great improvement over a traditional DC measurement technique for carbon-based self-sensing structural materials in terms of its ability to remove sensor drift. Additionally, the proposed measurement method is well suited for the simultaneous measurement of multi-sectioned self-sensing elements in comparison to various AC measurement techniques. The removal of sensor drift and the ability for simultaneous measurement of multi-sectioned materials allow for this approach to be used for damage detection and localization of self-sensing cement-based structural elements. The biphasic DC measurement approach is experimentally validated in this work for use with strain-sensitive and damage detecting cement-based structural elements.

The contributions in this paper are threefold: 1) a biphasic DC measurement approach for SHM applications of self-sensing materials is introduced and its ability to remove the electrical drift of the measurements is described; 2) the biphasic DC measurement approach is shown to be well suited for the characterization of a strain-sensing structural material, consisting of a cement paste doped with MWCNTs, over a range of static strains and sensing current frequencies; and 3) the novel measurement technique is validated for damage detection and localization, involving simultaneous, multi-channel measurements of self-sensing structural elements. This paper is organized as follows. The self-sensing structural material used throughout this work is introduced in section 2. The experimental procedures approach used for validation of the biphasic DC measurement approach is described in section 3. The biphasic DC measurement approach for self-sensing structural materials is provided in section 4. Results from experimental validation and the corresponding discussion are presented in section 5. The paper is concluded in section 6.

2. BACKGROUND

The fabrication process and sensing principles of the MWCNT-based self-sensing cementitious material used throughout this work are described in detail in D'Alessandro *et al.*[8] Briefly, these carbon doped cement-based composites are fabricated by doping traditional cementitious mixtures with carbon nanotubes to provide the cement-based composite with a piezoresistive strain sensing capability. Here, 1% MWCNTs (Arkema Graphistrenth C100) with respect to the mass of cement were mixed with water and a surfactant (Lignosulfonic acid sodium salt) using a sonicator tip after a preliminary mechanical mixing. Three specimens were cast: the first into a 51 x 51 x 51 mm^3 mold along with five stainless steel mesh electrodes (4x4 Mesh, 1.2 mm wire) as shown in figure 1(a), the second into a 40 x 40 x 160 mm^3 mold along with eight stainless steel mesh electrodes as shown in figure 1(b) and the third into a 100 x 100 x 500 mm^3 mold with 16 stainless steel mesh electrodes and 10 mm steel reinforcement as shown in figure 1(c). Each specimen cured for 28 days in laboratory conditions before testing.

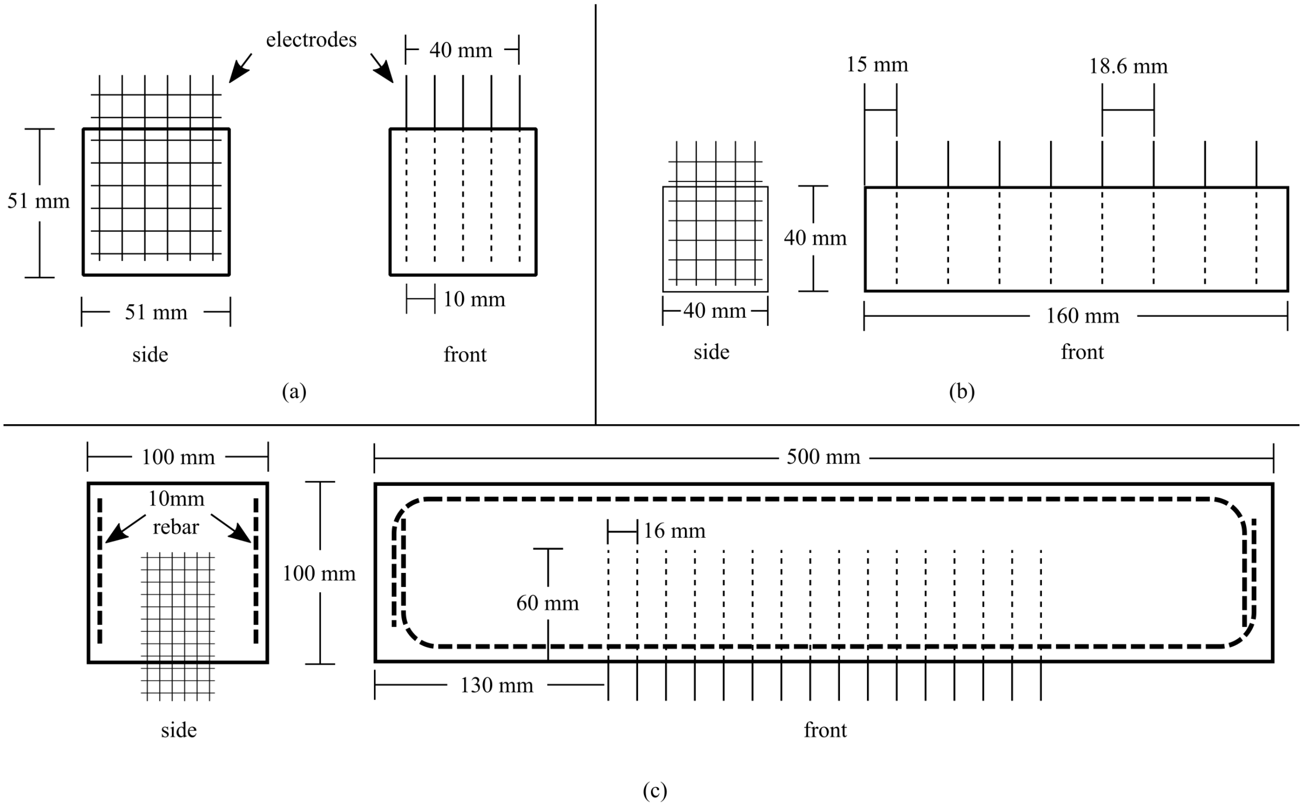


Figure 1. Self-sensing structural material consisting of MWCNTs suspended in a cement matrix with stainless steel meshes used for electrodes: (a) a 51 x 51 x 51 mm^3 cube sample for validation of the proposed biphasic DC measurement approach and strain sensitivity; (b) a 40 x 40 x 160 mm^3 beam for demonstrating simultaneous, multi-channel resistance measurements and damage detection; and (c) a 100 x 100 x 500 mm^3 reinforced beam for demonstrating damage detection under a four-point loading condition.

Various equivalent electromechanical models for strain-sensing cement-based composites with MWCNTs have been introduced in literature.[16,30] These models typically conclude that only resistance is influenced by the mechanical deformation.[16,30,31] Therefore, we simplify the resistance-strain relationship to

$$\frac{\Delta \mathrm{R}}{\mathrm{R}} = -\lambda \varepsilon \tag{1}$$

where R is the specimen's unstrained nominal resistance and ΔR is the incremental variation in electrical resistance caused by the axial strain, ε. λ gauge factor of the cement-based sensor.

3. EXPERIMENTAL PROCEDURES

Experimental validation of the biphasic measurement approach using four-probe resistance measurements is conducted in three stages. First, the static test configuration shown in figure 2(a-b) is used to test various sensing current frequencies and to validate the use of the biphasic measurement approach for strain sensitive self-sensing materials. The nanocomposite cement-paste cube (figure 1(a)) is placed in a frame consisting of an F-clamp with steel blocks used to evenly distribute the applied load onto the test specimen. Cardboard is used to insulate the test specimen from the steel blocks and a steel ball is added as a pivot to remove any eccentricity in the loading. The sensor is fully discharged before each test by connecting all the embedded contacts together for five minutes. Secondly, the eight-contact beam specimen (figure 1(b)) is tested as shown in figure 2(c-d). The beam is used to validate the biphasic DC measurement approach for damage detection and localization during fracture formation. Damage is induced in the center using a hacksaw while the beam is clamped to

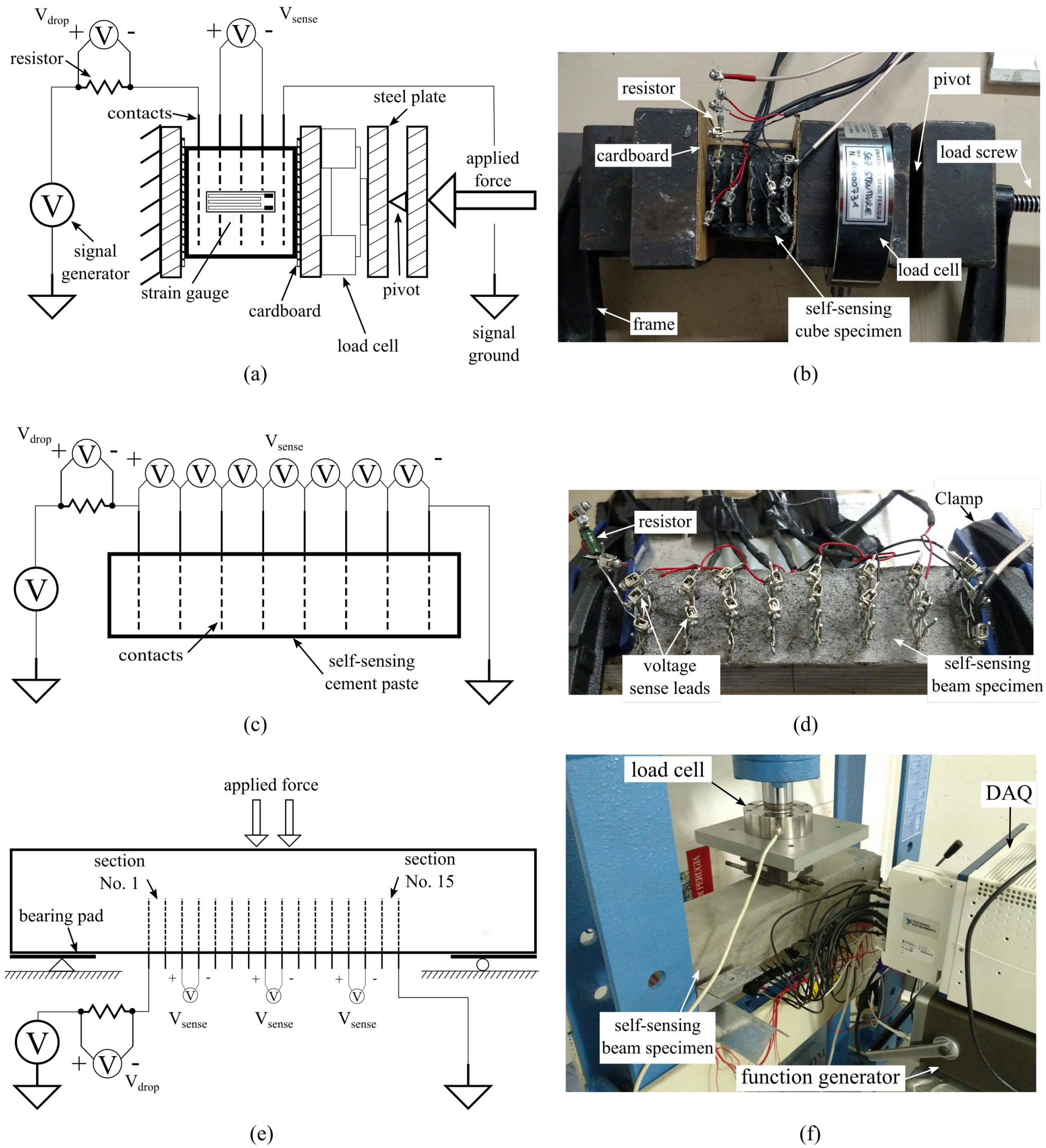


Figure 2. Experimental configurations: (a) electro-mechanical diagram of the cube test configuration with key components labeled; (b) picture of the cube test configuration; (c) electro-mechanical diagram of the eight-contact beam specimen; (d) picture of the beam test configuration; (e) electro-mechanical diagram of the sixteen-contact reinforced beam specimen; and (f) picture of the reinforced beam test configuration.

prevent movements during the process. Lastly, the sixteen-contact beam is tested under a four-point loading configuration for the purpose of validating the biphasic DC measurement approach for an uncontrolled damage case as shown in figure 2(e-f). The sixteen-contact beam is tested until failure in a hydraulic testing frame as shown in figure 2(f). Loads were applied using the four-point bending setup and measured using a load cell.

Voltage samples, (V_{sensed} and V_{drop}) were taken using a PXIe-4302 24-Bit analog input module in a differential voltage configuration. Voltage measurements were hardware-timed to bypass the DAQ's FIR filter and taken at 5000 samples per second (S/s). Voltage samples used for calculating the resistance were taken as the voltage sample closest in time to 80% of the total measure region of the cycle. A signal generator (Philips PM5132) with an output impedance of 600 Ω was used to provide the sensing current for both the biphasic measurement approach and DC measurement. The specimens' total current draw was obtained by monitoring the voltage drop over a wire round resistor placed in series with the specimen. Signal cables were fabricated to be as short as possible, consisting of RG174 cable and using tinned-copper screw-type connectors. Two strain gauges (KYOWA KC-120-120-A1-11M2R) were adhered onto opposite sides of the cube specimen (figure 1(a)) and the strain was taken as the average of the two measurements. A 2000 kg load cell (LAUMAS CL 2000) was used to monitor the compressive force applied to the system for the setup shown in figure 2(a-b) and a 10,000 kg load cell (LAUMAS CL 10000) was used for the setup shown in figure 2(e-f). Strain gauge and load cell data were obtained using a 24-bit bridge input module (PXIe-4330). All measurements were processed using a custom LabVIEW script interfaced over a PXIe-1071 chassis from National Instruments.

4. BIPHASIC MEASUREMENT APPROACH

The proposed biphasic electrical measurement approach works by sourcing a periodic measure/discharge signal in the form of an alternating square wave from a signal generator. The newly proposed method is the focus of a separate work,[32] its main features are introduced here for completeness. DC voltage measurements are made during the "measure region" of the signal while material depolarization is obtained during the "discharge region" of the signal (as shown in Figure 3(a)). Resistance values for the self-sensing structural material are obtained by dividing the measured voltage (V_{sensed}) by the current ($i_{calculated}$) flowing through the specimen.[15] Current is calculated by monitoring the voltage drop across the known resistor, arranged in series with the specimen that is being monitored. The current transiting through the known resistor and therefore through the cement paste sensor can be calculated as:

$$i_{calculated} = \frac{V_{drop}}{R_{in-line}} \tag{2}$$

where $R_{in-line}$ is the resistance value of the in-line resistor and V_{drop} is the voltage drop across the resistor. Figure 3(a) diagrams the applied voltage as well as the sensing voltage signal for the cube specimen introduced in figure 1(a). Here, a 1 Hz square wave with a 50% duty cycle ranging from -2.5 to 2.5 V is used as the sensing current for the cube specimen presented in figure 1(a). Discrete voltage samples are made during the measure region of the square wave at a constant time interval (80% of the measure region). A resistance value is calculated by dividing the measured voltage by the simultaneously measured current ($i_{calculated}$):

$$R = \frac{V_{sensed}}{i_{calculated}} \tag{3}$$

where the sampling rate of R in S/s is determined by the frequency of the sensing current, measured in Hz. The calculated resistance can then be used for damage detection in a damage-detecting material.[33] Equation (1) can be used to relate the measured resistance to strain for a strain-sensing material.[34]

4.1 Reductions in sensor drift

Comparison between a four-probe DC measurement and the proposed biphasic DC measurement approach for various sensing current frequencies is presented in figure 3(b). The sensing voltage is applied one second into the test. As expected, the four-probe DC measurement experiences a sharp increase in the observed resistance in the first few seconds due to material polarization. The resistance drift reduces as a function of the time the sensing current is applied. In comparison, the proposed biphasic DC measurement approach provides a constant

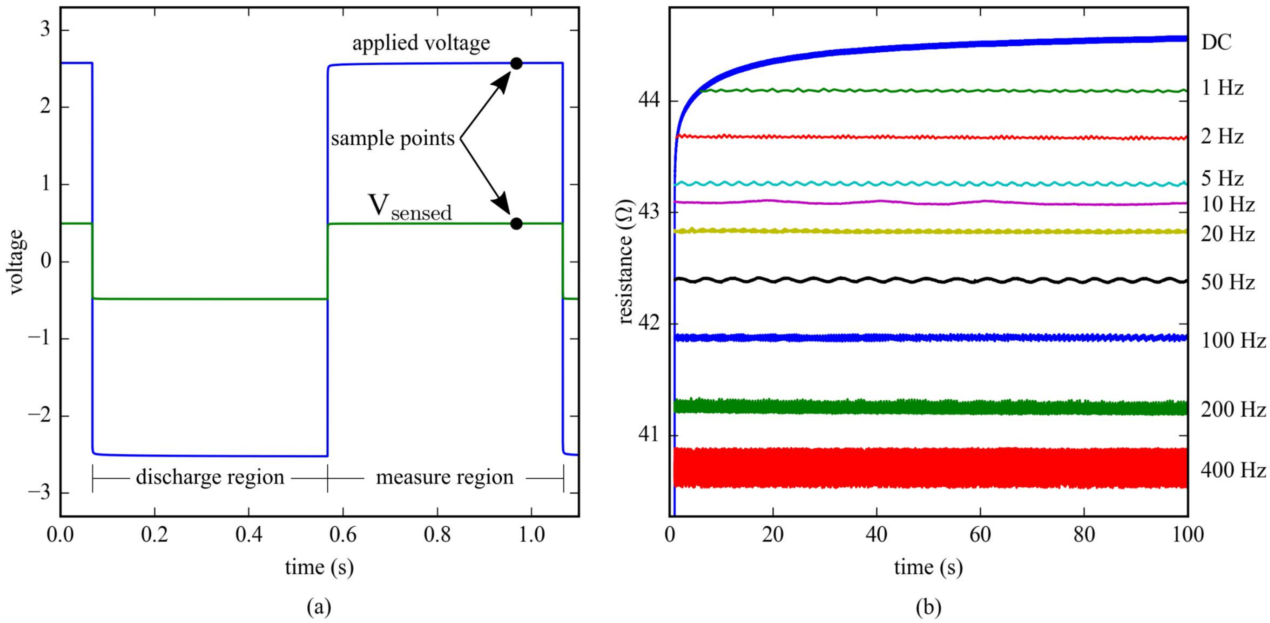


Figure 3. Biphasic DC measurement method: (a) electrical signals of a 1 Hz square wave: sensing current with 50% duty cycle showing the measure and discharge regions, as well as the sample points for the applied and sensed voltages; and (b) time-based comparison of traditional DC resistance and the proposed measurement approach using a 50% duty cycle and nine varying sensing current frequencies.

resistance measurement, with its measured resistance value depending on the frequency of the applied sensing current. Lower frequencies measure a higher resistance because the material has more time for polarization. The level of variation in the measured resistance value (noise) increases with an increase in sensing frequency. Measurement noise is assumed to be a function of various sources, including: (i) the 50 Hz noise present in the signal generator; (ii) variations from the 80% mark as denoted in figure 3(a) due to the DAQs consistent sampling rate of 5000 S/s providing a higher number of samples per cycles for sensing currents of lower frequencies; and (iii) material dependent electrical interactions between the carbon-based cement and the sensing current.[30] The use of dedicated electronics may greatly reduce the noise level of the proposed biphasic measurement approach. The sources of noise and their complex interactions is left to future work.

5. EXPERIMENTAL VALIDATION

This section presents the experimental validation for strain sensitivity and damage detection of carbon-doped cement composites.

5.1 Strain Sensitivity

The capability of the biphasic measurement approach to monitor a strain-sensitive structural material is presented in figure 4(a). The cement paste cube, shown in figure 1(a), was tested under quasi-static compressive loads. Loads were applied in 0.1 kN steps from fully unloaded to 2.5 kN. The strain was obtained by averaging the readings from the resistive strain gauges adhered to opposite sides of the specimen. An approximately linear bahevior of the sample specimen was found beyond 0.6 kN, relating to a measured strain of 60 $\mu\varepsilon$. For simplicity, a linear relationship between measured resistance and strain is assumed after the piezoelectric effect is activated around 60 $\mu\varepsilon$. The linear behavior of the cube specimen is annotated with a dashed red line in the range 60 - 260 $\mu\varepsilon$. The sensor response for the 20 loading cases ranging from 0.6 to 2.5 kN reports a linear relationship between the measured strain and resistance. As expected, the specimen resistance decreases as the force is applied,[9] resulting in a sensitivity of 0.002 $\Omega/\mu\varepsilon$. The value of the gauge factor agrees with that of similar samples (size

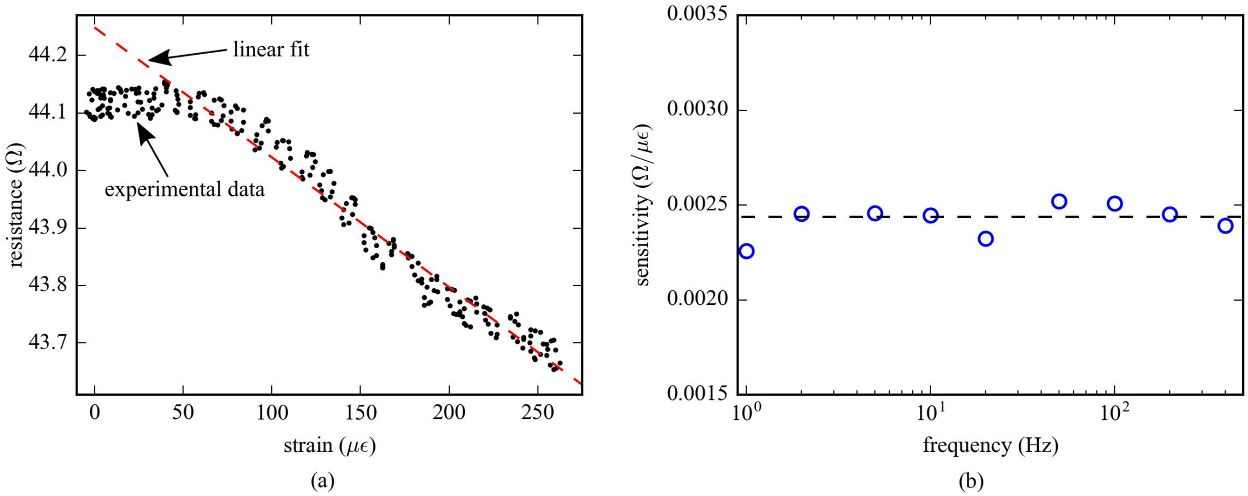


Figure 4. Strain sensitivity validation showing: (a) strain-resistance characterization for MWCNT cement-based sensor using the biphasic measurement approach; and (b) strain sensitivity as a function of applied sensing current.

and conductivity) presented in D'Alessandro *et al.*[8] demonstrating that the proposed biphasic DC measurement technique does not reduce the specimens strain-sensing ability.

The effect of changing sensing current frequencies on strain sensitivity is investigated next and presented in figure 4(b). As before, sensitivity was calculated in the assumed linear range from 60 to 260 $\mu\varepsilon$. Small variations in the sensitivity results are present in the range of frequencies presented, but the trend appears strongly linear. Linear regression of the data is shown in figure 4 as a dashed black line with an observed drift of 0.84% over the range of frequencies tested. As evidenced by the results, the biphasic measurement approach is capable of monitoring a strain-sensing material's strain state over a range of sensing current frequencies, further expanding the versatility of the method.

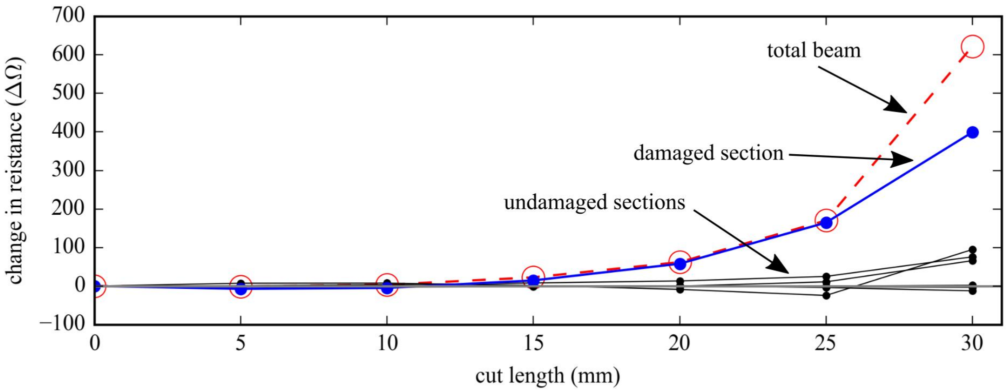
5.2 Damage Detection

The damage detection case is conducted on the eight-contact (seven section) non-reinforced cement composite beam shown in figure 1(b). The experimental setup shown in figure 2(c-d) and results are exhibited in figure 5. The resistance for each section is calculated by monitoring the voltage drop over each section using the proposed biphasic DC measurement approach. The current is assumed to flow fully through each contact, without any special considerations made for edge effects. Figure 5(a) presents the results in the form of change in resistance to provide a better comparison between readings. A controlled fracture is introduced into the center of section 4, in the form of a 1 mm wide crack (cut in figure 5(b)) made using a hacksaw. Cuts are induced in 5 mm steps from 0 to 30 mm with voltage measurements made starting with the undamaged state and after each cut.

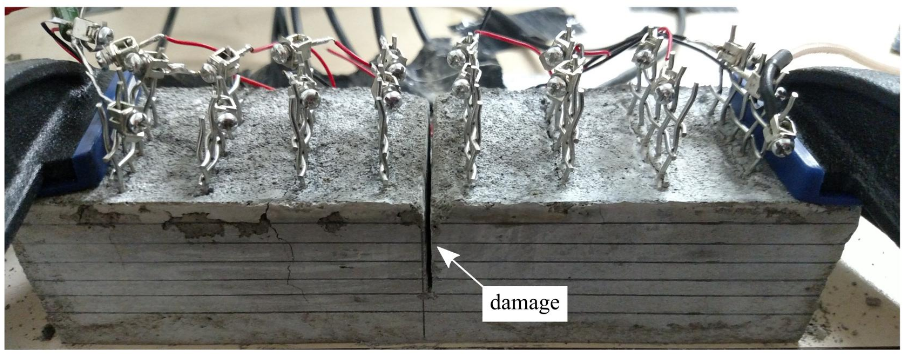
Results are presented in figure 5(a). The measured resistance of the center section (annotated as "damaged section") is seen to increase while the resistance for the undamaged sections remains constant. Additionally, the change in the beam's total resistance is also plotted. The increase in resistance is as expected, because the damage causes a decrease in the cross area of the specimen, resulting in an increase in the measured resistance.

For the damage case consisting of a 30 mm cut, an increase in the resistance in different sections of the beam is observed. The authors' hypothesis is that this change is a result of the beam settling under the clamping load after the final cut. Indeed, the beam was found to lift upwards in the center after the final cut was made and fail during removal from the testing setup. These results demonstrate that the biphasic DC measurement approach is capable of detecting and localizing damage in a damage detecting, carbon-doped material.

Lastly, a reinforced cement composite beam, shown in figure 1(c), is tested to validate the biphasic DC measurement approach for uncontrolled damage detection and localization in a four-point bending test. The experimental setup is presented in figure 2(e-f) and results are shown in figure 6. Ten loading cases were applied with the hydraulic cylinder and the applied force was obtained using a load cell as shown in figure 2(f). As



(a)



(b)

Figure 5. Experimental results for controlled damage on the eight-contact beam: (a) change in section resistance as a function of the induced cut length; (b) test specimen showing the damage induced into the center section.

before, the current was assumed to flow fully through the embedded contacts without particular assumptions for the area around the embedded contacts, the steel reinforcement, or the un-monitored sections at the ends of the beam. The validity of these assumptions is left to future work.

Figure 6(a) plots the measured loads for the displacement controlled test. Visible cracks appear in section 1 during the application of loading case 4 while cracks appear in section 15 during the application of loading case 7. The final failure occurred during the application of loading case 8 with a peak load of 113 kN. The resistance for sections 1 and 15 are plotted in figure 6(b) as a function of the measured load. For comparison, the three middle sections are also shown (undamaged sections), while the remaining sections are omitted for clarity. The damage is substantially greater in section 1 than in section 15, and it is confirmed by the increase in resistance for loading cases 4-7. The sharp increase in resistance after failure can be used to localize the damage cases. However, the ability to detect and localize damage before failure occurs is of greater interest. The detection and localization of damage, starting at loading case 4, is presented in the insert of figure 6(b). Damage can be detected early through the significant increase in resistance in comparison to measurements taken on other sections of the beam.

For sections 1 and 15, the cracks developed through the outermost contact. If damage were to occur on the wrong side of the electrode outside the current flow, the damage could have been hard to detect and localize without the use of an electro-mechanical model. A simple solution to this problem is the deployment of embedded contacts that span the entire length of the beam, therefore eliminating the possibility that damage forms outside the monitored area. While the increase in resistance from section 1 after loading case 4 is clearly visible, the increase in resistance in section 15 is less noticeable due to the magnitude of its damage when compared to section 1. Effectively detecting both damage locations (section 1 and 15) may require the use of an additional electro-mechanical model or more sensitive electronics to effectively capture.

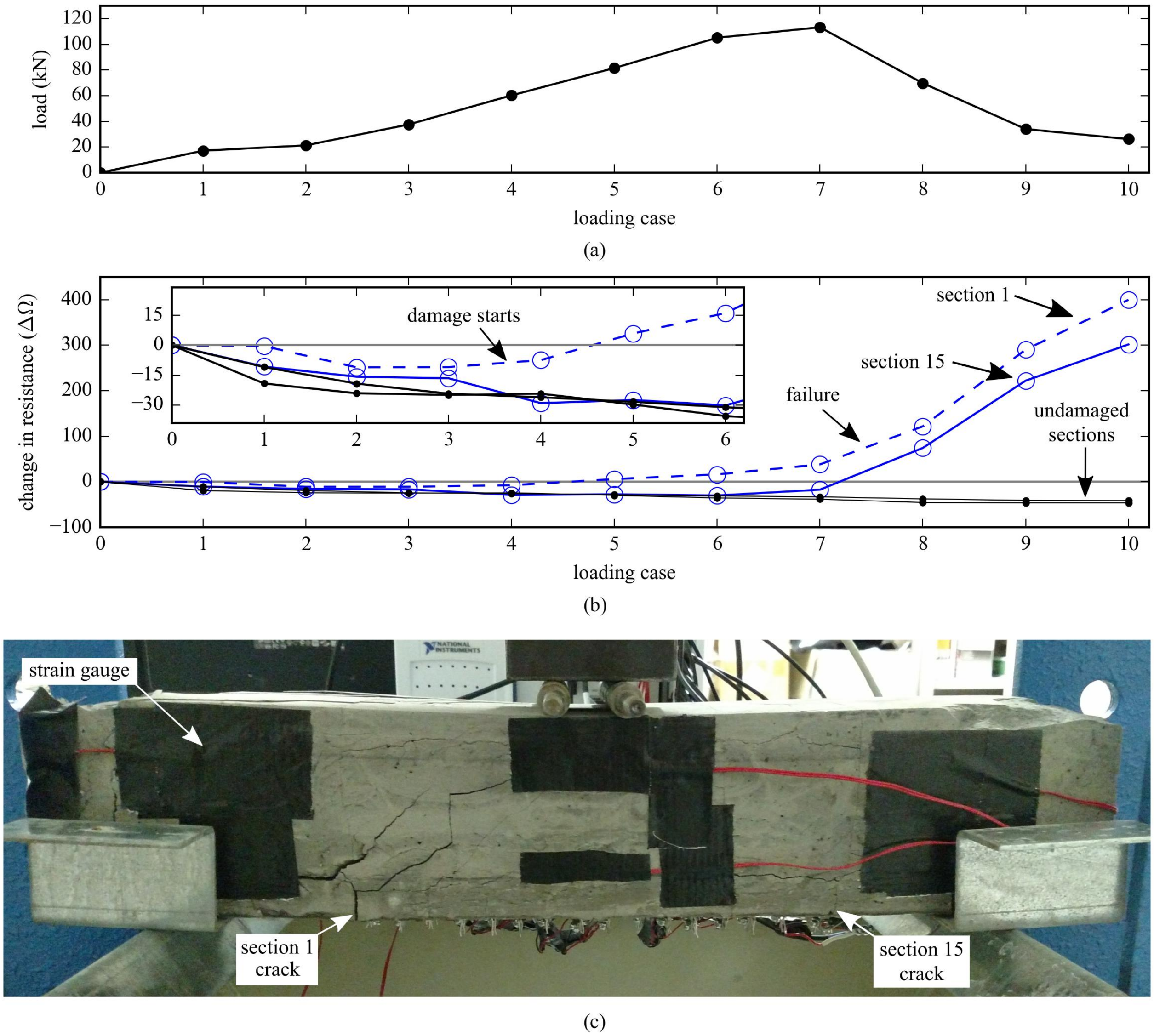


Figure 6. Experimental results for uncontrolled damage on the sixteen-contact reinforced beam: (a) measured load for each displacement-controlled loading cases; (b) change in resistance for selected sections as a function of the loading cases; and (c) test specimen showing the damage forming in sections 1 and 15.

6. CONCLUSION

This work introduced and reported on an electrical measurement approach that is well suited for use in the resistance measurement of self-sensing multi-functional structural materials. The proposed approach developed to remove the resistance drift present in the electrical measurements of many multi-functional materials. This drift has been well documented in carbon-doped cementitious materials and is often attributed to material polarization, changes in the material's dielectric constant, the direct piezoelectric effect, or the combination of other electrical effects. Elimination of sensor drift is achieved through applying a periodic measure/discharge signal in the form of an alternating square wave. Differential DC measurements are made during the signal's "measure region" while material depolarization is obtained during the "discharge region". Resistance values for the self-sensing structural material are obtained by dividing the measured voltage by the current flow through the specimen. The proposed measurement approach is capable of providing a consistent measurement for the self-sensing structural material, enabling the temporal comparison of signals. Additionally, the proposed measurement approach allows for simultaneous, multi-channel acquisition of adjacent sections in a sectioned self-sensing structural material, further increasing deployment opportunities of the proposed measurement approach.

The authors presented a comparison between the proposed biphasic DC measurement approach and DC resistance measurement in a four-probe configuration. Validation was achieved using a self-sensing structural material specimen, consisting of MWCNTs dispersed in a cement paste matrix. The biphasic DC measurement approach was found to remove the drift associated with the electrical behavior of carbon-based self-sensing materials. The same specimen was then characterized over a range of static strains, demonstrating that the approach can be used to monitor strain-sensing materials.

Validation for damage detection was performed using two multi-functional cement-based composite beams doped with MWCNTs. First, controlled damage was introduced into a 40 x 40 x 160 mm^3 beam to demonstrate the biphasic DC measurement approach's ability to detect and localize damage within the multi-sectioned MWCNT beam. Thereafter, a 100 x 100 x 500 mm^3 steel reinforced cement composite beam was loaded past failure in a four-point bending configuration. Even though damage occurred at the outermost contacts, changes in the beams internal resistance were still successfully tracked to provide damage detection and localization.

With prolonged static measurements, the proposed novel measurement technique shows great promises for a range of self-sensing structural materials. Self-sensing carbon-based structural materials could be used to monitor an engineered system's health, in civil, mechanical, and aerospace structures. Multi-channel acquisition enables damage detection and localization in large-scale deployments of self-sensing structural materials. Possible applications for self-sensing structural components in civil infrastructure include the use of sensors integrated into columns, bridge girders and pylons, or the deployment of smart mortars and smart bricks for masonry structures. Additional examples, using other carbon-doped composites, include the development of smart wing spars or self-monitoring shells for prolonged structural health monitoring in aircraft and wind turbine blades.

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