MONITORING STRAIN IN ENGINEERED CEMENTITIOUS COMPOSITES USING WIRELESS SENSORS

Tsung-Chin Hou and Jerome Peter Lynch
Department of Civil and Environmental Engineering, University of Michigan, MI 48109 USA

ABSTRACT

The emergence of new structural materials opens exciting venues for improving the strength and durability of civil structures. Engineered Cementitious Composites (ECC) are a special class of fiber reinforced cementitious composite (FRCC) that combine short polymer fibers with a cement matrix to produce a material, which undergoes strain-induced hardening and is ultra-ductile when loaded in tension. The unique electrical properties of FRCC materials render them a smart material capable of measuring strain and the evolution of structural damage. In particular, the material is piezoresistive with changes in electrical resistance correlated with mechanical strain. In this study, the piezoresistive property of ECC structural specimens are exploited to directly measure levels of tensile strain. To enhance the resistivity properties of the material without disrupting mechanical strength, small volume fractions of short steel or carbon fibers are included within the ECC matrix. Changes in ECC electrical resistance are measured using a two-probe direct-current (DC) resistance test as specimens are monotonically loaded in tension. To collect the resistance measurements of ECC specimens during testing, a low-cost wireless sensing unit is employed.

1 INTRODUCTION

Recent advancement of new civil engineering materials, such as fiber reinforced cementitious composites (FRCC), has presented new possibilities for the design of civil structures. FRCC materials exhibit superior tensile strength and ductility compared to ordinary concretes, rendering them well suited for use in structures exposed to cyclical and extreme live loads. A special class of FRCC material known as Engineered Cementitious Composites (ECC) has been optimized at the microstructure level to allow the composite to exhibit strain hardening and ultra ductility under tension [1]. Provided the mechanical durability of ECC, researchers are exploring the use of ECC materials in a variety of realistic structural applications including in highway bridge slabs [2], bridge piers [3], and concrete-steel beam-column connections [4]. With practitioners beginning to adopt ECC in real field structures, an opportunity exists to monitor the long-term performance of the material under realistic loading scenarios that can not be reproduced in the laboratory.

The structural engineering community has expressed great interest in monitoring the performance of civil structures to gain better understanding of structural nonlinear behaviors and to identify the onset of structural damage. A number of mature sensing technologies exist that can be used to accomplish these monitoring goals. For example, passive structural monitoring systems have been widely used in seismic regions to monitor the response of long-span highway bridges and critical buildings to earthquakes. These systems often consist of sensors (accelerometers and strain gages, just to name a few) with sensor measurements communicated by wire to centralized data repositories for future analysis. A second group of monitoring technology includes monitoring devices that perform non-destructive evaluation (NDE) of civil structures. NDE devices impart energy to the structure and measure corresponding structural responses. For example, ultrasonic transducers are used to detect internal cracks and flaws by exposing the material to ultrasonic waves and recording reflected waves that have traveled through the material. Today, many researchers are exploring the creation of new structural monitoring technologies that can improve the capabilities of current monitoring systems. In particular, interest has surrounded the development of wireless structural monitoring systems as proposed by Lynch *et al.* [5, 6]. Wireless sensing could be an important paradigm shift in the structural monitoring field because it promises low-cost installations and enhanced functionality compared to traditional wire-based counterparts. Already, a number of validation studies have been performed using wireless sensors as nodes in a large-scale global monitoring system [5] as well as for local non-destructive evaluation using piezoelectric active sensors [6]. A distinct advantage of wireless sensors is their ability to use their embedded computing power for real-time interrogation of measurement data. For these reasons, wireless sensors could be used to monitor the long-term behavior of new materials like FRCC and ECC when they are used in real field structures.

In this study, wireless sensing units are proposed for integration with ECC structural elements to monitor their response to tensile loads. In particular, the change of ECC electrical resistivity that results from strain will be measured by a wireless sensing unit and recorded. To enhance the piezoresistive properties of the material, short steel and carbon fibers are added to the polymer fiber-cement ECC material mix in volume fractions below their reported percolation thresholds. Standard two-probe resistance tests are conducted by a wireless sensing unit during monotonic tensile loading of the ECC structural specimens. The paper concludes with a discussion of the presented test results and suggestions for future research in the integration of wireless sensing and ECC materials.

2 RESISTIVITY OF CEMENTIOUS MATERIALS

The addition of short fibers to cement was initially intended to enhance the mechanical properties of resulting cement composites. However, researchers have just begun to explore the electrical properties of FRCC materials as a means of measuring strain and tracking the formation of crack damage [7]. The electrical resistance of cement-based materials, including concrete, has been studied since the 1950's when Hammond and Robson [8] first reported their findings on the electrical properties of concrete. Since then, the resistance of concrete has been an important design parameter considered in a number of applications including the design of concrete rail ties, electrical power plant slabs, and hospital operating room floors [9].

If a voltage potential, V, is applied across an FRCC material, electricity will flow parallel to the applied field with current, I, proportional to the applied voltage potential. The resistance of the material, R, is related to the current and voltage by Ohm's Law: $V = IR$. Since the resistance of the material is dependent upon the geometry of the specimen, resistance is normalized by the specimen geometry and is reported as a measure of a material's resistivity, ρ. Assuming the voltage potential is applied to a specimen by rectangular plates of area, A, which are separated by length, L, the material resistivity is defined as follows:

$$\rho = RA/L \tag{1}$$

The resistivity of cement and concrete materials can vary widely depending on the material composition and environmental conditions. In general, their resistivity can span from $1\text{x}10^4$ to $1\text{x}10^8$ Ω-cm; in this range, cement-based materials are considered to be semiconductors. In contrast, metals are highly conductive materials with resistivities below $1\text{x}10^{-4}$ Ω-cm while insulators, like paraffin, have resistivities above $1\text{x}10^8$ Ω-cm.

The electrical properties of an FRCC composite material can be modeled based on the composite's individual phases and interfaces. In contrast to metals where electrical currents are essentially the flow of free electrons, electrical currents in cement are the flow of ions in the porous matrix material. Electrical current can also be carried by the individual fibers if they are conductive. Steel and carbon fibers used in ordinary FRCC are highly conductive while polyvinyl alcohol (PVA) fibers commonly used in ECC are insulators, thus carrying no current. The transfer of electrical current from matrix to conductive fiber is also dependent on the physical interface that exists between the two phases (matrix and fiber).

An attractive feature of fiber reinforced cementitious composites is their piezoresistive behavior. When FRCC materials are mechanically strained, they experience a corresponding change in their electrical resistance. If the electrical resistance of an FRCC can be measured, the material can act as its own strain sensor. The piezoresistive behavior of FRCC materials can be attributed predominately to the cement matrix. While cement itself is piezoresistive, strain-induced changes in electrical resistance are not restored when the material is unloaded as a result of permanent cracks that form during loading. Only when fibers are included in the cement is the piezoresistive behavior reversible. The reversibility of the piezoresistive effect in FRCC materials is due to the ability of short fibers to bridge the cracks that form in the matrix under loading [7].

A number of methods have been proposed for measuring the resistance of FRCC materials. All of the methods can be classified as either direct current (DC) or alternating current (AC) resistance test methods. In DC resistance tests, a constant voltage potential is applied to generate electrical current in an FRCC specimen. While DC resistance testing is easy to perform, the method suffers from the development of polarization potentials in cement-based materials. Polarization is a buildup of charge within the material, similar in manner to the accumulation of charge in a capacitor. When a voltage is first applied to an FRCC specimen, polarization is observed as an increase in resistance immediately following the application of the external voltage potential. In DC resistance tests, the effect of polarization can be nullified by applying the voltage potential to the specimen ahead of its mechanical loading, thereby allowing the specimen time to converge to a steady state resistance value. To avoid polarization effects, some researchers advocate the use of AC resistance tests that apply an alternated (positive-negative) voltage [10].

3 STRAIN SENSING OF ECC PLATES IN TENSION

Engineered Cementitious Composites (ECC) are constructed using Type 1 Portland cement, silica sand, fly ash, water and short polyvinyl alcohol (PVA) fibers. The PVA fibers are essential to impart the ECC materials with excellent tensile strength, strain hardening behavior and ultra-ductility. Only a small amount of PVA fibers is necessary to attain optimal mechanical properties; in this study, a 2% volume fraction of PVA fibers is used. To enhance the conductivity of constructed ECC specimens, a small volume fraction of short conductive fibers is added during fabrication. One set of ECC specimens employs steel fibers (0.1% volume fraction) while another set uses carbon fibers (0.4% volume fraction). These small volume fractions ensure that the material has a lower resistivity without interfering with ECC mechanical properties. The steel and carbon fiber volume fractions are below reported percolation thresholds for the respective fiber types [7]. The percolation threshold is the fiber volume fraction at which the fibers of an FRCC are in continuous contact with one another thereby limiting electrical current to the fibers. The wet ECC mixture is placed in molds that cast ECC plate specimens with cross sectional areas of 12 mm by 38 mm and lengths of 30.5 cm. After 7 days, the specimens are removed from their molds to continue curing until mechanical testing occurs after the 28th day.

The resistivity of the ECC plate specimens is measured using a two-probe resistance test prior to loading. In such a test, the ECC specimen is connected in series to a resistor of a known resistance. As shown in Figure 1, a voltage potential is applied across the resistor-specimen circuit to induce the flow of electrical current through the material. Voltage is measured at the resistor-ECC specimen junction using the wireless sensing unit proposed by Lynch *et al.* [5]. To

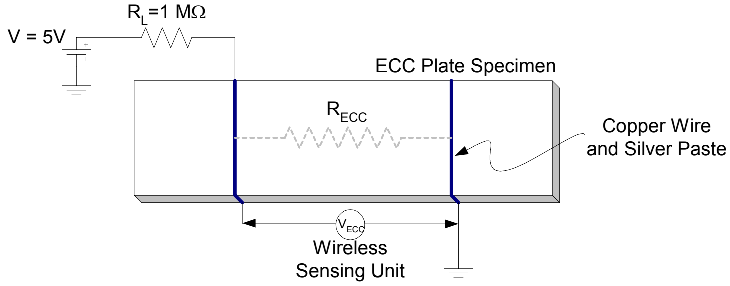


Figure 1: Two-point DC resistance test setup for ECC plate specimens

ensure the electrical current is well distributed across the entire cross sectional area of the ECC specimen, the voltage is applied using copper wires wrapped around the specimen and bonded to its surface with highly conductive silver colloidal paste. The resistance of the specimen, R_{ECC}, is a function of the measured voltage, V_{ECC}:

$$V_{ECC} = \frac{5R_{ECC}}{R_L + R_{ECC}} \tag{2}$$

Based on the geometry of the specimens, and the separation between the copper wires applying a voltage field, the material resistivity can be calculated. For the plain ECC specimen, the resistivity is measured to be 2.05×10^6 Ω-cm, while the resistivities of the steel and carbon specimens are measured to be 1.8×10^6 Ω-cm and 0.8×10^6 Ω-cm respectively. As anticipated, the resistivity of the steel and carbon doped ECC specimens are below that of the ordinary ECC sample.

An MTS 810 Material Test System is used to monotonically load ECC plate specimens in axial tension to initiate strain hardening behavior. The data acquisition system controlling the MTS 810 system records the applied load and the corresponding elongation of the plate. In addition, the resistances of the ECC specimens are measured by the wireless sensing unit during loading. At the conclusion of the test, the wireless sensing unit communicates resistance time-histories to a laptop computer for future analysis. For validation purposes, the Agilent 34401 digital multimeter is used to simultaneously record the resistance of the specimens. Figure 2 presents the setup of the ECC specimens during axial loading using the MTS 810 system.

Figure 3 presents the resulting stress-strain and resistance-strain curves for three plate specimens tested: undoped ECC, steel-doped ECC (SECC), and carbon-doped ECC (CECC). Based on the stress-strain curves of the three specimens, the ordinary ECC specimen had the best mechanical properties with strain hardening initiating at a stress of 4.3 MPa and 0.15% strain. The ultimate ductility of the ECC specimen was approximately 7% strain after which large-scale cracks initiate in the material. In contrast, the SECC specimen initiates strain hardening at a stress of 4.15 MPa and 0.28% strain. The specimen begins to lose its strain hardening behavior at 1.9% strain and rapidly fails after 2.5% strain. The CECC specimen initiates strain hardening at 0.17% strain and 4.8 MPa stress. However, the CECC specimen is least ductile with rapid failure at approximately 1.4% strain. While both SECC and CECC experience strain hardening and acceptable ductility, the inclusion of additional fibers in the ECC material mix reduced its mechanical performances below those of ordinary ECC.

All three ECC specimens exhibit excellent piezoelectric properties with linear relationships between electrical resistivity and strain; linear piezoelectric properties of the material make it an ideal candidate for use as a strain sensor. As shown in Figure 3(b), the CECC specimen has the greatest sensitivity to strain with a 1000% change in resistance at the ultimate strain of 2%. Strain

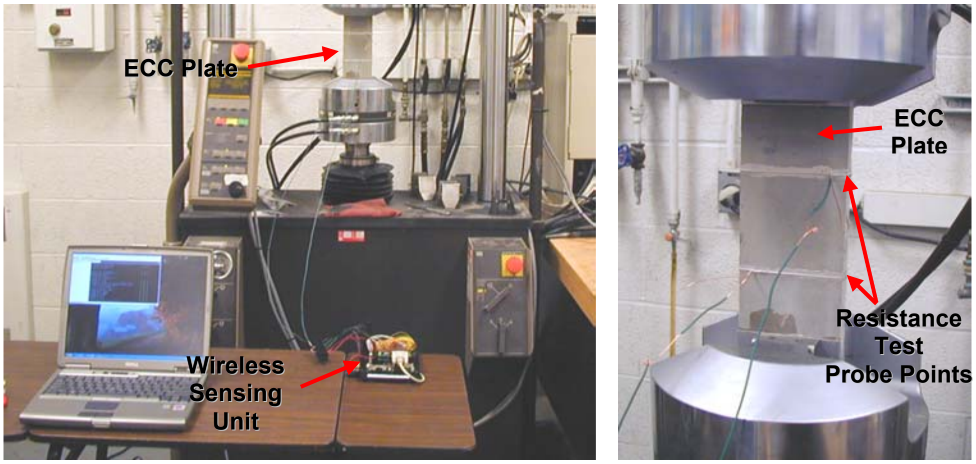
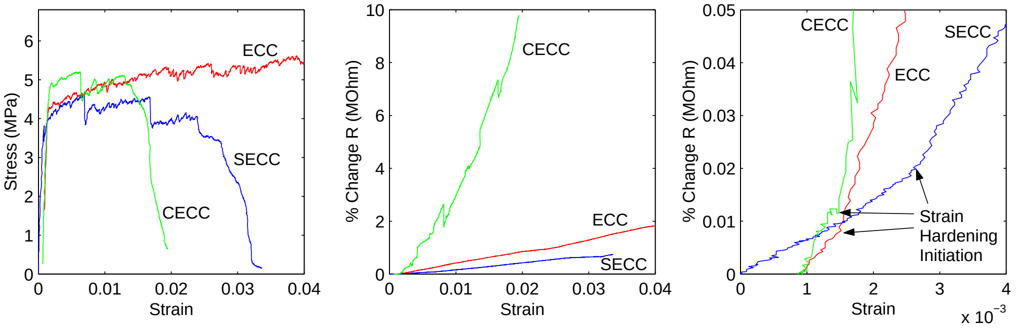


Figure 2: Tensile loading of an ECC specimen with a wireless sensing unit recording resistivity



(a) (b) (c)

Figure 3: ECC specimen results: (a) stress-strain behavior and (b),(c) resistance-strain response

sensitivity of the specimen can be reported by its gage factor which is the percent change in resistance per unit strain; $GF = (\Delta R/R)/\varepsilon$. The gage factor of the CECC specimen is calculated to be 502. The SECC and ordinary ECC specimens exhibit lower strain sensitivities resulting in gage factors of 22 and 45, respectively. An interesting characteristic is observed in the resistance-strain curves of all the specimens tested; the strain sensitivities of the three specimens change at the initiation of strain hardening. In a similar manner, the strain sensitivity again changes prior to ultimate failure. Sensitivity changes are observed by the change in slopes of the resistance-strain curves. Figure 3(c) is an enlarged plot of the resistance-strain curves at levels of strain where strain hardening is first initiated. As denoted in the plots, the change in slope (gage factor) of the resistance-strain curves can be attributed to initiation of strain hardening in the specimens. In addition to use of ECC materials as strain sensors, the distinct changes in gage factor exhibited by the material could be used to identify when strain hardening has initiated. With strain hardening tightly coupled with the formation of micro-cracks, this property can be used to indirectly identify the extent of cracking in ECC specimens.

4 CONCLUSION

This study exploits the piezoresistive properties of fiber reinforced cementitious composites (FRCC) so that they can be used as their own strain sensors. Three plate specimens constructed of

Engineered Cementitious Composites (ECC) were monotonically loaded in tension to induce strain hardening behavior in the material. Using a two-point probe resistance test, the resistances of the samples were measured by a wireless sensing unit. Based on the response of three ECC specimens tested, the ordinary ECC specimen had the best ductility at 7% strain while steel fiber and carbon fiber doped ECC specimens had sufficient ductilities of 2.5% and 1.4% strains respectively. As a result of linear changes in electrical resistance due to tension strain, all three specimens could potentially self-measure their strain in the field. An interesting feature of the material lies in the detectable change in resistance-strain sensitivity when strain hardening initiates. The onset of the change in sensitivity correlates the beginning of cracking in the ECC matrix resulting in a nonlinear change in the material conductivity. In contrast to the ordinary ECC specimen, the effect is less pronounced in the SECC and CECC samples since steel and carbon fibers electrically bridge the matrix microcracks. Additional work is already underway exploring the theoretical foundation for FRCC piezoresistive behavior. Furthermore, AC resisitivity tests are being considered to enhance the accuracy of strain measurements by eliminating polarization effects.

ACKNOWLEDGEMENT

The authors would like to express their gratitude to Prof. Victor Li and Shunzhi Qian, University of Michigan, for their assistance in preparing and testing the study's ECC plate specimens.

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