Carbon Yarns for Strain Sensing of FRC Elements under Cyclic Loading in the Uncracked Regime

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ABSTRACT

The goal of this study is to explore the use of carbon-based textiles to sense strain in fiber-reinforced concrete (FRC) elements. To answer this goal, the study investigates a new electrical configuration in which the carbon yarns function as internal devices within the FRC body. An impedance spectrum analysis is used to monitor changes in both electrical resistance and capacitance, focusing on tensile stresses in the healthy state of the element. The results show that the electrical responses consistently follow the mechanical loading and can be correlated to them for the purpose of strain sensing.

INTRODUCTION

Fiber-reinforced concrete (FRC) has been widely investigated for the development of multifunctional structural and self-sensory concrete elements [1-4]. The idea is based on monitoring changes in the piezoresistive properties of the concrete body. Since concrete matrix is a highly electrically resistive material, electrically conductive additives such as carbon fibers were applied [5-7]. By adding adequate volume fractions of carbon fibers, the conductivity of the concrete body can be significantly enhanced, enabling its monitoring capabilities. It is mainly pronounced when reaching the percolation threshold, in which adjacent fibers touch each other and an electrical path within the concrete body is formed [8-11]. It results in improved electrical properties, sensory capabilities, and structural performance.

The existing measurement methods for FRC elements rely on external devices such as copper electrodes to monitor the electrical properties of the concrete matrix and correlate them with mechanical strain or loading patterns [2, 5-6]. Yet, short fibers cannot be used as the main reinforcement system due to the brittle failure of concrete. Accordingly, studies in the literature have focused on monitoring the electrical response of FRC specimens under compression, with the experiments ending with the occurrence of cracking [2, 12-14].

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The current study aims to extend the sensing capabilities of FRC systems to include tensile stresses. Therefore, the proposed self-sensory concept offers to use the technology of intelligent TRC elements [15-21]. In such case, the textiles are used as the main reinforcement platform as well as the sensory device. The textile can carry tensile stress and maintain both its structural and sensory performances after cracking. The proposed electrical configuration offers to use the sensory capabilities of the carbon yarns to sense changes in the FRC body with no need for external monitoring devices.

To answer these goals, the study conducts an experimental investigation on textile and fiber reinforced concrete elements under flexural loadings, aiming to prove their sensory capabilities.

SENSORY CONCEPT

To sense changes in the electrical properties of the concrete, the study utilizes the electrical properties of two parallel carbon yarns that are embedded within the element. Since concrete matrix is highly resistive, its electrical properties are enhanced by additive short carbon fibers. In the proposed self-sensory textile and fiber-reinforced concrete elements, the carbon-based textile serves simultaneously as the main reinforcement platform and as the internal sensory device. The hypothesis of the study argues that the embedded yarns can be used to sense changes in the electrical properties of the concrete body and by that to monitor the mechanical response of the element. It is important to note that, opposed to previous studies that integrated the carbon yarns into the measurement system by connecting their both ends [15-21], the current study uses a different approach. The electrical connections are performed by connecting one end of the yarns to the DAQ system, see the electrical scheme in Fig.1. In such case, the measured changes in electrical properties are associated with the conductive medium between the parallel yarns. It results in an electrical circuit of parallel resistor and capacitor. The following equations can be used to describe the electrical impedance in the given *R*||*C* circuit:

$$Z_{R||C} = \frac{R}{1+(\omega RC)^2} - j \cdot \frac{\omega R^2 C}{1+(\omega RC)^2} \tag{1}$$

$$|Z_{R||C}| = \frac{R}{\sqrt{1+\omega^2 R^2 C^2}} \tag{2}$$

where *R* and *C* are the electrical resistance and capacitance of the concrete, respectively, and ω is the frequency of the applied electrical current ($\omega=2\pi f$).

The AC-based measurements are based on scanning the response spectrum of the impedance by using an LCR analyzer. The frequency range of the electrical current is 20 Hz to 1.5 MHz. The values of *R* and *C* are calculated by using a nonlinear least-square minimization method that minimizes the differences between the measured and theoretical response spectrums of the impedance [20-21]. It is performed by a post-process procedure.

The study focuses on the healthy stage of the element, in which the matrix is uncracked. In this stage, the load carrying mechanism is governed by the concrete body which carries most of the tensile stress. Exploring this stage is important for proving the monitoring capabilities of the carbon yarns as an internal sensory device.

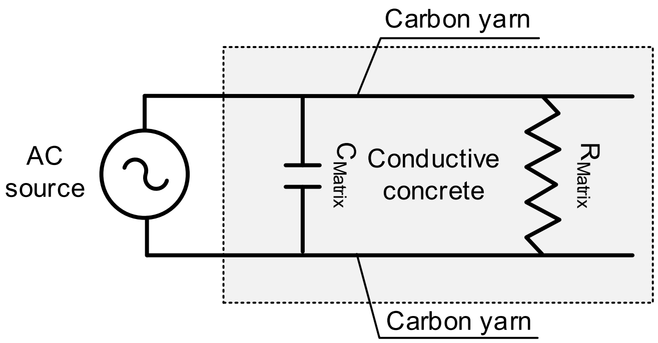

Figure 1. Smart textile and fiber reinforced concrete *R*||*C* electrical scheme

MATERIALS AND METHOD

This section describes the cementitious matrix, production of smart textile and fiber reinforced concrete specimens, the loading procedure, and the monitoring setup.

Cementitious Matrix

The study uses a high-strength Portland cement (PC) based cementitious matrix [21]. The mixture's components are: cement CEM I (52.5) 790 kg/m^3, sand (0.6 mm) 1448 kg/m^3, water 316 kg/m^3, silica fume (Elkem 920) 158 kg/m^3, and superplasticizer (ENT-11) 23.7 kg/m^3. The components were added gradually to the mixer. The mixing process resumed for about 16 minutes, with a commercial mixer suitable for cementitious mixtures. Short carbon fibers were added to the mixture to enhance its conductivity. Fiber content of 1.2%, with respect to the mass of cement, was chosen to ensure that electrical percolation has occurred. The fibers were first mixed with water and then added to the mixture. The short carbon fibers, named Tenax-A HT C124, are commercial fibers produced by Teijin company LTD. The material's properties of the fibers are: filament length 3 mm, filament diameter 7 μm, mass density 1.77 g/cm^3, tensile strength 4100 MPa, tensile modulus of elasticity 240 GPa, elongation at break 1.7%. The strength properties of the matrix are investigated at the age of 28 days according to EN 196-1:2005. Standard cubes (50/50/50 mm) are used for compression strength tests, and beams (40/40/160 mm) for flexural strength tests. The strength properties are: $\sigma_c = 75.16 \pm 7.31$ MPa, $\sigma_f = 13.30 \pm 0.95$ MPa.

Smart Textile and Fiber Rinforced Concrete Specimens

The study investigates smart textile and fiber reinforced concrete specimens under flexural loadings. The geometrical dimensions of the specimens are: length 300 mm, width 70 mm, and height 15 mm. The specimens were reinforced by a single textile layer. The textile layer is composed of carbon and AR-glass yarns. The properties of the yarns are summarized in Table I. Ten carbon yarns are positioned in the longitudinal direction (warp direction - 0°) parallel to potential tensile stress. AR-glass yarns are located in the perpendicular direction (weft direction - 90°), preventing electrical linkage between carbon yarns. The textile is located 5 mm above the lower face of the specimen's cross-section, corresponding to the tensioned zone of the specimen. The cementitious mixture was cast into the mold and then cured within lime-saturated water for 28 days.

Loading and Monitoring Setups

The specimens are investigated under flexural loading by using an Instron loading machine (Model 5966, force capacity of 10 kN), see Fig.2. The loading scheme is a four-point bending experiment. The total span is 210 mm, and the distance between loads is 120 mm. Cyclic loading procedure is chosen to investigate the monitoring capabilities of the elements. Eight load cycles are performed, with four different load levels. Each load cycle consists of the following stages: holding (at unloaded phase), loading to target load, holding (at the target load), and then unloading. Each holding stage, at unloaded or loaded phase, resumed for about 100 seconds. The duration of 100 seconds was chosen based on the rate of the electrical measurement, allowing sufficient data to be collected for monitoring the elements.

Various mechanical and electrical parameters are monitored during the loading experiment, including: the load by the loading machine; displacement by using an LVDT deflection sensor (Instron 2601-044, linear stroke ±50 mm, accuracy ±0.5%); the strain at the front face of the beam by using digital image correlation (DIC) technique (using the commercial software LaVision DaVis 10); the response spectrum of the impedance (using an LCR analyzer -Keysight 4990A-010 Impedance Analyzer). The measurement rate of the response spectrum of the impedance is 2.3 sec per scan (0.43 Hz).

TABLE I. Carbon and AR-glass yarns material's properties

Property	Carbon yarn	AR-glass yarn
Filament diameter [μm]	7	27
Specific mass density [g/cm^3]	1.81	2.68
Linear density [Tex]	1600	2400
Modulus of elasticity [GPa]	270	72
Elongation at break [%]	1.9	2.4
Tensile strength [GPa]	5	1.7
Electrical resistivity [Ω/m]	15	Infinity

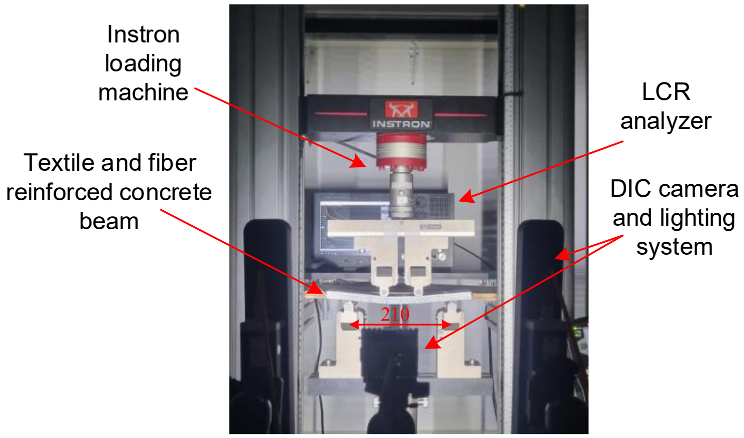

Figure 2. Experimental setup

RESULTS AND DISCUSSION

Fig.3 presents the mechanical and electrical responses of a representative smart specimen under cyclic loadings. Since the focus is on the healthy stage, the stresses are calculated with respect to the concrete cross-section and the loading scheme. The strain measurements are integrative over the length of the specimen, taken at the height of the carbon yarn from the DIC analysis. The relative electrical resistance and capacitance change are calculated with respect to initial measured values of R_0 = 1330 Ω, and C_0 = 0.331 nF. Table II summarizes the mechanical and electrical changes in each of the eight load cycles. The relative electrical changes are based on about 40 impedance spectrum scans for each load cycle.

From Fig.3, it appears that the relative electrical resistance and capacitance change follows the mechanical loading. It is also observed that the electrical resistance and capacitance have opposite trends. When the stress increases, the electrical resistance increases, and the capacitance decreases. It is associated with the tensile strain in the concrete body, see the strain measurements (red line) in Fig.3. When the matrix is strained two main mechanisms govern the electrical response: elongation of the short carbon fibers and slight increase in the distance between adjacent short carbon fibers. Both mechanisms contribute to the increase in electrical resistance, which is in a good agreement with the common decrease in resistance under compressive stress [5-6, 13-15]. In case of capacitance, these effects cause a reduction in the polarization of the conductive medium, leading to a decrease in capacitance upon loading. Furthermore, it is seen that both electrical properties consistently and repetitively follow the tensile strain in the element. From Table II, it is seen that the intensity of the electrical signals, calculated as the relative electrical change with respect to the unloaded phase in each load cycle, increases with the applied mechanical stress.

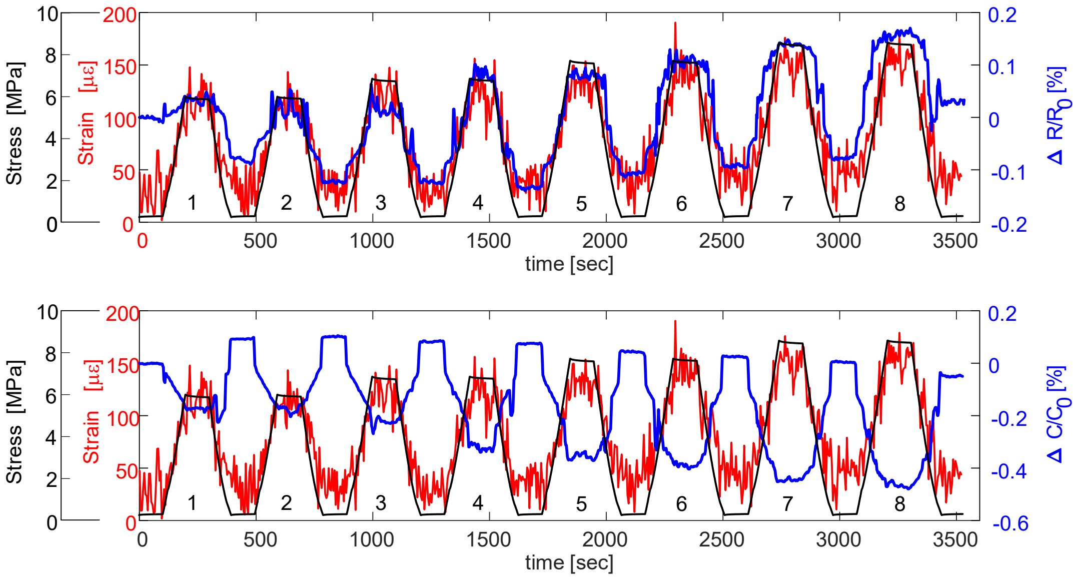

Figure 3. Cyclic loading of smart textile and fiber reinforced concrete beam - mechanical and electrical response

TABLE II. Specimen's mechanical and electrical responses to cyclic loading

Load cycle	Stress [MPa]	ΔStrain [μs]	$\Delta R/R_0$	$\Delta C/C_0$
1	6.0	68	0.035	-0.173
2	6.0	79	0.093	-0.266
3	6.85	89	0.141	-0.323
4	6.85	93	0.205	-0.401
5	7.70	94	0.215	-0.428
6	7.70	103	0.214	-0.433
7	8.55	107	0.232	-0.470
8	8.55	108	0.235	-0.470

To highlight the sensory capabilities of the proposed smart textile and fiber reinforced concrete element, it is offered to correlate the mechanical and electrical responses by using a relative gauge factor ($\overline{GF}$). Since the intensities of the electrical changes are different, as well as their sign, two relative GFs are proposed: for the resistance $\overline{GF_R} = \frac{\Delta R/R_0}{\Delta \text{strain}}$, and for the capacitance $\overline{GF_C} = \frac{\Delta C/C_0}{\Delta \text{strain}}$. A positive $\overline{GF_R}$ of 50.8 and negative $\overline{GF_C}$ of -74.9 are obtained. Both GFs have good coefficients of determination (R^2>0.92). These results reflect the high consistency and sensitivity of the proposed intelligent element.

It is concluded that the proposed sensory method can be used for the development of smart fiber reinforced elements. Since carbon yarns can function as primary reinforcement system and carry tensile stresses in cracked elements, the method can be extended for cracked specimens.

CONCLUSIONS

This study investigated the sensory capabilities of carbon-based textile embedded within FRC elements to sense electrical changes in the concrete body. The investigation focused on the healthy state of beams under cyclic loading. Results showed that carbon yarns have the capability to monitor electrical changes of the concrete body. Specifically, it was demonstrated that by measuring the impedance response spectrum, changes in both the electrical resistance and capacitance of the concrete can be simultaneously obtained. Both electrical properties were consistent and followed the applied stress and strain. Verification of the consistency was demonstrated by the concept of gauge factors. Exploring such correlations is vital for the future development of smart self-sensory structures.

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