Detecting Cross-Sectional Degradation in TRC Elements by Advanced TDR Technique

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ABSTRACT

This study explores the capability of smart self-sensory carbon-based Textile Reinforced Concrete (TRC) elements to locate and detect cross-sectional degradation. The concept involves connecting carbon yarns into electrical circuits using Time Domain Reflectometry (TDR) technique to measure electrical changes caused by wetting events. To detect cross-sectional degradation, the monitoring approach compares measurements from the current wetting event to those of a healthy reference measurement. The study presents the capability of the new monitoring concept by experimental investigation. It is demonstrated that the smart sensory carbon yarns successfully detect the location and estimate degradation of the cross-section of the elements.

INTRODUCTION

The growing demand for intelligent, hybrid, and sustainable structural systems has driven interest in advanced materials such as carbon-based textile reinforced concrete (TRC). This technology combines a high-performance cement matrix with high-strength textile meshes, offering the development of thin, lightweight structures with enhanced durability [e.g. 1].

Utilizing the electrical conductivity of the yarns that composed the textile, such as carbon yarns, demonstrate the potential of TRC structures to serve as smart hybrid systems with structural health monitoring capabilities [2-13]. These applications include monitoring applied loads [1, 2–3], detecting cracks occurrences [5], estimating integrative strain [5–6, 10–11], and identifying water infiltration through cracked zones [15–16]. The monitoring techniques were usually based on either direct current (DC) or alternating current (AC) systems [2–3, 8–9], and they demonstrate the capability of the self-monitoring system to provide global information about the structures.

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Recently, Gaben and Goldfeld [4-6] adopted the Time Domain Reflectometry (TDR) technique to detect the location of cracks under mechanical loading. The method involved connecting two parallel carbon yarns to an energy source and analyzing the reflected electrical signals. Since cracks initiated by breakage of the sleeve filaments, a portion of the electrical current is reflected and analyzed. By exploring changes in the impedance spectrum before and after the formation of crack, its location was identified. Despite the promising results of these studies, the implementation of the TDR in TRC structures faced several challenges that limited both the measurement range and spatial resolution. Furthermore, only the location of cracks could be detected, while their severity remained undetermined. Therefore, as a preliminary investigation into the detection of the severity of cracks, the current study develops an identification procedure that assesses the cross-sectional degradation along the TRC elements. This is achieved by measuring changes in the response spectrum of the impedance due to wetting events.

The study demonstrates the effectiveness of the proposed procedure through experimental investigation, presenting its capability to detect cross-sectional degradation in TRC elements.

SENSORY CONCEPT

The objective of this study is to develop a monitoring method that detects the degradation in thickness and its location along TRC structures. This is achieved by combining two sensory concepts, the TDR based identification procedure [4-7], and the smart water leakage detection concept [e.g. 7, 11-13].

The TDR technique operates by sending an electrical signal through coaxial cables, which typically have a constant impedance and a known velocity coefficient. When a fault or discontinuity occurs along the cable, part of the signal is reflected. The time it takes for the reflection to return is used to estimate the location of the defect. Implementation of the TDR technique in continuous carbon yarns is not a straightforward act. It is associated with the variation of the impedance with the yarn's length and the nonconstant or unknown velocity coefficient of the yarn. Furthermore, both properties vary due to mechanical straining. To address these limitations, it was proposed to use a pair of parallel carbon yarns connected to TDR based data acquisition (DAQ) system, one serving as the signal transmitter and the other as insulation, see Ref. [5]. Despite these adaptations, the measurement range remained limited and was constrained by the spatial resolution of the system. Therefore, only the location of cracks at a limited distance could be accurately identified. To amplify the measured electrical signal, the study utilizes the smart water leakage detection method [e.g. 11-13]. The concept is based on monitoring changes in the measured electrical signals from a pair of parallel carbon yarns due to wetting events. The hypothesis of the study is that by analyzing the electrical signals before and after wetting events by the TDR technique, the degradation of cross-sectional thickness can be assessed. It should be noted that, opposed to the original TDR-based methods [4–6], in which impedance changes were triggered by the breakage of sleeve filaments due to cracking, the current study uses wetting events that yield external moisture change to alter the electrical properties of the circuit.

The identification procedure includes the following steps:

Performing reference data at a healthy known state:

1. Measuring the electrical impedance spectrum ($IS^0(x)$) before the wetting event. Note that two set of measurements are taken (from both ends of the yarns), that is from Port-1 and Port-2. The measurements procedure is detailed in [5].
2. Performing a wetting event.
3. Measuring the electrical impedance spectrum after the wetting event ($IS^w(x)$).
4. Exploring changes in the $IS^w(x)$ relative to $IS^0(x)$, which are defined as the impedance spectrum change $ISC(x)= IS^w(x)- IS^0(x)$.
5. Evaluating the minimum peak value of ISC(x), defined as $ISC_{min}=min[ISC(x_{min})]$.
6. Correlating the value of the ISC_{min} to the current cross-sectional state.
7. Detecting the location of the wetting event by exploring the coordinate of the minimum peak value (x_{min}) to its physical location using an adequate corelation function, see [7].

Collecting new data at a new state:

8. Repeating steps 1-7 at the new state.

Comparing between reference and new states:

9. Determining the difference between ISC_{min} of the current state and the reference state, ΔISC_{min}, as the severity of the degradation in the cross-sectional area.

Measurements were carried out using a Keysight P500B Streamline Vector Network Analyzer (9 kHz to 4.5 GHz, 2-port), with a selected frequency range of 300 kHz to 500 MHz for the TDR function.

MATERIAL AND METHOD

TRC elements are constructed by composing a carbon-based textile mesh as the main reinforcement system and Magnesium Phosphate Cement (MPC) as the cementitious matrix. This section outlines the mechanical and electrical properties of the reinforcement system and the matrix, the geometry of the specimens, and its production process.

Carbon-based textile mesh

The study uses textiles composed of carbon and AR-glass yarns. In the longitudinal direction (0°), six carbon yarns are aligned, in the transverse direction (90°) AR-glass yarns are placed. Carbon yarns are used as the smart sensory agent. The use of electrically insulated AR-glass yarns in the transverse direction prevents electrical interference between the sensory carbon yarns. The textile is stitched using a pillar configuration with a warp-knitted grip structure. The mesh size is about 7–8 mm.

The mechanical and electrical properties of the yarns are detailed in [2- 3]. The carbon yarn is electrically characterized as an RL electrical circuit, with properties depending on the yarn's length (x) as follows [2]:

$$R_x = 0.22 + 0.015 \cdot x_{[mm]}\ [\Omega] \quad (1)$$

$$L_x = 826 + 1.54 \cdot x_{[mm]}\ [nH] \quad (2)$$

Cementitious matrix

The study uses a commercial Magnesium Phosphate cement (MPC) matrix, produced by ICL Group Ltd. MPC is a production of acid-based solution, dead burnt magnesia and potassium-based phosphate [3, 8] and is considered as green cement [17]. To enhance the ductility of the matrix, short aramid fibers (AF) were incorporated. The AFs are a commercial product (Technora CF320) manufactured by Teijin Frontier company Ltd. They are 3 mm long and are electrically insulated, further mechanical details can be found in [3]. The fibers were added at a volume fraction of 0.5%. The MPC mix ratio was 1:4 (water to dry material).

The mechanical properties of the MPC with the additive AF are determined according to EN 196-1:2005 at the age of 28 days. The tensile and compression strengths are 13.4 ± 1.07 MPa and 61.91 ± 8.4 MPa, respectively. The electrical properties of the matrix were investigated in [3]. It was found that the MPC matrix is almost an electrically insulated matrix, the measured impedance at 28 days is more than 100 kΩ/m.

Production of carbon-based TRC specimens

The geometric properties of the specimens are: 500 mm long, 50 mm wide and 8 mm thick. A single textile layer is positioned in the middle of the cross-section of the specimen. As seen in Fig. 1.

Local degradation of the thickness is achieved using a Dremel 4250 equipped with a diamond blade, which was used to make notches along the specimens at different positions. The selected zones were isolated as seen in Fig. 2.

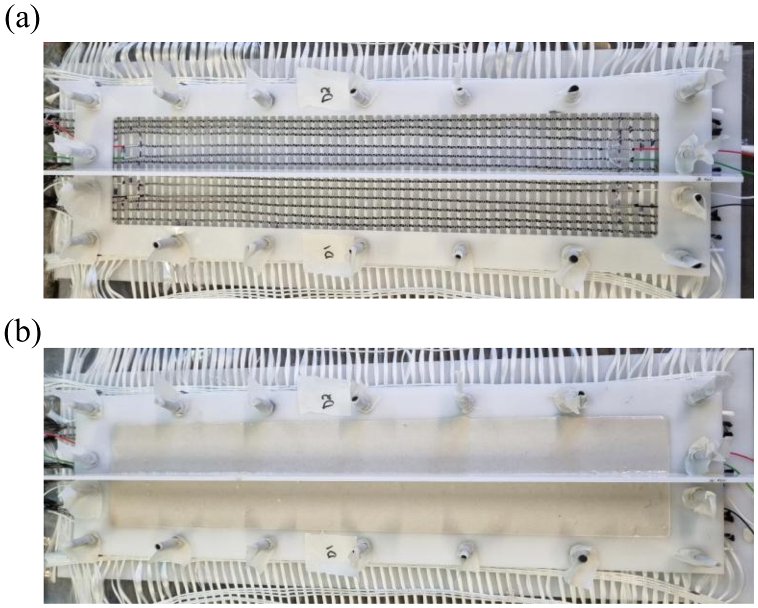

Figure 1. (a) Photo of the textile within the mold; (b) Carbon-based TRC specimens after casting.

(a)

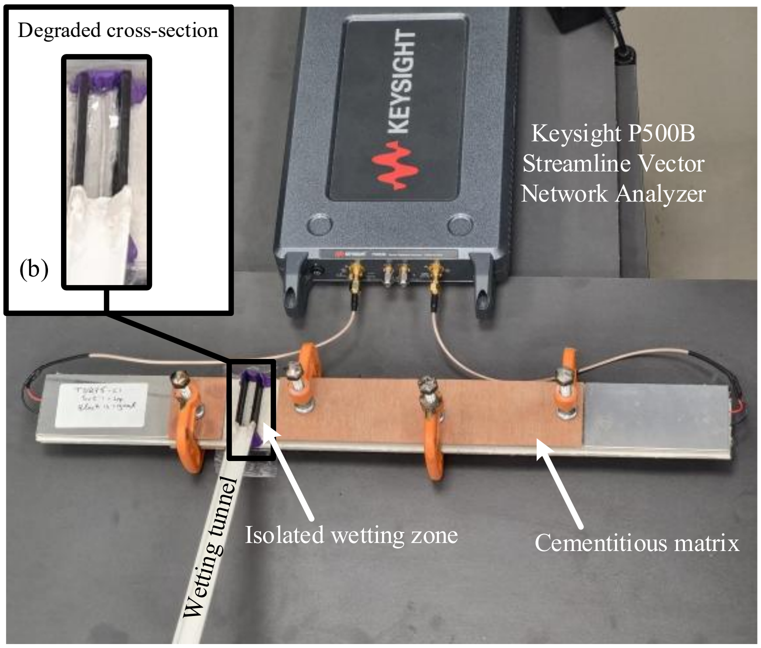

Figure 2. Photos of (a) Wetting setup; (b) Healthy state; (c) Degraded state.

Wetting events

The study uses the smart water leakage detection method [e.g. 11-13]. Fig. 2 describes the wetting setup. Wetting events were performed by wetting the selected zone with 5 ml of water (electrical conductivity of 1200 µS). This procedure was repeated at the healthy and degraded states. At least three wetting cycles (with intervals of about 24 hours) were performed for each state.

RESULTS AND DISCUSSION

Demonstration of the concept is explored on three TRC specimens. Specimen A: notch position at 6 cm. Specimen B: notch position at 12 cm. Specimen C: notch position at 18 cm. Each specimen was wet at two states: healthy (no notch) and degraded cross-section (with notch).

The sensory concept was applied to evaluate the minimum peak impedance value (ISC_{min}), after each wetting event. Fig. 3 presents the values of the minimum impedance of a representative experiment for each specimen. It is clearly seen that the measurements are consistent, indicating the reliability of the electrical measurements.

Table I presents the ISC_{min} values for all specimens in each state and the evaluated ΔISC_{min}. It is seen that in all specimens the values of ISC_{min} at the degraded state are lower than the values of ISC_{min} at the healthy state. It is associated with the rapid moister change that is sensed by the yarns, which is an indication of the degradation of the specimen's cross-section.

The values of the ΔISC_{min} are in range of 9% - 27%. This relatively wide range is due to two main factors: First, the different distance of the various locations from the energy source and its effect on the loss of the electrical signal, see also [5]. Second, the nonconstant depth of notches that were performed manually by a Dremel cutting device. Nevertheless, the monitoring system successfully monitored the cross-sectional degradation in the specimens. Furthermore, the locations, calculated by correlation x_{min} to actual location, were accurately evaluated from both ends of the specimens as seen in Table I.

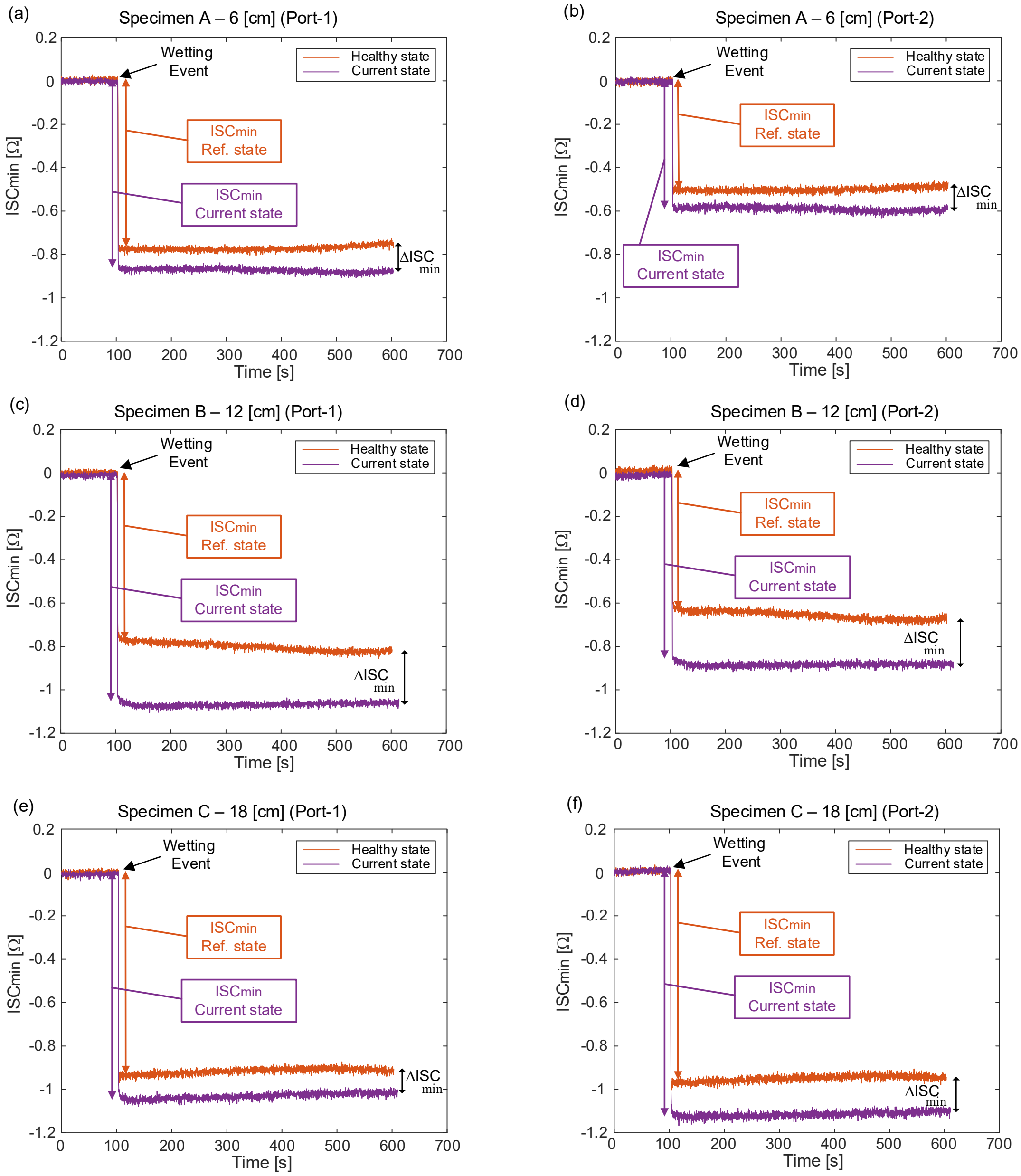

Figure 3. ISC_{min} values over time for healthy and current states: (a) Specimen A – Port-1; (b) Specimen A – Port-2; (c) Specimen B – Port-1; (d) Specimen B – Port-2; (e) Specimen C – Port-1; (f) Specimen C – Port-2.

Table I. Summary of the wetting events

		Specimen A		**Specimen B**		**Specimen C**	
		Port-1	**Port-2**	**Port-1**	**Port-2**	**Port-1**	**Port-2**
ISC_{min} values [Ω]	Healthy #1	-0.7629	-0.5013	-0.7271	-0.5901	-0.9154	-0.9494
	Healthy #2	-0.7713	-0.4997	-0.7848	-0.6464	-0.9445	-0.9972
	Healthy #3	-0.7560	-0.4739	-0.8012	-0.6558	-0.8931	-0.9510
	Healthy avg.	**-0.7634**	**-0.4916**	**-0.7710**	**-0.6308**	**-0.9177**	**-0.9659**
	Current state #1	-0.8726	-0.5898	-0.8861	-0.7028	-1.0074	-1.0892
	Current state #2	-0.8896	-0.5803	-1.0008	-0.8177	-0.9558	-0.9776
	Current state #3	-0.8219	-0.5609	-1.0669	-0.8834	-1.0301	-1.1143
	Current state avg.	**-0.8614**	**-0.5770**	**-0.9846**	**-0.8013**	**-0.9978**	**-1.0604**
ΔISC_{min} [%]		**12.83**	**17.36**	**27.69**	**27.02**	**8.72**	**9.78**
Physical location by x_{min} [cm]		**5.7**	**7.2**	**11.4**	**13.0**	**13.2**	**19.4**
Exact location [cm]		6	6	12	12	18	18

SUMMARY AND CONCLUSIONS

This paper presented a preliminary demonstration of the potential of using carbon yarns as smart sensors to detect cross-sectional degradation in TRC specimens. It was achieved by combining the Time Domain Reflectometry (TDR) approach and the smart water leakage detection method. The trigger of the sensory concept was achieved by changing the external moisture enabling changes in the electrical impedance measurements.

Three specimens were wet at the healthy and degraded states, and the identification procedure was applied to estimate the cross-sectional degradation. It was demonstrated that the sensory system successfully distinguished the degraded cross-section state and accurately located the wetting zone from both ports.

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