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Sensing capabilities of carbon based TRC beam from slack to pull-out mechanism

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ABSTRACT

The paper explores the sensing capabilities of a carbon based textile reinforced concrete (TRC) composite element to monitor its structural mechanisms. The concept is based on continuous carbon rovings knitted into glass textile mesh that simultaneously serve as the structural reinforcement and as the sensory system. The loading procedures which starts from a healthy state, to micro and macro cracked state, and ends with a completely pull-out of the tensioned rovings is strongly affected by the micro-structural mechanism of the carbon rovings within the concrete matrix. It is found that the measured electrical resistance is characterized by this mechanism and can reflect the structural condition. Therefore, it can serve as a structural health monitoring system. The paper demonstrates these sensing capabilities along the entire range of the loading procedure, even up to progressive failure mechanism, where traditional sensing devices usually failed to produce meaningful information.

1. Introduction

Hybrid textile reinforced concrete (TRC) composite structures combine the advantages of high performance material and structural systems with those of integrated monitoring system. The technology is based on a textile net made of continuous fiber rovings (glass and carbon), which are embedded within the concrete structures, and serve two purposes simultaneously, reinforcement and monitoring. The textile reinforcement can easily follow a curved geometry of the structure, and due to the superior corrosion resistance of the reinforcement material, minimum concrete coverage is needed. Therefore, it is possible to produce thin walled TRC composite structures that can be used in various applications such as pipes, tanks and shell like structures (Silva et al. [1], Shames et al. [2]). These advantages can be greatly advanced by integrating monitoring functionalities within the existing reinforcement textile. Traditional sensing systems can be implemented to the structure externally, either by strain gauges, or even internally within the textile, such as optical fibers (Montanini et al. [3], Krebber et al. [4]). However, when severe damage or failure occurs such sensing systems are usually damaged as well. On the other hand, the hybrid carbon rovings have the capabilities to function even when progressive damage or structural failure occurs. The goal of this study is to investigate the sensing capabilities of the carbon rovings up to complete structural failure. Opposed to (Goldfeld et al. [5,6]) which focused on the sensing capabilities of the carbon based TRC structures during its designed service life, the current study aims to explore its sensing capabilities up to complete failure. Specifically, we aim to prove that the measured electrical signal is stable and sensitive from the very initial loading phases and up to failure. The hypothesis is that micro and macro structural mechanism can be reflected and characterized by the electrical resistance measured by the carbon rovings.

The structural mechanism of TRC composite structures is completely different than the structural mechanism of reinforced concrete structural elements with traditional steel re-bars. In the case of reinforcement with steel re-bars, the cross sectional area as well as the steel strength are not affected by cracks. However, in the case of TRC structures, since the reinforcement rovings are made of thousands of filaments, the bonding mechanism between the rovings and the concrete matrix plays a significant role in the load carrying capacity of the roving and as a result of the element. In the latter case, due to the mechanism of the bonding between the concrete and the filaments within the roving, the filaments of the roving that are located along the interface with the concrete (called the sleeve filaments, Bartos, [7]) break and only a reduced number of filaments, that are located at the core of the roving, can further carry on the loading (see for example, Bentur et al. [8], Yardimci et al. [9], Shilang et al. [10]). Therefore, an adequate design allows

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only distributing multiple micro-cracks along the structures. Moreover, for the case of TRC structures, along the very beginning phase of the loading process, the structural response of the TRC structures is characterized by a unique response, which is attributed to the self-organization of the roving within the concrete matrix defined as the "slack", Soranakom and Mobasher [11,12]. Slack is incorporated into a yarn stress-strain relationship by adding a slight initial delay response prior the beginning of the elastic part. The failure mechanism of the TRC structures is also different. For the case of conventional reinforced concrete structures, loading beyond its ultimate capacity leads to crushing of the compressed concrete and eventually to yielding of the tensioned steel re-bars. While for the case of TRC structure, after the crushing of the compressed part of the cross-section the tensioned carbon roving continues to carry the load by the inner core filaments, and the failure at the cracked zone is characterized by pull-out mechanism (Banholzer, [13], Banholzer et al. [14], Hartig et al., [15], Hegger et al. [16]).

Obviously, the unique micro-structural mechanism of the TRC composite elements influences its macro-structural response. The hypothesis of this study claims that these unique responses can be sensed by the measured electrical resistance of the carbon rovings.

The structural sensing capabilities of continuous carbon rovings embedded in a concrete element have been investigated in the literature first by Wen and Chung [17] and Wen et al. [18], and recently by Goldfeld et al. [5,6]. These studies demonstrated that the measured electrical resistance of the carbon rovings can be successfully correlated to the structural condition. However, they focused on the correlation between internal microstructural phenomena, such as the degradation of the interface between the fiber and the concrete matrix, and the measured resistance along limited spectrum of the structural response. They focused on the electro-mechanical response along the linear-elastic regime of the structure which characterized by microstructural phenomena and is considered as a strain sensing. Advanced sensing capabilities which extends beyond the aforementioned sensing capabilities have not been investigated and is a crucial sensing aspect of TRC composite structures. The goal of the current study is therefore to thoroughly investigate and correlate between the structural and the electrical behaviors of a TRC element along a wide spectrum of the micro- and macro-structural mechanisms; starting from the very beginning response of the TRC beam characterized by slack, to the linear elastic regime, the formation of multiple distributed micro-cracks, opening of one major crack, crushing of the concrete and ending with pullout-slip response of the tensed carbon rovings. Investigating the sensing capabilities along the entire spectrum is important for the understanding of the electro-mechanical mechanism of TRC structures.

The hypothesis of this study claims that the micro-structural process generates electrical response and therefore the measured electrical response of the continuous carbon rovings can be correlated with the micro-structural process and thus reflect the structural condition. In order to achieve the goals of the current study and prove its hypothesis, the study experimentally investigates the correlation between the micro-macro- structural and the electrical responses of TRC composite beam under monotonic flexural loading up to structural failure mechanism.

2. Experimental investigation

The investigation is based on monotonic loading test of a TRC composite beam sample. It aims to investigate the micro and macro structural response as reflected by the measured electrical response. Specifically, it aims to explore the correlation between the structural and the electrical response by investigating the sensing capability of carbon rovings along the entire loading process. Starting with the very beginning response of the TRC beam characterized by the slack, to the linear elastic regime, the formation of distributed micro-cracks, opening of one major crack and ending with pullout-slip response of the carbon rovings. The properties of the sensory textile, the beam samples, the sensing concept and the testing scheme are presented next. The procedure for the compensation for the effect of temperature on the sensing system is also discussed.

2.1. Sensory textiles

The sensory textile is based on two types of rovings: rovings made of glass fibers and rovings made of carbon fibers [5]. The glass rovings are the main reinforcement platform. The carbon rovings are also part of the main reinforcement and they are used as the sensory agent. The material properties of the glass and the carbon rovings are given in Table 1.

The reinforcing textile is a warp knitted grid structure with a mesh size of 7–8 mm (see Ref. [5] for more details). The carbon rovings have been inserted in the warp knitting process as warp yarns by replacing some of the glass rovings. In the weft direction, only glass fiber rovings are used. This configuration, which limits the sensing capability to a unidirectional one, avoids potential electrical linking between one longitudinal carbon roving and the other. The reinforcing rovings are knitted with warp-knitting yarns made of polypropylene. The stitch type of the warp knit is pillar. The production of the glass/carbon textile uses a conventional process that does not involve any modifications in terms of tribology or tension control of the rovings. This is achieved by selecting fiber materials that are suitable to be used in such standard process and it demonstrates that the production of the sensory textile does not involve cost-intensive modifications.

The textiles were installed with no specific or special treatment. The carbon filaments were surface treated during their production process. Their surface is slightly oxidized in order to provide better chemical bonding properties. The process also etches and roughens the surface in order to achieve better mechanical bonding properties. In the production process, sizing with 1% weight ratio was used. After the textile production of warp knitting, the carbon fabric was not coated with any additional polymer. Special treatment such as epoxy impregnation can improve the mechanical behavior (Shilang et al. [10], Kruger et al. [19], Qinghua and Shilang [20]). The concrete matrix was not modified with any electrical conductive compound and therefore it serves as isolating dielectric.

The electrical integration of the rovings of carbon fibers into the data acquisition (DAQ) system uses un-insulated wire ferrules that were threaded through the carbon rovings and were crimped using crimping tools. The connectors were installed at the ends of each carbon roving and they were embedded into the concrete while casting the beam. Picture of the textile within the mold before the casting is given in Fig. 1a. Therefore, only the electrical wires have been extracted from the concrete beam. This electrical con-

Table 1
material properties of the glass and the carbon rovings.

	Glass roving	Carbon roving
Specific mass density [kg/m^3]	2680	1800
Modulus of elasticity [GPa]	72	240
Filament Tensile strength [MPa]	1700 (elongation 2.4%)	4000 (elongation 1.7%)
Filament diameter	19 μm	7 μm.
Filament count		50,000
Electrical resistance [Ω/m]	Infinity	13