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Enhancements in Bond in Textile Reinforced Concrete: Experiments and Modeling

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Abstract

Textile reinforced concrete (TRC) has been subject to intense R&D effort, as it known to improve the brittle tensile properties of the concrete. The bond between the textile bundle and the cement matrix is a crucial factor that control TRC elements performance. Unfortunately, methods to improve the bond between textile fabrics and a concrete matrix are limited. This paper evaluates techniques to improve bond in TRC systems through a multi-scale approach using experimental and numerical methods. Specifically, the pullout behavior of textile fabrics within a cementitious matrix through various treatment mechanism is evaluated. Then the direct tension response of the composite TRC systems is evaluated across treatment mechanisms. Three-dimensional nonlinear finite element models are used to simulate experimental behavior and understand how treatment mechanisms influence local pullout response, crack opening in direct tension, and strain distribution.

Keywords

Textile, Fabric, Textile-reinforced concrete, Pull-out, Tensile, Numerical model

Introduction

TRC materials have been developed with the goal of enhancing mechanical and durability performance of cementitious materials [1-6]. The use of textile fabrics modifies the brittle mechanical behavior of cementitious matrix into a ductile system with enhanced tensile characteristics such as strength, strain capacity, and damage resistance. The use of TRC provides an alternative reinforcing mechanism to traditional steel-reinforced concrete which suffers durability issues such as corrosion. Structural performance of conventional reinforced concrete elements with steel reinforcement can be enhanced with carbon-based textiles which are flexible, have a high strength-to-weight ratio, and have excellent durability and mechanical properties [7-11]. TRC materials also have smaller section sizes which lowers volumetric quantities of cementitious materials needed in a structural element [12]. Possible applications of TRC could include repair and strengthening structural concrete elements, and building slender, lightweight, modular, and free-form structures.

A textile carbon yarn is made up of hundreds to thousands of filaments. The filaments are spaced closely together and the spacing between each filament can be smaller than an individual cement particle. As a result, hydrated cement particles have difficulty penetrating within this space, lowering the bond strength between the matrix and the yarn [11, 13]. Consequently, the internal filaments do not come into contact with cementitious matrix; however, the outer filaments do. Therefore, the bond between the textile yarn and the cementitious is entirely developed through the external surface of the yarn [14, 15]. This limits the bonding and consequently the reinforcement efficiency of the TRC mechanical properties. The remedy lies in filling the bundle spaces with a polymer (epoxy for example), thus facilitating full utilization of all filaments within the yarn during loading. Nevertheless, the interfacial bonding between the hydrophilic cementitious matrix and hydrophobic epoxy coating is rather weak, which can lead to severe delamination between them, an undesired phenomenon especially when structural concrete elements are considered.

This study investigates the use of enhancing the bond between the textile fabric and cementitious matrices through the use of cementitious and supplementary cementitious materials. Specifically, a series of specimens were tested and simulated by applying silica fume (SF) on the yarn surface in various mechanisms. Additionally, a series of pull-out experiments were simulated and compared to results previously published whereby yarn was treated with cement [16]. The results of the experiments and simulations show improvements in key mechanical properties and cracking patterns by changing the interfacial behavior.

Materials and Method

A fine-grained concrete was used for the matrix (Table 1). The textile fabric used in this study is two-dimensional (2D) biaxial weft insertion warp knitted carbon fabric with opening of 4 x 4 mm (The Institute of Textile Technology of RWTH Aachen University (ITA), Germany). The yarns along the warp (lengthwise) and the weft (crosswise) directions were composed of multifilament carbon of 800 tex held together with a stitched polyester yarn in tricot pattern. The carbon yarn tensile strength was 1722 MPa, modulus of elasticity of 203 GPa with a cross section of 0.452 mm^2.

The direction of the reinforcement was along the warp yarns. For TRC preparation, the carbon-based textile sheet was first brush-coated by epoxy resin on both faces of the textile sheet. Manual pressure (roller) was applied to the textile to facilitate optimal epoxy penetration between the filaments. SF decoration was then immediately carried out by sprinkling the particles on both faces of the wet epoxy-impregnated textile sheet. The decorated textile was cured at room temperature for (24 h, 60% relative humidity). The TRC composite was prepared by pouring the fine-grained concrete on top of the textile sheet, fixed in the middle of a mold, until complete filling. Vibration was applied during this process to allow optional concrete penetration in between the textile gaps. A composite material plate of 0.3 x 0.3 x 0.02 m^3 was with a single fabric layer at the middle was obtained. It was demolded after 24 h aging and cured in tap water for 7 days, followed by 21 days in either saturated NaCl solution or tap water, at room temperature. At the age of 29 days, the plate was cut to five samples of 0.3 x 0.05 x 0.02 m^3, five reinforcing yarns at each sample. The samples were then dried at room temperature for 24 h, until testing under tension.

Table 1: Fine-grained concrete mixes design.

Mixed materials (kg/m³)					% SP by cement weight	W/C
Cement	Sand	SF	Water	Superplasticizer		
434	795	87	173	13.0	3.0	0.40

The tensile behavior of the TRC samples was conducted with Instron 5982 instrument with a load cell capacity of 100 kN equipped with clamps owing a maximum load capacity of 15 kN and controlled by Bluehill 3 software (Bluehill®). The clamps were tightened using a torque wrench to ensure a uniform force onto the samples. The experiment was performed with a displacement rate of 0.005 m/min.

Results and Discussion

The tensile behavior of the TRC systems (Ref and SF) is presented in figure 1 [17]. The figure demonstrating enhanced tensile behavior of the silica-coated system (SF) compared to the Ref. Comparing the stress developed at the first crack of the two systems showed high first crack stress value for the SF system (~1480 MPa) compared to the Ref system (~510 MPa) attesting of high bond strength between the textile and the matrix. The improved bond strength (calculated by the ACK model) enhanced the bond strength values by 122%, emphasizing the advantage of coating the textile with SF particles. The SF particles at the textile-matrix interface generate a pozzolanic reaction between the textile and the cement-based matrix leading to the improved bonding [11].

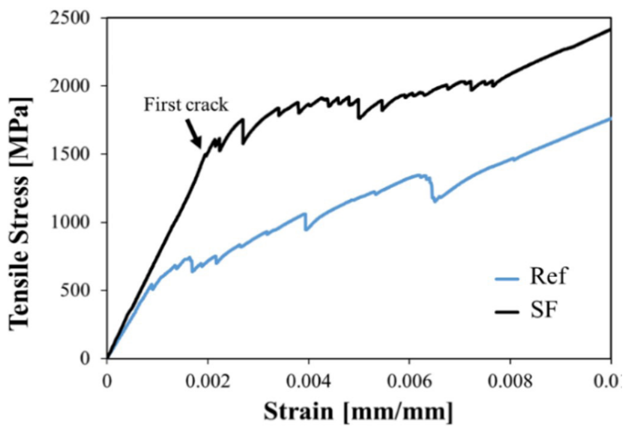

Figure 1: Tensile response of TRC with SF decoration on the textile surface as compared to a Ref TRC without any surface decoration [17].

Overview and geometry of computational models

Two physical experiments were simulated as part of this work: (1) a pull-out experiment, and (2) a direct tension experiment. The experiments were modeled using DIANA FEA [18]. Modeling input parameters were chosen to simulate the conditions of the physical experiments.

The geometry of the pull-out experiment is shown in figure 2a and is meant to mimic previously published research by one of the authors [16]. The rectangular hexahedron specimen had side lengths of 20 mm x 20 mm x 10 mm. The specimen was meshed with 8-noded 2.5 mm x 2.5 mm x 2.5 mm solid brick elements and assigned material properties of

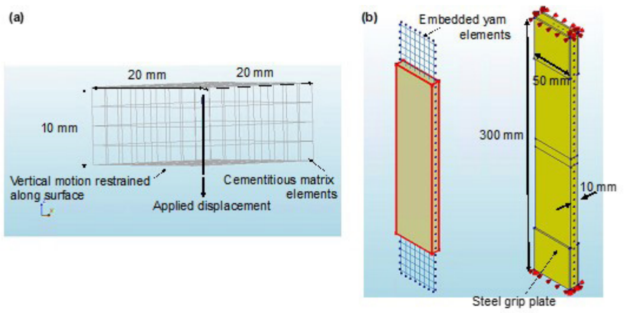

Figure 2: Computational geometry for **(a)** pull-out experiment and **(b)** tension experiment.

cementitious matrix, described in the next section. The yarn was simulated using 2.5 mm long 2D beam elements with a line-solid interface used to connect the fabric to the cementitious material. The fabric was centered in the 20 mm x 20 mm surface. The fabric was extended 5 mm beyond the exterior face of the hexahedron specimen where a displacement-based load was applied in 0.001 mm increments. The bottom surface of the hexahedron was restrained in the vertical direction at all nodes and restrained against movement in the two perpendicular directions at one corner node.

The geometry of the tension experiment is shown in figure 2b. The overall dimensions were 10 mm x 50 mm x 300 mm. The specimen was meshed with 8-noded solid brick elements that were 10 mm x 10 mm x 10 mm x 10 mm in size. The yarn bundle was simulated with embedded reinforcement elements with bond-slip behavior defined by interface characteristics obtained through the pull-out experiments. The yarn was simulated with a cross-sectional area of 0.462 mm^2 at a spacing of 4 mm in the longitudinal direction and 6 mm in the transverse direction. A 50 mm square aluminum plate with a thickness of 2 mm was incorporated at the bottom and top of the specimen to prevent localized damage of the cementitious material. A displacement-based load with a 0.01 mm increment was applied at the top surface. Deformation was restrained to prevent out-of-plane movement.

Material models

The cementitious matrices in both geometries were simulated using a series of nonlinear material models. In tension, a total strain based fixed crack model was used with exponential softening based on fracture energy. The tensile strength of the model was assumed to be 3 MPa and the first mode fracture energy was assumed to be 0.05 MPa-mm. Compression was simulated using a parabolic softening model with a compressive strength of 45 MPa and a compressive fracture energy of 5 MPa-mm. The elastic modulus of the cementitious matrix was taken as 23 GPa with a Poisson's ratio of 0.2. The yarn reinforcement was simulated as an elastic material with a modulus of 200 GPa. The aluminum plate was simulated as an elastic material with a modulus of 70 GPa.

The interface was assigned a nonlinear response using a bond-slip interface failure model that is traditionally used to simulate the interface behavior between concrete and reinforcing steel. The interface was simulated in terms of interfacial shear stress vs. slip between the yarn reinforcement and cementitious matrix. The stress-slip curve consisted of five branches: (1) an initial ascending linear elastic response with high stiffness, (2) a second an ascending response with a lower stiffness compared to the first branch; (3) a constant stress with increasing slip branch that was used to simulate peak strength; (4) a descending stress with increasing slip branch to simulate loss of interfacial strength; and (5) a branch of constant stress to simulate residual strength. Input parameters to describe this interface behavior are described in the next section.

Pull-out simulation results

The pull-out experiments were simulated through a procedure in which key the interface stress-slip response fits the experimental results [16]. In this procedure, maximum shear stress, residual shear stress, and key relative slip values were assumed, and values were iterated such that experimental and simulation pull-out responses matched. The pull-out force vs. displacement curves is shown in figure 3 for the experiments and simulations. The pull-out response of a Ref yarn, and a yarn in which cement powder was placed in a fresh and gelated state are shown for Ref.

As can be seen, the simulation captures the overall shape of the pull-out curve well, including initial stiffness, pull-out force, and residual strength. Through iterative inverse analysis, the model is also able to capture changes that occur in the pull-out response caused through the use of the cementitious powder placed in various states following the results of Alatawna et al. [16].

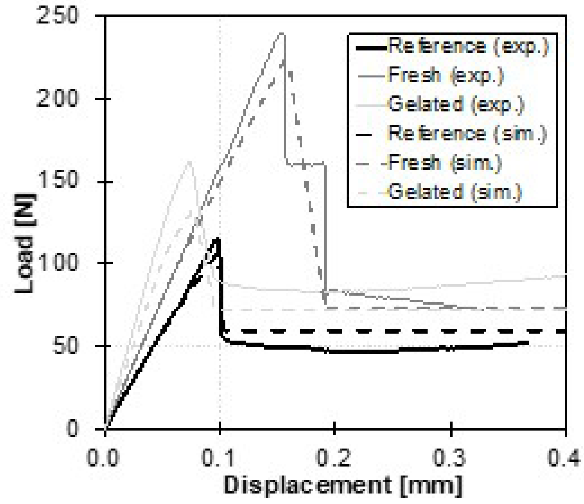

Figure 3: Pull-out force vs. displacement of experiments and simulations.

Direct tension simulation results

Direct tension experiments were simulated for specimens with the various treatment mechanisms by changing interface properties between the embedded textile reinforcement and the cementitious matrix. Figure 4 shows contours of tensile strain, representing simulated cracking development in the TRC systems with varying interface properties based on the results reported in figure 3. As shown in figure 4, varying amounts of cracking could be simulated by changing interface properties between the embedded textile reinforcement and

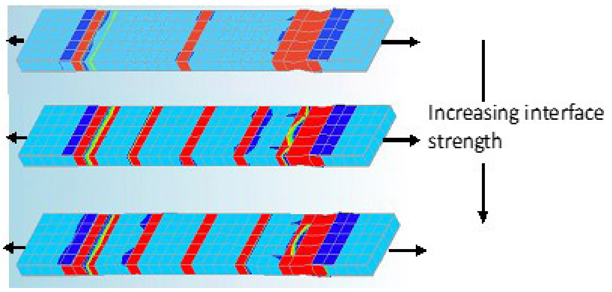

Figure 4: Pull-out force vs. displacement of experiments and simulations.

the cementitious matrix, as was observed in the experiments following Zamir et al. [11] and Alatawna et al. [17]. The results confirm experimental observations that changes to interface properties influence cracking development in the textile reinforced systems.

Conclusion

This study investigated the use of SF to improve the bond between a textile fabric and a cementitious matrix. SF was applied to the wet-epoxy impregnated textile sheet and cured for 24 h in a 60% relative humidity environment. When SF was applied, a three-fold increase in first-cracking strength was observed, indicating the positive influence the SF treatment has on the bond between the fabric and cementitious matrix. Numerical simulations were also carried out to predict behavior of treated TRC systems through simulation of pullout experiments and direct tension experiments. An inverse analysis procedure was completed to predict the pull-out response with various treatment mechanisms. Direct tension results showed that more cracks could be developed by increasing the interface strength. The results of this study are being used to further enhance the mechanical properties of TRC materials with additional numerical and analytical work underway. Further development of the numerical simulation to predict TRC tensile performance based on textile-matrix bonding is required in addition to deep understanding of yarn-matrix interface microstructure.

Acknowledgments

None.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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