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Pull-out of textile reinforcement in concrete

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HIGHLIGHTS

- Pull-out tests of TRC to gain better knowledge of the complex bond behaviour.
- Local-bond slip relationship evaluated from experimental data.
- 1D and 3D numerical models to simulate complex global bond behaviour.
- 3D models validated the simplified assumptions applied in the 1D model.

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ABSTRACT

Textile Reinforced Concrete (TRC) has emerged as a promising novel alternative offering corrosion resistance and both thinner and light-weight structures. Although TRC has been extensively researched, the formalization of experimental methods and design standards is still in progress. The aim of this work was to extract local-bond behaviour from pull-out tests of basalt and carbon TRC and utilize these in both simple (1D) and advanced models (3D) to yield the global structural behaviour. The simulation results from the 1D and 3D models are able to simulate the complex behaviour of TRC with a reasonable level of correlation.

1. Introduction

A recent innovative attempt to improve the sustainability of reinforced concrete is the development of Textile Reinforced Concrete (TRC) encompassing a fine-grained concrete matrix reinforced by a multi-axial non-corrosive textile mesh. This relatively new composite material has been extensively researched at collaborative research centres 532 and 528 at RWTH Aachen University and Dresden University of Technology [1] over the past decade. Collaborative efforts spreading across USA, Germany, Brazil and Israel have also played a major role in this field [2]. It was discovered that TRC can be utilized to build slender, lightweight, modular and freeform structures and eliminate the risk of corrosion. The completion of a pedestrian bridge fabricated solely of TRC [3] and the development of thin self-supporting TRC sandwich elements [4] are examples of the possible realizations. It was also proven to be an adequate strengthening material for existing reinforced concrete structures in a variety of applications [5,6]. To sum up, a report entitled RILEM TC 232-TDT encompassing test methods and design of Textile Reinforced Concrete, in progress since 2009, has been compiled, however is not yet available for public use [7]. The purpose of this particular report is to provide guidelines for testing methods, a design manual and an update of the TRC state-of-the-art report [8].

In fibre composite materials, such as TRC, bond behaviour between the yarn or roving and the cementitious matrix is a principal factor influencing the global structural behaviour [9]. Yarns or rovings consist of multitudes of filaments which creates a complex heterogeneous structure. For that reason, the characterization of the bond behaviour is critical in terms of input for numerical models analysing the structural behaviour of TRC. Pull-out testing is a typical method utilized to gain understanding of bond phenomenon related to reinforced concrete. Since the lack of standards in this field, testing methods and numerical methods to evaluate the pull-out behaviour of yarns or rovings in TRC used in similar

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research need to be explored and considered. Bond properties of TRC have been investigated using various textile pull-out test configurations while focusing on differing textile meshes and influential parameters by Krüger [10], Xu and Li [11], Sueki et al. [12], Ortlepp et al. [13], Lorenz and Ortlepp [14] and Zhang et al. [15]. For instance, in [12], a parametric study of varying embedment lengths, textile meshes and cement mix types as well as processing methods were incorporated. Specimens reinforced by alkali-resistant (AR) glass, polypropylene and polyvinyl acetate meshes were prepared using casting, pultrusion or vacuum techniques. Successively, the use of analytical methods followed the experiments of the abovementioned works such that the experimental pull-out behaviour of a single continuous yarn from a matrix was described analytically using closed form equations [9,12,14–16]. Various damage models such as a triple linear shear-stress slip model have been assumed to characterize the yarn pull-out behaviour incorporating both adhesion and frictional load transfer [9,16]. In brief, experimental results from pull-out tests appear to successfully verify the developed analytical and numerical models [9,12,14–16].

Direct pull-out tests are included in this research to characterize the complex pull-out behaviour of a textile mesh-structure embedded in a concrete matrix with a particular focus on basalt and carbon TRC. More specifically, the pull-out of a single roving from the textile mesh was carried out which resulted in a representative smeared pull-out behaviour of the embedded mesh structure. Varying embedment lengths were used to quantify bond capacity and textile rupture failure modes. Based on the experimental results, a local bond stress–slip curve was obtained. Thereafter, the calibrated local behaviour was used as material input data in two numerical models to simulate the global behaviour experienced by the pull-out specimens. An analytical 1D bond model originally developed by Lundgren et al. [17] to analyse the bond stress–slip behaviour of corroded ribbed steel reinforcement was modified for textile reinforcement. Also, in the 1D model, a stepwise calculation and superposition is needed to obtain the bond stress–slip behaviour for the entire pull-out specimen. Moreover, a 3D non-linear finite element model of the conducted pull-out tests was developed and used to validate the assumptions related to the simplest 1D bond model. Using simplified models to study bond capacity of TRC concrete is necessary to better understand complex structural behaviour.

2. Experimental study

The presented work is a part of a larger experimental scope, primarily conducted at the Danish Technological Institute (DTI) and evaluated at Chalmers, which encompassed flexural and pull-out tests of TRC. The experimental work presented here focuses on direct pull-out tests of TRC specimens reinforced by basalt and carbon meshes having the underlying purpose to characterize the corresponding bond phenomenon. The mechanical properties of the cementitious matrix were also obtained through compressive and tensile splitting tests.

2.1. Pull-out testing

At present, no standard test setup to investigate the pull-out behaviour of TRC is available; as such, relevant experimental work from literature was revealed to help establish an experimental setup. The main types of test configurations known from literature include one-sided and double-sided pull-out tests. For example, one-sided tests were conducted by Banholzer [18], wherein single yarns were embedded in a concrete matrix at one end and in an epoxy resin block at the other. This type of test is, however, said to yield a behaviour that is incomparable of that of a textile mesh [14]. As for two-sided tests, either symmetrical [19] or unsymmetrical anchoring lengths [10] can be implemented. The benefit of using unsymmetrical anchoring lengths is that a longer length guaranteeing adequate anchoring of the yarn/roving can be incorporated into the setup [14].

The pull-out test setup and specimen configuration employed in this work was designed based on the double-sided unsymmetrical test by Krüger [10] and Lorenz and Ortlepp [14]. The pull-out test specimens used in the presented experimental work measured 400 × 100 × 15 mm and reinforced by one layer of reinforcement mesh. Unsymmetrical anchorage lengths, denoted A and B in Fig. 1, were defined for each specimen. A singular roving from the textile mesh was exclusively tested from the TRC specimen in order to yield representative smeared pull-out behaviour. The embedment length chosen was generally based on the distance of the cross-threads, specified as *Short* (35 mm), *Medium* (70 mm) and *Long* (87.5 mm) for basalt and *Short* (25 mm), *Medium* (50 mm) and *Long* (75 mm) for carbon. The prescribed embedded length was limited to the upper end of the specimen by means of a single saw cut crossing the roving to be tested and a breaking point marked by two saw cuts isolating the examined roving. The breaking point does not designate the definitive breaking point of the roving in itself, but rather the location of crack initiation.

The pull-out tests encompassed the evaluation of varying embedment lengths in order to characterize both pull-out and rupture of the textile roving as failure modes. Up to three specimens were produced for each selected embedment length in order to obtain a representative trend of the pull-out behaviour. The pull-out test specimens were configured such that the rovings along the pull-out direction later shown in Fig. 3 were positioned in the direction of the machine pull-out force (see Fig. 2). The layer of textile mesh was fastened by the framework used to cast the specimens causing the mesh to become slightly taut yet not pre-stressed which could have slightly reduced the initial waviness of the mesh. As per [1], pre-stressed TRC members exhibit higher peak loads at the expense of lower slip and a more brittle behaviour.

The experimental setup developed to conduct the pull-out tests is illustrated in Fig. 2. The load was applied by a hydraulic jack on top of the rigid frame structure. On top of the hydraulic jack, a 25 kN load cell was placed in order to measure the load. The ends of the test specimen were affixed by two wood clamps which were used to transfer the load to the specimen. The load was transferred symmetrically to the wood clamps by means of steel rods on both sides of the specimen which were further linked to connections fixed to the rigid frame structure. The total specimen deformation, i.e. crack-opening relationship at the breaking point, of the test specimen was measured using two linear variable displacement transducers (LVDT) positioned on either side of the centre of the specimen. Load and deformations were measured and stored every second by means of a data logger.

2.2. Material description

The pull-out test specimens were fabricated of a fine-grained concrete matrix according to the mix composition stated in Table 1. The mean concrete cylinder compressive strength corresponding to 28 days, f_{cm}, was derived from material test results to be 53.6 MPa. Based on f_{cm}, the mean modulus of elasticity, E_{cm}, was estimated to be 36.4 GPa using CEN [20]. Lastly, the mean value of the tensile splitting strength tests was found to be 4.7 MPa.

Two different types of textile meshes fabricated of carbon and basalt were included in this study. The carbon mesh used was produced by SGL group (Germany) is SIGRATEX grid 300 with a mesh spacing of 30 × 30 mm with roving fineness of 1600 tex. Lastly, Geo-grid mesh (Zhejiang GBF, China) fabricated of basalt with silane sizing. It has a configuration of 25 × 25 mm with a roving fineness of 2000 tex. The geometry, configuration of the cross-threads and pull-out direction pertaining to these textile meshes are depicted in Fig. 3. As well, corresponding nominal material properties from the manufacturers are listed in Table 2.

2.3. Result summary

2.3.1. Basalt

The force versus total deformation trend corresponding to the basalt specimens for all embedment lengths are described in Fig. 4. The total displacement corresponds to the mean displacement recorded by the two LVDTs for the entire specimen. In Fig. 4, it is observed that as the embedment length increases, the maximum force increases and occurs at a larger deformation. A pull-out failure mode was solely yielded for *Short* specimens, while rupture was the common failure mode for both *Medium* and *Long* specimens. In the case of pull-out failure, the pre-peak bond behaviour is governed by adhesive bond which is followed by the destruction of the adhesive bond occurring due to debonding of the roving from the matrix. Lastly, the remaining pull-out force is based on friction, as described in [16]. As can be seen in Fig. 4, there was, however, especially for the tests with embedment length 87.5 mm, a rather long plateau with roughly constant load, before a sudden loss of capacity at rupture of the textile roving.

The average maximum force corresponding to *Short* specimens was 721 N ($\sigma = 79$), 1423 N ($\sigma = 63$) for *Medium* and 1662 N ($\sigma = 139$) for *Long*. Causes of variability in the results are presumed to be: uneven bond penetration through cross-section of roving, potential bond irregularities along embedment length (weak zones), human error in sample preparation as well as limited experimental sample size.

2.3.2. Carbon

Fig. 5 depicts the force versus total deformation trend for the carbon specimens for all embedment lengths. Similarly to basalt, the maximum force increases and the related deformation also slightly increases as the embedment length gets larger. The maximum force corresponding to *Short* specimens was 629 N ($\sigma = 32$), 1050 N