Evaluation of pull-out behaviour in textile reinforced concrete

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Abstract

Concrete reinforced with conventional steel is one of the most commonly used building materials, yet it has historically shown disadvantages in terms of durability and vulnerability to corrosion attack. Various remedial methods have been applied to overcome the shortcomings of this building material, such as increasing the concrete cover, which, however, leads to an increased self-weight of the structure. Over the past decade, Textile Reinforced Concrete (TRC), encompassing a combination of fine-grained concrete and non-corrosive multi-axial textile fabrics, has emerged as a promising novel alternative offering corrosion resistance, as well as thinner and light-weight structures such as foot bridges and façade elements. Although TRC has been extensively researched, the formalization of experimental methods and design standards is still in progress.

The aim of this paper is to quantify and model the bond behaviour of TRC basalt fibre meshes. The bond between the textile fibre mesh and fine-grained concrete matrix is a critical element influencing the overall performance of this composite material. The yarn structure is rather complex including a multitude of outer and inner filaments; thus inevitably, the constituents of one yarn are unevenly bonded to the concrete matrix. As such, experiments help quantify complex material behaviour which can be further used to develop and calibrate analytical and non-linear finite-element models.

The bond behaviour of TRC was characterized through means of direct pull-out tests with unsymmetrical embedment lengths such that the test specimens were notched at a prescribed breaking point. The test specimens consisted of one-layer of reinforcement mesh, centrally cast, made of basalt fibres. The applied force and average deformation of the test specimen were measured. The evaluation of varying embedment lengths was explored in order to quantify pull-out and textile rupture failure modes. The experimental results were thereafter evaluated using an analytical 1D bond model. Pull-out and rupture failure were observed in the experimental pull-out results. A local bond stress-slip curve was calibrated for the basalt specimens based on the experimental results. Finally, it was observed that the simulation results from the 1D bond model had a reasonable correlation with the experimental results in spite of the complex bond behaviour of TRC.

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 multi-axial non-corrosive textile fabrics. 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. 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 [3]. The purpose of this report is to provide guidelines for testing methods, a design manual and an update of the TRC state-of-the-art report [4].

In fibre composite materials, such as TRC, bond behaviour between the textile yarns and the cementitious matrix is a principal factor influencing the global structural behaviour [5]. A textile reinforcement yarn consists 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 aforementioned RILEM TC 232-TDT report is not yet publicized, testing methods and numerical methods to evaluate the pull-out behaviour of textile fibre yarns used in similar research need to be explored. For instance, the pull-out behaviour of a single continuous yarn from a matrix was described analytically using closed form equations [5-8]. Various damage models such as a triple linear shear-stress slip model have been assumed to characterize the fibre pull-out behaviour incorporating both adhesion and frictional load transfer [5, 6]. Experimental results from pull-out tests successfully verify the developed analytical and numerical models [5-8].

1.1 Research aim

Direct pull-out tests are included in this research to characterize the pull-out behaviour of the yarn-structure embedded in a concrete matrix, while particularly focusing on basalt fibre reinforcement in this paper. The yarn structure is rather complex including a multitude of outer and inner filaments; thus inevitably, the constituents of one yarn are unevenly bonded to the concrete matrix. As such, these tests provide valuable material input data for the calibration of analytical models as well as the development of non-linear finite-element models of TRC structures.

2 Experiments

The presented work is a part of a larger experimental scope, primarily conducted at the Danish Technical 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 fibre 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 (see Section 2.2).

2.1 Experimental setup

The pull-out test setup and specimen configuration was designed based on the double-sided unsymmetrical test by Krüger [9] and Lorenz and Ortlepp [8]. The pull-out test specimens prescribed for the presented experimental work measured 400 x 100 x 15 mm and were reinforced by one layer of reinforcement mesh. Unsymmetrical anchorage lengths, defined as A and B in Fig. 1, were defined for each specimen. Only one yarn was tested and the embedment length chosen was primarily based on the distance of the cross-threads, specified as *Short* (35 mm), *Medium* (70 mm) and *Long* (87.5 mm). The prescribed embedded length was limited to the upper end of the specimen (above breaking point) by means of a saw cut which localized the yarn to be tested. Two more saw cuts were made to define the breaking point of the examined yarn.

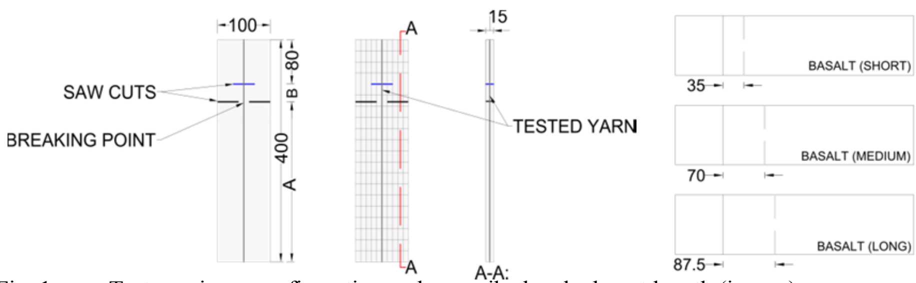

Fig. 1 Test specimen configuration and prescribed embedment length (in mm)

The pull-out tests encompassed the evaluation of varying embedment lengths in order to characterize both pull-out and rupture of the textile as failure modes. Three specimens were produced for each selected embedment length in order to obtain representative average pull-out behaviour. The pull-out test specimens were configured such that the weft yarns 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.

The experimental setup developed to conduct the pull-out tests is illustrated in Fig. 2. The test was conducted according to force control such that 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 LVDT deformation transducers 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.

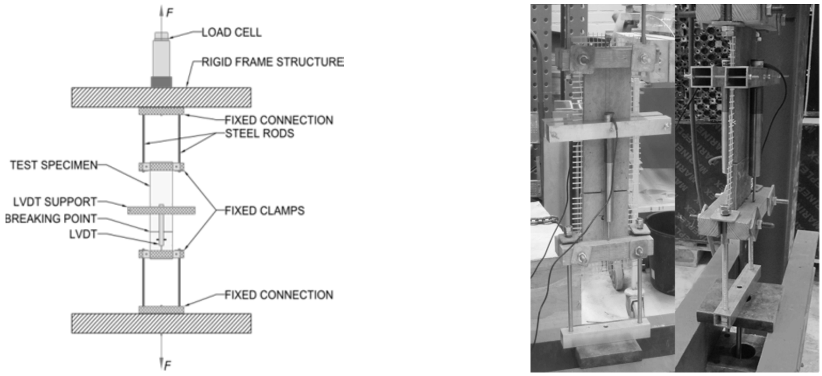

Fig. 2 Sketch (left) and photo (right) of experimental test setup

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 EN 1992 [10]. Lastly, the mean value of the tensile splitting strength tests was found to be 4.7 MPa. The pull-out tests were conducted between 94 to 99 days of maturity such that the modulus of elasticity increased to 43 GPa.

Table 1 Composition of the fine-grained concrete, mass in kg per m^3 of concrete.

Matrix composition	Density [kg/m^3]	Quantity [kg/m^3]
Low alkali cement (Z 52.5)	3200	406.0
Fly ash	2300	121.0
Microsilica	2200	22.0
Glenium SKY 532 – SU	1100	7.6
Amex SB22 (air entrainer)	1010	3.0
0/4 Sand	2640	1400.0
Water	1000	170.6

The textile reinforcement mesh included in this study was the Geo-grid mesh (Zhejiang GBF, China) fabricated of basalt with silane sizing. It has a configuration of 25 x 25 mm with a yarn fineness of 2000 tex. Corresponding material properties are listed in Table 2. Basalt appears to be an overall effective reinforcement solution [11]; however, its use in TRC is relatively limited. Basalt fibres are mineral fibres extracted from volcanic rock and its raw material content and morphology can differ greatly depending on its source. This variability in raw materials poses a challenge, as this variability can have a large influence on the chemical and mechanical properties and durability of the fibres [12].

Table 2 Material properties for basalt Geo-grid.

Property	Dimension	Value	Comment
Yarn cross-sectional area	[m^2]	0.755×10^{-6}	Assumed circular cross-sectional area
Specific surface weight	[g/m^2]	303	From manufacturer
Tensile strength	[MPa]	1898	From manufacturer
Young's Modulus	[GPa]	100	From manufacturer

2.3 Results

The average force versus total deformation for the basalt specimens for all embedment lengths are illustrated in Fig. 3. The total displacement corresponds to the mean displacement recorded by the two LVDTs for the entire specimen. In Fig. 3, 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 the *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 yarn from the matrix. Lastly, the remaining pull-out force is based on friction, as described in [6]. Rupture failure is marked by a sudden loss of capacity after the peak force is attained. Furthermore, it should be noted that the maximum force occurred at varying slips for each specimen; therefore, the average curve underestimates the true peak values. As such, the average maximum force corresponding to all *Short* specimens was 721 N (σ = 79 N). As for the *Long* specimens, the average maximum force and standard deviation (1662 N, σ = 139 N) was greater than that of the Medium specimens (1423 N, σ = 63 N). An increase in variability is likely due to an increase in potential bond irregularities, so-called weak zones.

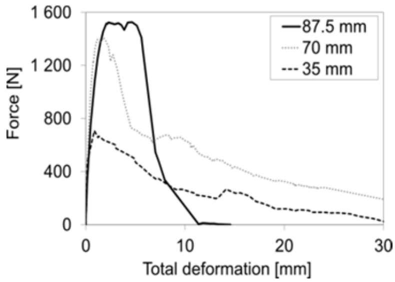

Fig. 3 Average experimental results for all embedment lengths

3 Numerical bond model

An analytical 1D bond-slip model developed by [13], principally used to analyse the bond stress-slip behaviour of corroded ribbed steel reinforcement, was modified for textile reinforcement in this scope of the work. To commence, the steel reinforcement is replaced by a prescribed singular continuous textile yarn assumed to be homogeneous with a circular cross-section wherein the transverse yarns are excluded. Accordingly, the differential equation expressing equilibrium conditions along the reinforcement in tension can be defined as Eq.1:

$$\frac{\pi \cdot \phi^2}{4} \cdot \frac{d\sigma}{dx} - \pi \cdot \phi \cdot \tau = 0 \quad (1)$$

where φ is the reinforcement diameter, σ is the stress in the reinforcement and τ is the bond stress. The model was developed to analyse the bond stress-slip behaviour of the equivalent textile yarn within the so-called anchorage length, thus the stress in the reinforcement is assumed to be in the elastic range. The deformation of the surrounding concrete is assumed to be negligible; thereby the displacement of the reinforcement is equal to the slip. Furthermore, to solve the equilibrium equation stated in Eq. 1, boundary conditions based on the pull-out of an equivalent textile yarn having a length of L and a prescribed displacement u_L were defined. The response of the pull-out tests were computed using a differential equation solver in MATLAB [14]. For further details regarding the development and implementation of the 1D bond-slip model, see Lundgren, Kettil [13].

3.1 Local bond stress-slip curve

The shape of the local bond stress-slip function depends on material properties, geometry, and stress distribution of both the surrounding concrete and textile yarn. The local bond stress-slip function can typically be estimated using various numerical [15] or analytical methods [5, 7, 8]. In this research, the first estimate of a local bond stress-slip function was obtained from the experimental results (force versus total deformation) from the *Short* specimens (see Fig. 3). Firstly, the distribution of bond stresses was assumed as uniform along the Short zone of the specimen (above breaking point) with the *Short* embedment length, such that the general bond strength equation (Eq. 2) could be applied.

$$\tau = \frac{P}{\pi \phi L} \qquad (2)$$

where P is the load, φ is the nominal diameter of the yarn; and L is the embedded length (35 mm). Furthermore, it was also assumed that the Short and Long zones (below the breaking point) initially distribute the slip equally each by 50 %, and after peak all slip was on the side with the Short embedment length. Thereafter, the initial estimate of the local bond-slip was modified until a reasonbable fit for all embedment lengths was obtained (see Fig. 4 (left-top)). The calibration of the bond stress-slip curve was accomplished by a power-function in the pre-peak region ($0 \leq s \leq s(\tau_{ult})$) and by a linear function in the post-peak region ($s(\tau_{ult}) \leq s \leq s_{ult}$) similarly to that proposed in the *fib Bulletin 55: Model Code 2010* for bonded FRP rebars [15].

3.2 Results

To determine the total deformation from the 1D bond-slip model, the slip contribution from the Short zone and Long zone (refer to Fig. 4 (left-bottom)) are summed. The slip from the Long zone includes an assumed linear-elastic recovery curve to zero slip after the peak force. The experimental and numerical results for all embedment lengths compared in Fig. 4 (right) depict a reasonably good correlation. The 1D model generally simulates sufficient stiffness prior to the peak without a significant overestimation of the maximum force. As for post-peak behaviour, the rupture of the yarn causing a sudden drop in stiffness is not captured using the 1D model for the *Medium* and *Long* specimens.

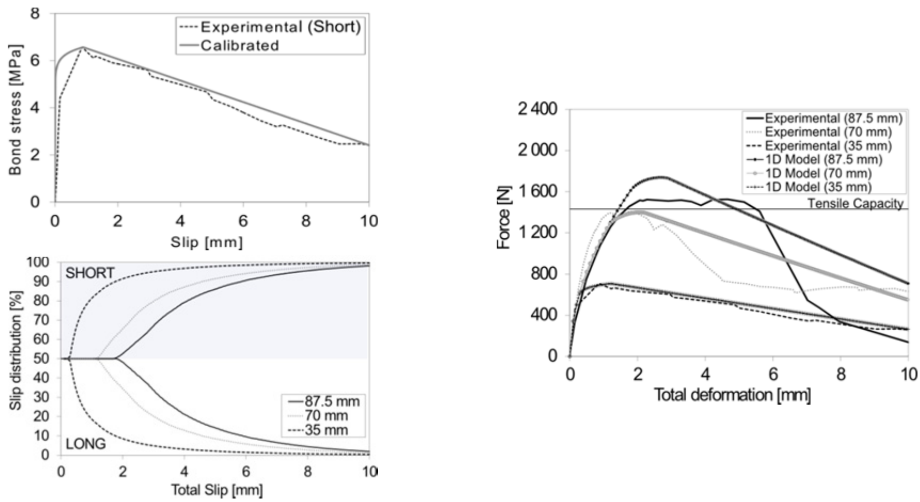

Fig. 4 Calibrated local bond-slip (left-top), slip distributions of Short and Long zones versus total slip (left-bottom) and average experimental results versus 1D bond-slip model for all embedment lengths (right)

4 Conclusions

The bond behaviour of basalt fibre reinforced concrete was characterized in this work by means of direct pull-out tests. Pull-out failure was observed for *Short* specimens, while rupture failure was noted for *Medium* and *Long* in the experimental pull-out tests for basalt reinforced concrete specimens. Thereafter, a local bond stress-slip curve was calibrated for the basalt specimens based on the experimental results related to the *Short* specimens. Moreover, applying this local bond stress-slip curve in a simple 1D bond model demonstrated a reasonable force versus total displacement correlation with the experimental results. Overall, it has been demonstrated that the complex heterogeneous structure could be simplified using a continuous and circular yarn without cross-threads.

Acknowledgment

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