Investigation of Stress Transfer Behavior in Textile Reinforced Concrete with Application to Reinforcement Overlapping and Development Lengths

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Summary: This paper concerns with the investigation of stress transfer mechanisms between yarns and concrete matrix and their influence on the overall behavior of textile reinforced concrete (TRC). This investigation considers textile reinforcement splices and textile reinforcement development lengths and carried out by means of Finite-Element simulations and fracture mechanic approaches. A first modeling procedure is made towards analyzing and investigating the damage mechanisms in TRC specimen under tension loading which are mainly characterized by matrix cracking and yarn pullout. This modeling approach allows for considering the yarn crack bridging which is a main characteristic behavior of TRC. In the same manner, 3D Finite-Element models are conducted for calculating the required reinforcement development lengths and the reinforcement overlapping lengths. The conducted approach takes into account different damage mechanisms observed in the corresponding experimental investigations which are also used for calibrating the modeling procedures. Moreover, the presented approach covers a wide range of required textile reinforcement overlapping lengths and development lengths and provides the corresponding ultimate loads.

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1 Introduction

The stress transfer between yarns and matrix is an essential mechanism that strongly influences the overall behavior of TRC, in particular at locations of reinforcement anchoring and overlapping. Moreover, practical engineering applications of TRC call for certain values of the required reinforcement development lengths and overlapping lengths, thus, a good understanding and appropriate analysis of stress transfer mechanisms are needed. This analysis is made in the framework of experimental and mechanical investigations. However, the results presented in this paper are concerned with the mechanical analysis of stress transfer mechanics, and it is carried out by means of the continuum mechanics analysis, numerical simulation, and fracture mechanics approaches. Furthermore, the relevant experimental work is used in calibrating the mechanical analysis. In this research we refer to textile reinforcement as “yarns” where the single yarn is a bundle of huge number of fibers, however, in the conducted mechanical modeling procedures, the yarn is considered as a compacted section.

2 Experimental observation of stress transfer mechanisms

The experimental investigations of stress transfer in TRC are conducted in the framework of the subproject B5 at the collaborative research center SFB 528 at TU Dresden.

Figure 1(a) shows a schematic representation of the experimental investigation carried out to determine the required reinforcement development lengths, $L_e$ (LORENZ & ORTLEPP [3]). However, for certain matrix mechanical properties and for specific textile reinforcements, the main parameter used in this experiment is the development length, $L_e$, in the sense that several experiments regarding a wide range of $L_e$ are conducted. Afterwards, a final resulting relation is established, which presents the required reinforcement development lengths and the corresponding maximum force (see Fig. 9). Nevertheless, in relation to the value of $L_e$, two failure modes are examined, yarn pullout and yarn rupture. However, for a specific experiment which corresponds to a certain value of the development length, $L_e$, the typical measured quantities are the yarn force, $F$, the crack opening, $w$, and the total elongation, $dl$, of an area with initial length of 200 mm in the upper part of the specimen. Consequently, the characteristic outputs of these experiments are characterized by the yarn force-crack opening relation, $F(w)$, in addition to the yarn force-elongation relation, $F(dl)$.

The measured $F(w)$ relation involves the following stages (see Fig. (1)):

OA: Elastic behavior of the specimen; the force increases with no emerging cracks in the specimen, however, point A corresponds to the initiation of the first crack which occurs at the predetermined breaking point.
Fig. 1: Experimental setup and measured data to determine the required reinforcement development lengths in TRC

BC, BC': The force increases until either the maximum pullout resistance force, $F_{P,u}$, along the development length or the ultimate yarn tensile strength force, $F_{G,u}$, is reached. However, the failure criterion is determined according to the size of the development length. However, the conducted experimental investigations reveal that generally, for a development length, $L_e \geq 145 \text{ mm}$, the yarn rupture is examined.

CD: The failure mechanism is characterized by the yarn pullout along the development length; the force decreases by the evolution of the damage along the matrix-yarn interface until the full fracture along the interface is completely examined.

DE: Yarn pullout mechanism continues with frictional stresses in the matrix-yarn interface.

3 Damage mechanisms in TRC under uniaxial tensile loading

The experimental investigations conducted on TRC specimens under uniaxial tensile loading show a typical damage mechanism represented by multiple cracks bridged by the continuous yarns; however, this damage behavior is a combination of two main fracture approaches: the matrix cracking and the yarn pullout.

In order to examine the damage behavior of TRC, it is very important to have a good understanding of all the individual damage mechanisms which are observed in the relevant exper-
iments. Therefore, we follow a proposed analysis procedure in which we start by investigating local stress concentrations and crack initiation in TRC specimen under tensile loading. Afterwards, the two important material properties in the context of damage and failure of TRC, the bond behavior in the yarn-matrix interface and cracking of the fine grained matrix are analyzed. This allows for the modeling and numerical simulation of the multiple cracking behavior of TRC tensile specimen by integrating all the yarn pullout mechanisms at all the potential discrete cracks. Finally, analysis of stress transfer in TRC regarding the textile reinforcement development and overlapping lengths is conducted.

3.1 Local stress concentrations and cracks initiation

The uniaxial tensile test conducted on TRC specimen indicates a typical crack pattern which corresponds to the locations of the transversal reinforcements. In fact, we can explain this type of crack pattern by analyzing the structure of the yarn itself. Each single yarn is a bundle of huge number of filaments which contacted to each other via low bond strength in the radial direction of the yarn cross section; therefore, the yarns themselves can be regarded as hole-like volumes inside the composites which cause, consequentially, stress concentrations at the holes locations. Fig. 2 illustrates a 3-dimentional heterogeneous Finite-Element simulation of TRC specimen which clearly demonstrates the stress concentrations according to the preceding explanation.

3.2 Mechanical modeling of matrix-yarn shear bond behavior

3.2.1 Experimental observation in yarn pullout test

The bond behavior between the yarn and surrounding concrete matrix is one of the main characteristic material properties of TRC and it affects the overall behavior of this composite essentially. In order to determine the characteristic material behavior of the matrix-yarn interface one-sided pullout experiments are performed (LORENZ & ORTLEPP [2]). In the pullout
experiment, a TRC specimen with predetermined crack is prepared, so that a yarn embedding length of $L_e=18\, mm$ can be pulled out gradually from the matrix. The main output data of the pullout test is the pullout force-crack opening relation which is generally called “the pullout curve”. By applying an appropriate inverse analysis procedure we can obtain the characteristic bond behavior of the interface as a shear stress-shear slip relation (Richter [8], Lorenz & Ortlepp [2]). This relation consists of an initial elastic part (the adhesion), a damage initiation point which corresponds to the ultimate bond strength, $\tau_m$, in addition to a damage evolution representing the degradation of bond stresses (the debonding process) until the full breakage of the adhesion occurs. The later behavior after the full breakage of the adhesion between the yarn and the matrix will be frictional shear stresses. The constitutive bond behavior is generally affected by the mechanical properties of the matrix material and the yarn coating, in addition to the layout of the used textile reinforcement like the waviness and the knitting of the nodes of the textile grid etc. Fig. 3 shows two bond laws and the corresponding scalar damage variable according to two different types of textile reinforcements; however, a main difference between the two types of the used textiles is that the textile used in Fig. 3(b) has mainly no waviness along the yarns lengths and it has a higher maximum bond strength in comparison to the textile type 1 used in Fig. 3(a).

![Fig. 3: Matrix-yarn bond law and the corresponding damage variable for two different types of textile reinforcements](image)

### 3.2.2 Numerical simulation of the pullout test

In the framework of the Finite-Element simulation, 3-dimensional heterogeneous models are performed on the meso-scale by considering all the main structural components of TRC, the matrix, the yarn, and the yarn-matrix interface layer. However, and as mentioned before, the bond behavior in the yarn-matrix interface is characterized by a slip-based interfacial model defined by a shear stress-shear slip material law. This bond behavior is considered explicitly a mode II fracture mechanism and, therefore, can be represented efficiently by means of the cohesive zone model with a predefined traction-separation law.
The conducted modeling allows for capturing the stress distribution during the pullout mechanism. For instance, Fig. 5 shows shear stress distribution along the interface according to three different values of the crack opening, \( w_1 = 0.06 \text{ mm}, w_2 = 0.11 \text{ mm} \) and \( w_3 = 0.13 \text{ mm} \).

![Fig. 4: Finite-Element simulation of the pullout investigation](image)

**3.3 Matrix cracking**

The experimental investigations carried out on the cracking behavior of fine grained concrete matrix under tension loading indicate a typical softening behavior expressed by a matrix tensile stress-crack opening relation, \( \sigma_m(w) \). This damage behavior which is considered explicitly a mode I fracture mechanism can also be efficiently modeled by means of the cohesive zone model with predefined traction-separation law. However, in our modeling procedures, we use the softening relation, \( \sigma_m(w) \), of the fine grained concrete matrix cracking presented by Brockmann [7].

**3.4 Application to multiple cracking in TRC tensile specimen**

The multiple cracking mechanism is a main characteristic damage behavior which is always observed in TRC under tensile loading (JESSE [9]). Indeed, the multiple cracking process corresponds to a crack pattern involves macro cracks which are bridged by the continuous yarns, and it is usually recognized as “yarn crack bridging mechanism”. Furthermore, the yarn crack bridging mechanism is a combination of two fracture behaviors; the cracking of the fine grained concrete matrix in addition to the yarn pullout ((RICHTER & ZASTRAU [6]). Yarn crack bridging behavior is analyzed by means of the Finite-Element approach by conducting 3-dimensional heterogeneous models on the meso-scale, see Fig. 5. In the conducted model-
ing approach, the cohesive zone model is used to characterize the bond behavior of the matrix-yarn interface, while the matrix cracking is recognized by means of the discrete cracking approach in the sense that every crack is modeled by double faces connected partially to each other through a cohesive layer. The experimentally determined softening behavior of the matrix cracking is used to characterize the constitutive behavior of the cohesive layer. In this model, the transversal yarns are not modeled, however, their influence on matrix stress concentrations and, therefore, in crack initiation are considered by only the partially connection of the crack faces through the cohesive layer, i.e. at the locations of the transversal yarns in a defined neighborhood of the considered main yarn reinforcement the modeled double faces of the matrix are not connected. The fraction of the connected areas is determined in a way that we get the same increasing in matrix stresses that are observed in the mechanical models which are already conducted for analyzing the matrix stress concentration and which consider the fully 3-dimensional structure of the reinforcement layer. Figure 6 shows the mean stress-mean strain relation according to both the Finite Element simulation and the corresponding experimental investigation. A good matching between the mechanical model and the experimental investigations can be observed.

Fig. 5: Finite-Element simulation of TRC specimen under uniaxial tensile loading

It should be noted that small values of viscosity parameter in a viscous regularization approach have been used for the cohesive elements employed for simulating the discrete cracks of the matrix, this approach is very helpful to overcome the convergence problems that correspond to the softening behavior and stiffness degradation in the constitutive behavior of the matrix cracking. However, several attempts have been made to determine the best values of the viscosity parameter in relation to the time increment used in the Implicit integration approach to avoid any compromising results.
4 Stress transfer in TRC in application to reinforcement development lengths

Reinforcement’s end anchoring is an important part of TRC members where a particular mechanism of stress transfer between the yarn and the matrix is observed. In order to get an appropriate understanding of stress transfer mechanism at these locations, and to investigate the corresponding damage behavior, a mechanical analysis is carried out by means of the continuum mechanic, numerical simulation, and fracture mechanics approaches. The required experimental data used for calibrating the developed mechanical model are provided by the subproject B5 (LORENZ & ORTLEPP [3]). However, and for a definite value of the reinforcement development length, the corresponding experiment shows two different failure modes, the yarn pullout and the yarn rupture. Nevertheless, the mode of failure is determined according to the value of the development length, $L_{c}$, in the sense that for higher values of $L_{c}$, the yarn rupture is observed, whereas for smaller values of $L_{c}$, the yarn pullout is examined. It should be pointed out that the conducted experiments provide us with measured data of forces and displacements as main outputs, while the developed mechanical model is intended to encompass more relevant data, in particular the stress distribution in the matrix and in the yarn-matrix interface. We can conclude that for a definite anchoring length the deterministic maximum force, $F_{\text{max}}$, is characterized by the yarn pullout capacity, $F_{p,u}$, in the lower part of the specimen, i.e. along the development length, unless the ultimate yarn tensile strength force, $F_{G,u}$, is reached. Therefore, one can cover this criterion by the following relation:

$$F_{\text{max}} = F_{p,u} = a_{c} \int_{0}^{L_{c}} \tau_{b}(x)dx \leq F_{G,u},$$

where $\tau_{b}(x)$ is the distribution of the bond shear stress in the matrix-yarn interface along the development length and, $a_{c}$ is the characteristic circumference of the yarn’s cross section.

In the numerical simulation, we tend to recognize all damage mechanisms observed in the corresponding experiments, therefore, we consider the yarn pullout mechanism by using the
cohesive zone model. In the same manner, the multiple cracking behavior which is examined in the specimen is recognized by using the same modeling techniques already conducted for analyzing the behavior of TRC specimen under tensile loading, see Fig. 5.

Figure 7 illustrates the measured displacements according to the presented mechanical model, these measured displacements are: the total displacement, $u_z$, (equivalent to the machine displacement in the corresponding experiment), the crack opening at the predetermined breaking point, $w$, and the total elongation, $dl$, of an area of an initial length of 200 mm in the upper part of the specimen at which the multiple cracking process is observed. In fact, the analysis of the measured displacements illustrated in Fig. 7 can give a clear understanding of the damage process in the tensile specimen. For instance, one can distinguish the following “key points”:

$A$: Starting of the crack opening, $w$, at the predetermined breaking point, at which the maximum matrix tensile strength is reached.

$B$ to $C$: Developing of the multiple cracking mechanism in the upper part of the specimen.

$D$: The damage of the matrix-yarn interface reaches the free end of the yarn, the interface along the complete development length, $L_e$, is damaged.

![Figure 7](image_url)

**Fig. 7:** The measured displacements $u_z$, $w$, $dl$ according to the conducted Finite-Element simulation

Figure 8(a) illustrates the yarn force-crack opening relation, $F(w)$, in addition to the yarn force-elongation relation, $F(dl)$, where the elongation is considered for an area of initial length of 200 mm in the upper part of the specimen. Whereas Fig. 8(b) shows the $F(w)$ relation according to the presented mechanical model and the corresponding experiment, and one can observe a good matching, however, the slight difference in the part after the maximum force is reached can be explained for the reason that the conducted model does not consider the part of the specimen between the glued clamping steel sheets in the upper part of the specimen, where an additional pullout of the yarn in the upper part is expected. Nevertheless,
the discretization of this part is feasible, but of course, with more required data regarding the clamping condition like the applied pressure and the shear stress between the matrix and the steel plates etc. and above all, with more numerical costs.

In fact, the $F(w)$ relation is considered to be the deterministic output which characterizes the damage behavior, in addition to the corresponding deterministic maximum force. Whereas the $F(dl)$ relation gives mainly an indication of the multiple cracking process in the upper part of the specimen.

(a) numerical yarn force-crack opening and yarn force-elongation relations

(b) Experimental and numerical yarn force-crack opening relation

Fig. 8: Yarn force-crack opening and yarn force-elongation relations according to a reinforcement development length $L_e = 60 \, mm$

Indeed, the same modeling procedure was extended in the framework of a parametric study which considers a wide range of practical values of the required development lengths. Figure 9 demonstrates the deterministic maximum force in the yarn as a function of the required reinforcement development length, $L_{e,req}$. The illustrated results are presented according to the corresponding experiments and the relevant Finite-Element modeling. A good matching between the experimental results and the results of the conducted mechanical modeling is observed. In the numerical simulation the ultimate tensile strength force of one yarn is set to $F_{G,u} = 870 \, N$, which results in a critical value of the development length of $L_e = 145 \, mm$, at which the yarn rupture is the critical failure mode.
5 Stress transfer in TRC in application to reinforcement overlapping

Reinforcement’s overlapping which are also recognized as reinforcement splices are also important structural details in TRC members where stress transfer mechanisms between the yarns and the matrix incorporated with different damage mechanisms are observed. Moreover, the practical engineering application of TRC requires definite values of the requisite overlapping lengths in regarding to the applied loads. Therefore, a mechanical analysis of damage behavior and the failure modes observed at these locations is needed. Figure 10 shows a mechanical modeling of the corresponding experimental setup which was carried out in the subproject B5 (LORENZ & ORTLEPP [1]) to determine the ultimate load for a reinforcement overlapping length of $L_u = 60$ mm. The presented model is a 3-dimensional heterogeneous Finite-Element model which considers the structural components of TRC on the meso-scale in addition to all the potential damage mechanisms observed in the corresponding experiment. Damage behaviors in locations of reinforcement overlapping can be addressed by the matrix cracking, crack closure mechanisms, yarn pullout, in addition to the yarn rupture. However, the crack closure mechanisms come out from the kinematic equilibrium of the cracked matrix parts in the overlapping area, where every matrix part satisfies the equilibrium condition under the yarn forces (Fig. 10(b)), however, the yarn forces are varying during the gradual increase of the elongation. In Fig. 11, the cracks are denoted by $w_i$, but in the same time, the term $w_i$ is also used as the value of the opening of the corresponding crack. It should be pointed out that in a similar manner as for the development length problem, two failure modes are examined: the yarn pullout or the yarn rupture, therefore, the deterministic maximum force, $F_{max}$, is characterized by the yarn pullout capacity, $F_{P,u}$, unless the ultimate yarn tensile strength force, $F_{G,u}$, is reached. Indeed, the tested specimen is not symmetric because of the predetermined breaking point (notched crack) which is executed in advance at...
the location of the first crack, \( w_0 \), consequently, no symmetric crack opening behavior in the conducted models is observed.

Figure 10: Finite-Element simulation of TRC specimen to determine the required overlapping length \( L_u \)

Figure 11(a) provides a comprehensible description of the development of all the potential cracks in relation to the applied displacement, \( \dot{u}_z \), whereas Fig. 11(b) illustrates the measured total force-elongation relation, \( F(\dot{u}_z) \) according to the conducted modeling approach. Moreover, the damage behaviors which are observed in this experiment can be characterized by the “key points” illustrated on Figure 11 as the following:

A: Limit of the linear elastic behavior with the initiation of the crack \( w_0 \) which occurs at the predetermined breaking point in the investigated specimen.

AA’: Propagation of the crack \( w_0 \) along the entire section at the notch location. Whereas point A’ corresponds to the full separation of the crack faces.

B: Initiation of the crack \( w_4 \).

C, D: Initiation of the cracks \( w_3 \) and \( w_2 \) respectively.

E, F: Point E corresponds to the starting of crack closure mechanism at cracks \( w_3 \) and \( w_2 \), whereas point F represents the full closing of these two cracks which means that all the cracks \( w_1, w_2, w_3 \) are closed. However, the crack closure mechanism causes an
increasing of the slip in the matrix-fiber interface and, consequently, an increasing in shear stresses which corresponds to an increasing in yarn forces (the hardening part FG on Fig.11(b)).

G,K: The maximum bond strength of the matrix-fiber interface is reached at the free end of the yarn along the overlapping length, and afterwards, the damage evolution of the bond stresses is examined (part GK). Point K indicates that the matrix-yarn interface is completely damaged along the overlapping length, and therefore, the yarns are pulled out with a frictional stresses along the interface (part KL on Fig.11(b))

(a) The measured cracks openings, \( w_i \), in relation to the total elongation, \( \bar{u}_z \), in the conducted Finite-Element simulation

(b) Total force-elongation relation according to a reinforcement overlapping length, \( L_u = 60 \text{ mm} \)

Fig. 11: Results of Finite-Element simulation of TRC specimen with reinforcement overlapping length of \( L_u = 60 \text{ mm} \)

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