TEXTILE REINFORCED CONCRETE PART II: MULTI-LEVEL MODELING CONCEPT

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Abstract

In this paper the development of a consistent material model for textile reinforced concrete is presented. Load carrying and failure mechanisms at the micro, meso and macro scales are described and models with the focus on the specified scales are introduced. The models currently being developed in the framework of the collaborative research center are classified and evaluated with respect to the failure mechanisms being captured. The micromechanical modeling of the yarn and bonding behavior is discussed in detail and the correspondence with the experiments focused on the selected failure and interaction mechanisms is shown. The example of modeling the bond layer demonstrates the application of the presented strategy.

Keywords: Multiscale, Model calibration, Material model, Textile reinforced concrete

1. Introduction

The development of a consistent material model for textile reinforced concrete requires the formulation and calibration of several sub-models on different resolution scales. Each of these models represents the material structure at the corresponding scale (Fig. 1) with a focus on specific damage and failure mechanisms. The following correspondence between the scales and the observable components of the material structure and their interactions are specified:

- micro level
  - filament, matrix
  - bond filament - matrix
- meso level
  - yarn, matrix
  - bond yarn – matrix
- macro level:
  - smeared concrete model
  - smeared textile

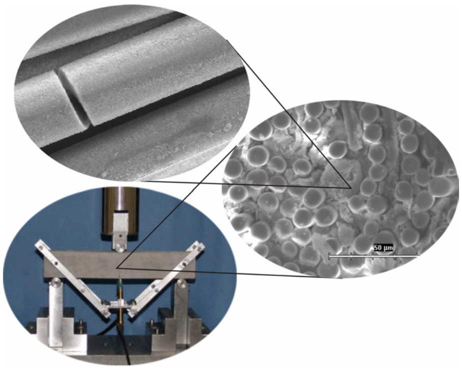

Figure 1: Resolution scales

While the models at the micro level are able to capture the fundamental failure and damage mechanisms of the material components (e.g. filament rupture and debonding from the matrix) their computational costs limit their application to small size representative unit cells of the material structure. On the other hand, the macro level models provide a sufficient performance at the expense of limited range of applicability. Generally, all the scales must be included into the assessment of the material performance. The chain of models at each scale may be coupled (1) conceptually by clearly defining the correspondence between the material models at each level or it may be coupled (2) adaptively within a single multiscale computation to balance accuracy and performance in an optimal way [1][2].

Due to the complex structure of the textile reinforced concrete at several levels (filament – yarn – textile – matrix) it is a non-trivial task to develop a multiscale model from scratch. It is rather more effective to develop a set of conceptually related sub-models for each structural level covering the selected phenomena of the material behavior. The homogenized effective material properties obtained at the lower level can be verified and validated using experiments and models at the higher level(s).

For the effective coordination of such a model development, it is important to characterize the focusing of every sub-model by specifying the following characteristics:

- material components and their structural configuration distinguished at the selected scale of resolution
- load/failure mechanisms and their interactions reflected in the model within the material structure at the selected scale of resolution.

By using this characterization, it is easier to assess the validity of the model and to formulate interfaces between models at the different resolution scales.

2. Damage and failure mechanisms

The fundamental failure mechanisms included in the textile reinforced concrete may be appointed to the reinforcement, to the matrix and to their bond. It is important to note, that both the reinforcement and the matrix are highly inhomogeneous materials with a complex microstructure. Obviously, the failure process in the TRC microstructure is more complex than in the case of the steel reinforced concrete or fiber reinforced composites where only one of the material components is inhomogeneous.

In the case of the reinforcement, the elementary mechanisms in the material behavior are appointed to the filaments with linear elastic behavior and brittle failure. The filament ensemble constituting the yarn exhibits nonlinear behavior due to the disorder in the filament structure. The delayed activation of individual filaments leads to the low increase of the stiffness in the beginning of loading, the friction between filaments influences the maximum stiffness reached during the loading and both these effects influence the rate of the failure after reaching the maximum force. In both the filaments and the yarn we may also observe the statistical size effect leading to the reduced strength with an increasing length [3].

The fine grained concrete matrix exhibits the evolution of microcracks in the fracture process zone which gradually close up to the macro crack. The complex heterogeneity of the material structure governing this process cannot be captured by micromechanical considerations, so that the meso level scale of resolution is applied and the localization process is observed and modeled in phenomenological terms.

The interaction between the reinforcement and matrix can be defined at the three scales shown in the Fig. 2. The elementary behavior describes the interaction filament-matrix including the bonding, debonding and friction. In the case of the yarn, we may also distinguish the bonding, debonding and friction phase, however, in each of these phases there are all interaction modes between filaments and matrix included. Furthermore, the yarn-matrix interaction includes the filament rupture and filament-filament friction. As a result, the yarn-matrix interaction cannot be reflected by a bond layer without thickness and needs to be analyzed in detail in micromechanical terms. If the cracking in the matrix is included in the interaction between the reinforcement and matrix the tension stiffening phenomenon occurs. The most complex interaction is encountered at the level of the textile structures embedded in the matrix. In this case, the two- and three-dimensional interaction between the crack evolution, crack bridging and yarn debonding occurs.

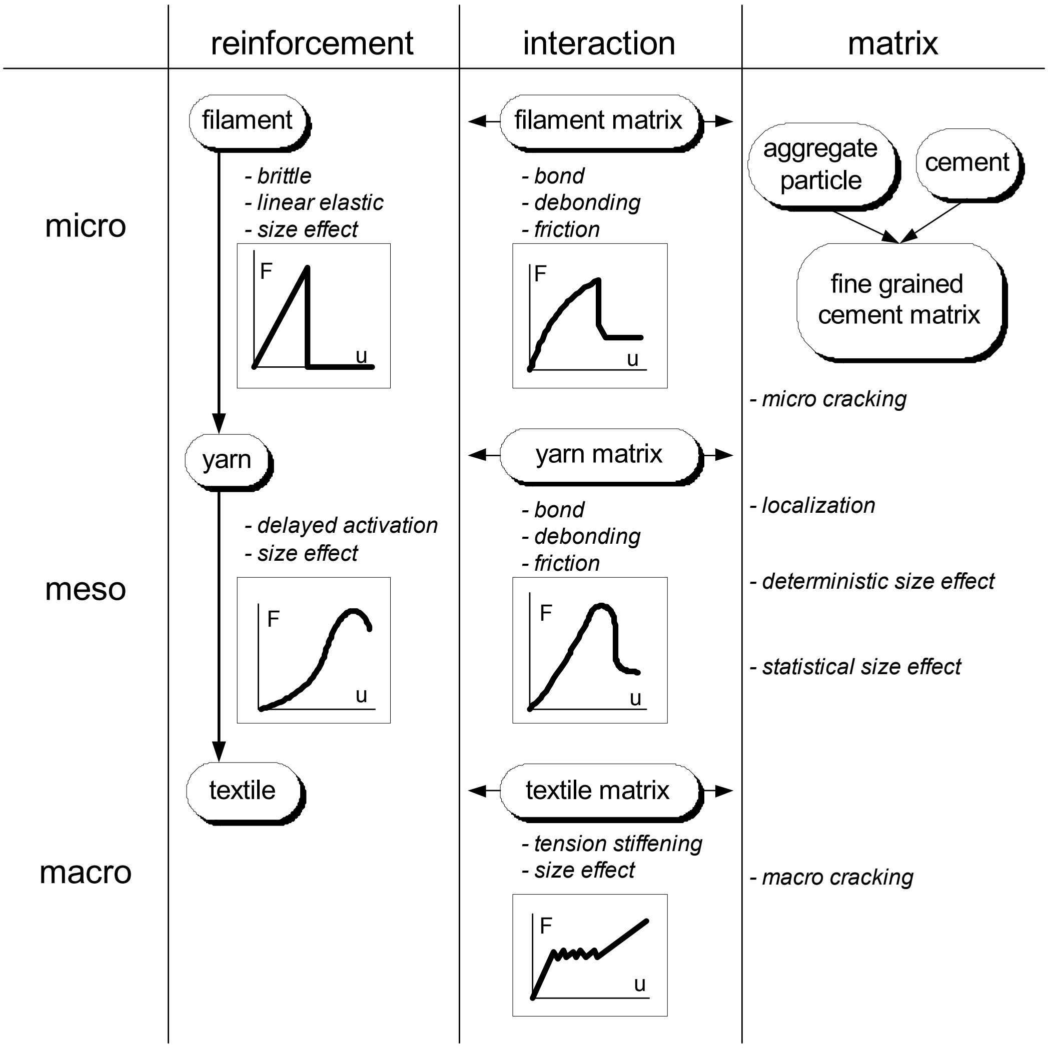

Figure 2: Correspondence between scales, components and phenomena

In the list shown in Fig. 2 we distinguish the phenomena that may be appointed to the individual structural components, e. g. the filament behavior and filament-matrix interaction. On the other hand, the phenomena of delayed filament activation and size effect result from the disorder included in the structuring of the individual material components in the ensemble. The size effect phenomena may be recovered in the reinforcement, matrix and in their interaction and emphasizes the importance of the statistical representation of the material structure at the micro- and meso level.

3. Experimental observation and evaluation of the identified phenomena

After reviewing the elementary and complex phenomena occurring in the TRC we discuss the possibilities of isolated observation of the particular phenomena or distinguished interaction of more phenomena in the experiment.

The filament behavior and the statistical size effect is tested on the single filament tensile test. The expected distribution of strength follows the Weibull curve derived from the weakest-link model. The filament ensemble is tested using the yarn tensile test with varied specimen length in order to evaluate the variability of the material properties and disorder over the yarn length.

The filament-matrix bond characteristics are calibrated using the single-filament pull-out experiment. The elementary interaction between the filament ensemble and the matrix is tested by using the one- and two-sided pullout experiments. Additionally, the direct characteristics about the material structure in the bond are obtained from the micrographs taken on the cuts of the pull-out body cross section. Furthermore, the tracing of the whole failure process is possible by recording the light transmitted by the filaments during the pull-out test so that the instantaneous number of broken filaments in the bond layer can be determined at each level of the control loading [4].

The interaction between the debonding and crack evolution in the matrix in the one-dimensional stress state is tested upon tensile experiments on textile reinforced concrete slabs. Finally, the interaction in the two-dimensional case is tested upon textile reinforced concrete thin plates with the surface crack tracing using the photogrammetry [5][6].

The classification of the most important experiments with respect to the phenomena occurring during the loading is provided in the Table 1.

experiment	bond			debonding			friction				filament rupture	matrix cracking	crack propagation
component/ Interaction	M-F	M-Y	M-T	M-F	M-Y	M-T	F-F	M-F	M-Y	M-T	F	M	M
tensile test on filaments											●		
tensile test on yarn							●				●		
pull-out filament	●			●				●					
pull-out yarn	●	●		●	●		●	●	●		●		
tensile test on TRC slabs	●	●		●	●		●	●	●		●	●	
tensile test on textile reinforced plates	●	●	●	●	●	●	●	●	●	●	●	●	●

Table 1: Correspondence between experiments and failure mechanisms
(M: matrix, F: filament, Y: yarn, T: textile)

4. Submodels on different resolution scales

Micro level

The micro level model represents the bond layer between the yarn and the matrix in form of the representative distribution of filaments in the matrix (Fig. 3). The interaction between filaments and matrix is defined by the bond model reflecting the phases of bonding, debonding and friction. The material parameters are determined using experimental data from several sources: filament pullout test, computer tomography photos, tension tests on filaments and yarns as well as pullout test on yarns. Using this model and the experimental data we are able to derive the effective bond law of the bond layer between the whole yarn (filament assembly) and the matrix which can be used at the higher modeling levels.

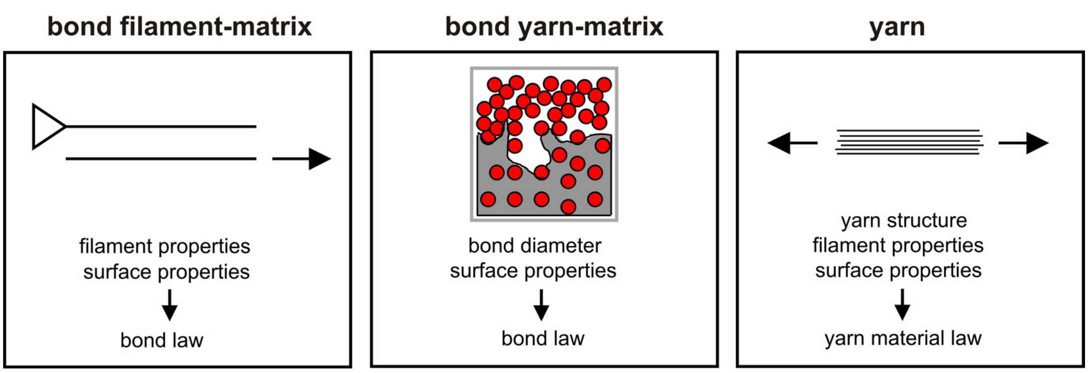

Figure 3: Models at the micro level

In following the individual phenomena are discussed with respect to the proposed submodels.

Interaction between filaments within the bundle

The structural properties and their variation along the fiber are modeled by the accumulative recording of the individual filament responses with randomized properties to get the overall response. The model allows us to introduce parameters that phenomenologically represent the disorder in the filament bundle. The resistance of a single filament is computed by applying the theorem of the extreme value distribution. The delayed activation of the filaments is taken into account by the density distribution of the activation strain $\varepsilon_{0,}$. The variation of tensile strength and Young modulus is modeled by random fields. The redistribution of the forces upon the filament rupture follows the equal load sharing rule (ELS) [7]. The friction between the filaments is neglected. With this model it is possible to describe the phenomenon of delayed activation increasing ductility and stiffness with increasing sample length and the statistical size effect on the tensile strength of the yarn. The material characteristics derived from this model are the characteristics of the disorder in the filament bundle in the form of the statistical measures of waviness in the individual filaments and the distribution of strength along the single filament. The calibration of this model is performed by using the filament and yarn tensile tests with the varying length [3].

Interaction between filament and matrix

This model describes the bond between a fiber and the surrounding matrix. Assuming a multi linear shear-stress slip relation the pull-out curve for a filament can be analytically computed.

The shear-stress slip relation is calibrated by minimizing the quadratic error between the experimentally determined and the analytically calculated curve.

The interaction between the filament and the matrix involves the phases of bonding and debonding including the damage of the interface and the subsequent friction. This interaction is captured by the finite element model that is calibrated using the filament pull-out experiments. The filaments are modeled by nonlinear one-dimensional elements connected by a zero-thickness interface element to the matrix. This model provides the basis for the construction of the representative unit cell to determine the effective properties of the microstructure in the bond layer and yarn. The calibration of the shear stress-slip constitutive law is done in the framework of the automated calibration procedure using the Hook-Jeeves and evolutional strategies [8].

Interaction between yarn and matrix

This model regards a representative section of the interface layer and takes the deterioration of the bond with increasing distance between filament and matrix into account. The section is projected onto an alignment normal to the perimeter of the roving. Filaments with the same position on this alignment are represented by bond layers. The bond quality for each layer is defined by a function of the distance from the matrix. Each bond layer is represented by a one-dimensional element and is connected to the matrix by a zero-thickness interface element.

This model is able to describe the effect of the variation in the bond performance on the portions of filament debonding and filament rupture during the debonding of the yarn. The calibration of the model is performed both using the load-displacement curve and the curve of representing the instantaneous fraction of the broken filaments during the loading process. The later latter is obtained by optical recording of the light transmission through the unbroken filaments.

Meso level

The first goal of the numerical simulation at the meso level is to capture the failure process during the debonding of a yarn from the matrix without the ambition to truly reflect details of the failure process in the microstructure. For this purpose, the subroving model [9][10] introduces the variation in the bond quality between individual filaments and the matrix in order to capture the gradual failure of the bond layer. This model classifies the filaments of a roving into sleeve and core filaments so that the bond layer is divided in outer and inner bond. The sleeve filaments are surrounded by the matrix to different degrees. This degree is described by the contact angle represented by a predefined distribution. The filaments with same bond quality, e. i. the same contact angle are grouped into subrovings. The subrovings and the core filaments are represented by one-dimensional nonlinear cable elements. Each subroving is connected to the matrix by an interface element. The associated multi linear bond law is scaled by its contact angle. Furthermore it is connected to the core filaments by another interface element.

Interaction between debonding and matrix cracking

The interaction between the debonding and the evolution of the cracks in the matrix in form of the crack alignment and crack bridging is modeled in terms of the fracture mechanics with the effective properties derived by using the models specified earlier. The micromechanical model of the bond layer allows to derive the effective properties required for the debonding criteria (critical energy release rate). For the validation of the simulated crack propagation the photogrammetric tracing of the crack evolution in the thin plates mentioned earlier is applied.

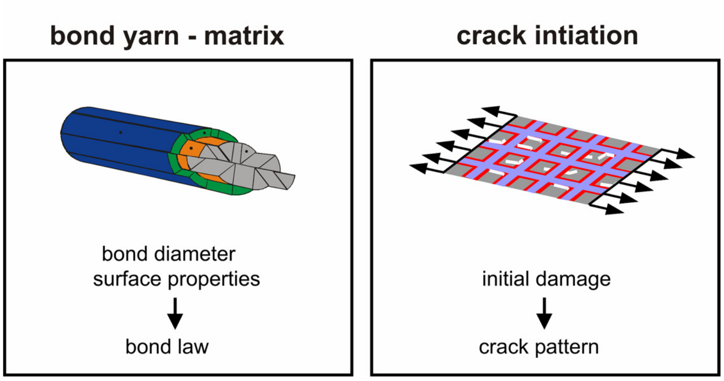

Figure 4: Models at the meso level

Macro level

At the macro level the determined effective material parameters become incorporated into smeared concrete models and layers characterizing the textile structures in combination with concrete [11]. The interactions at the lower resolution scales are smeared into the effective material properties assigned to one layer of the layered shell model. These are used for calculation at the level of structural elements and validated using experimental data from the tensile tests and three- or four- point bending tests (Fig. 5).

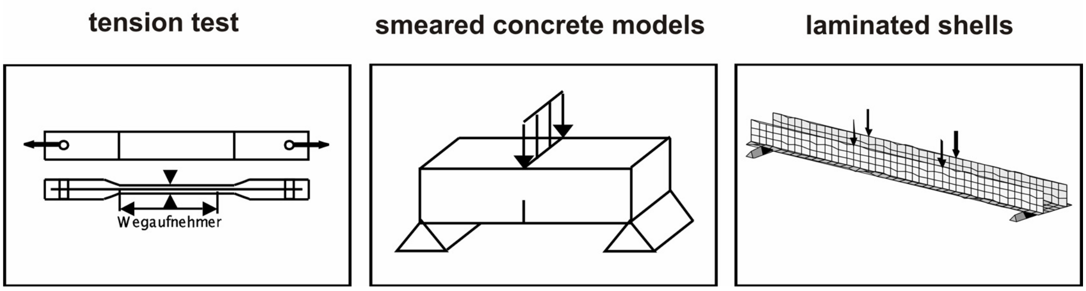

Figure 5: Models at the macro level

5. Derivation of the micromechanical bond characteristics

Having briefly described the modeling strategy applied within the collaborative research center we now focus on the example of the modeling of the bond layer. The phenomena to be included are the filament rupture and the filament bond, debonding and friction. The contact between the single filament and the matrix has been characterized by a bond model with parameters calibrated using the single filament pull-out experiment. What is sought is the representative configuration of the filaments and the matrix in the bond layer. The basic assumption in setting up this distribution is the decrease of the bond quality from the outside to the inside of the yarn. The calibration of the bond quality may be performed by using the optical recordings of the light transmission identifying the filaments broken during the pull-out test.

In the Figure 6 the experimental response in terms of load-displacement curves and curves showing the progression of the fraction of unbroken filaments is shown.

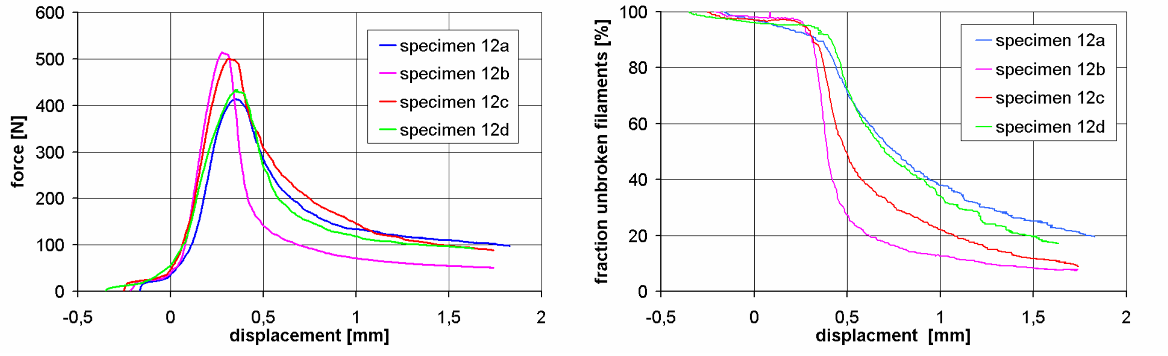

Figure 6: load-displacement curve, fraction of unbroken filaments

The influence of a linear, a quadratic and a cubical bond quality distribution on the pull-out curve and the process of filament rupture is shown in Figures 7 and 8. While the linear and the quadratic approaches result in a sharp bend of the pull-out curve at the beginning of filament rupture, the cubical distribution leads to a curve that is more ductile and resembles the pull-out curves measured during the experiments. This is the result of very similar reproduction of the sequence of filament rupture.

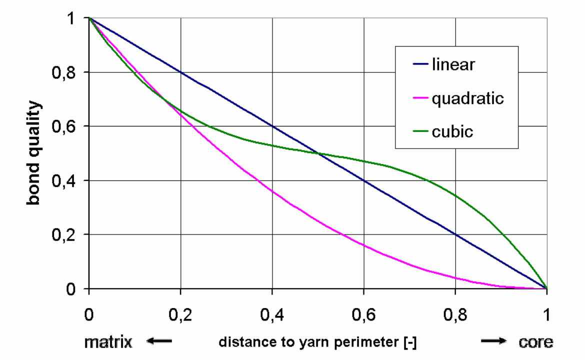

Figure 7: bond quality distribution

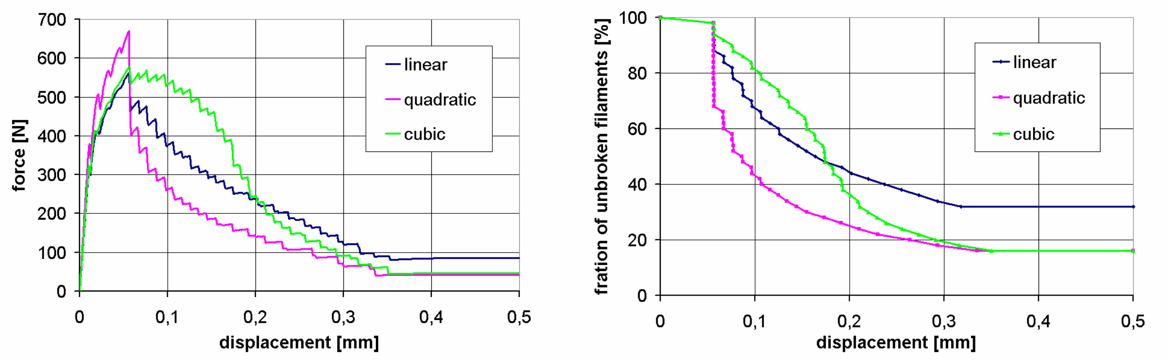

Figure 8: load-displacement curve, fraction of unbroken filaments

While the bond quality distribution determines the post-peak gradient of the pull-out curve the maximum pull-out force is primarily dependent on the tensile strength of the filaments. This correlation is documented in Figure 9. The maximum pull-out force decreases with the decreasing tensile strength of the filaments.

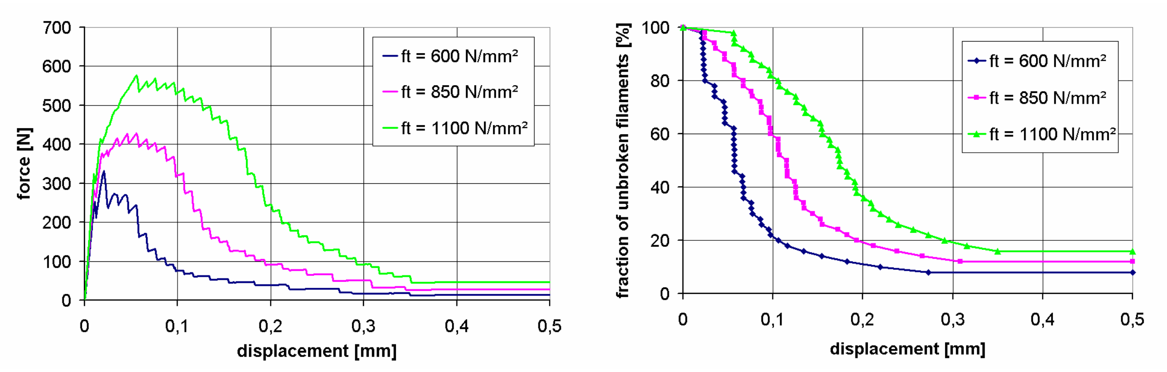

Figure 9: load-displacement curve for different filament strengths f_t

The initial slope of the pull-out curve is also dependent on the bond quality. The decrease in the maximum bond performance results in the decreasing portion of filament fracture. Therefore, the variation range of this parameter is limited. The reduction of the initial stiffness that can be observed in the experiments can not be reproduced by solely reducing the bond quality. As a consequence, the explanation of the reduction is existence of the gap between the macroscopic boundary of the matrix and the first contact of the filaments with the matrix inside of the specimen, i.e. the start of the microbonding between filament and matrix, which is illustrated in Figure 10. The influence of this gap on the initial stiffness is demonstrated in Figure 11. The initial stiffness decreases with increasing gap.

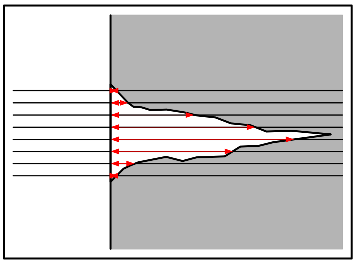

Figure 10: Gap between matrix boundary and begin of microbonding

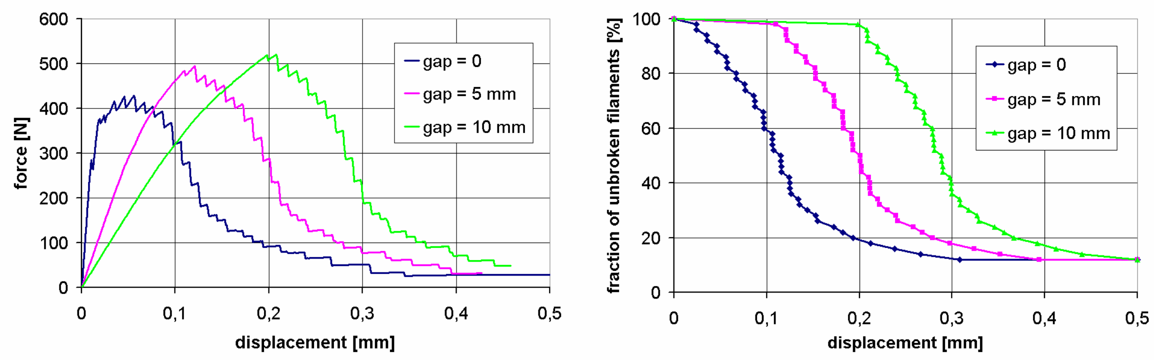

Figure 11: load-displacement curve for different gaps

Using the parameters described above a calibration of the model is possible which is exemplified in Figures 8, 9 and 11. Of course, the calibrated distribution of the bond quality across the yarn cross section may be viewed in different ways as well. Other possibilities are the effective debonding embedding length and the contact angle distribution.

6. Conclusions

The modeling strategy for supporting the development of the textile reinforced concrete is based on the assumption, that there is no perfect model able to capture all the aspects of the material behavior. The models developed must have a clearly defined validity and they are to be applied together in order to study the material response at various scales of material resolution.

7. Acknowledgement

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