

Concrete Reinforced with Stitch-Bonded Multi-Plies—A Review

**by J. Hausding, T. Engler, G. Franzke, U. Koeckritz, and
P. Offermann**

Synopsis: This paper presents the research activities in the field of textile reinforced concrete carried out by the Institute of Textile and Clothing Technology (ITB) of the Technische Universitaet Dresden, Germany. Extensive research has been conducted with the aim to fully use the tensile strength of the applied high-performance fiber material in the reinforcing textile. To achieve this, the textile machinery was adjusted and improved and new testing methods were developed. This research has resulted so far in several innovative applications for the repair of buildings as well as the production of precast concrete members. This paper was originally presented in 2005 Spring ACI Convention, New York under the title “State of the art and perspectives of textile reinforcements of concrete components.”

Keywords: AR glass filament yarn; stitch bonding; textile; textile reinforced concrete

2 Hausding et al.

Jan Hausding was born in 1978 in Pirna, Germany. He studied mechanical engineering and graduated from TU Dresden in 2004. He works as a research associate at the Institute of Textile and Clothing Technology (ITB) of the TU Dresden.

Thomas Engler was born in 1970 in Freital, Germany, and graduated from HTW Dresden University of Applied Sciences in civil engineering in 1997. He works as a research associate at the ITB.

Dr. Gerd Franzke was born in 1954 in Dresden, Germany. From 1974 to 1978, he studied mechanical engineering at the TU Dresden. From 1978 to 1984, he was research associate at the Department of Construction Technology of the TU Dresden. Since 1984, he has worked as a research associate at the ITB. In 1985, he obtained his Doctor's degree at the TU Dresden.

Uwe Koeckritz was born in 1975 in Dresden, Germany, and graduated from TU Dresden in mechanical engineering in 2001. He works as a research associate at the ITB.

Prof. Peter Offermann was born in 1940 in Goerlitz, Germany. In 1968, he obtained his Doctor's degree at the TU Dresden. He worked in managing positions for several companies holding tasks in research and development. In 1984, he was appointed Professor at the TU Dresden and in 1990; he became Head of the Institute of Textile and Clothing Technology.

INTRODUCTION

Textile reinforced concrete is a new and innovative building material with excellent properties and offers a versatile scope of design. It is an interesting alternative (but also a possible combining component) to common building materials such as steel or short-fiber reinforced concrete. Possible applications are the repair of buildings as well as the production of precast concrete parts.

Arranging the reinforcing component, in the form of long fibers assembled to yarns, in the load direction and not randomly such as with short fibers is decisive in its ability to carry the tensile and bending forces. By using long fibers the load capacity is increased, whereas the number of fibers can simultaneously be reduced. Long fibers processed in modern textile machinery are the most effective way of producing textile reinforcements.

Since 1993, fundamental research has been conducted at the Institute of Textile and Clothing Technology (ITB) of the Technische Universitaet Dresden, Germany, to develop load-adapted textile reinforcements. During this time, a broad range of mock-up applications have been developed, such as concrete formwork systems, sandwich elements, acoustical insulation elements, precast façade and balustrade panels, multi-layer composite tubes, abrasion-resistant layers and reinforcements for concrete masts.

AR glass filament yarn

Concrete has a low tensile strength. This must be compensated by creating a composite of concrete and reinforcing material. The reinforcing effect is most significant when the modulus of elasticity of the reinforcing material is much higher than that of concrete, thus the stiffness of the composite is drastically reduced when cracks form. The reinforcing material must consistently withstand the alkaline environment and not be allowed to corrode. By utilizing alkali-resistant (AR) glass fibers, the advantage of textile reinforcements can be fully exploited, namely thin and light-weight parts with no minimum concrete cover necessary. The properties of these fibers are well suited for the reinforcement of concrete: high tensile strength of 1400 MPa or 200 ksi (yarn), sufficient linear elastic breaking elongation of 2 %, modulus of elasticity between 70,000 MPa (10,150 ksi) and 80,000 MPa (11,600 ksi), low density of 2.8 kg/dm³ (175 lb/ft³), good adhesion to concrete and a good cost-performance ratio with an average price of 24 €/dm³ (680 €/ft³) [1]. It has to be taken into consideration that 1 % fiber volume in the composite is sufficient to bear the load. The fineness of the yarns ranges between 300 and 2500 tex (g/1000 m or 0.0035 lb/mile).

These yarns consist of several hundred and up to thousands of single filaments (continuous fibers) with diameters between 5 and 25 µm (200 and 985 µin.). The cohesion between the filaments of one thread is maintained in the concrete. Only the outer filaments are integrated in the cementitious matrix. Those fibers that lie in the core of the yarn have no direct contact with the matrix, but only with their neighboring filaments.

Carbon filament yarn

Carbon filaments offer superior properties, which make them a very interesting material for the reinforcement of concrete. The tensile strength of the filaments ranges between 3000 MPa (435 ksi) and 5000 MPa (725 ksi) (high tenacity fibers). In the yarn itself, it is still about 2000 MPa (290 ksi). This is accompanied by a very low density of 1.8 kg/dm³ (110 lb/ft³), low creeping and heat expansion, good damping characteristics and a high resistance to acids, alkalis and organic solvents. However, their application in cementitious matrices is still rare [1]. Since they are sensitive to lateral pressure and are highly conductive, processing these fibers is difficult, but possible on state-of-the-art textile machinery. The knowledge gathered for glass filament yarns has to be adopted for carbon filament yarns. The aim is to compensate for the more unfavorable adhesion to concrete and the higher price (depending on the yarn properties 40 €/dm³ or 1130 €/ft³) by optimally using the fiber properties in the composite.

TEXTILE STRUCTURES

Utilizing fiber reinforcements as textile sheets fitted to the form of the building component brings many advantages. It makes reinforcement near the surface possible not only in rounded and bent components, but also in straight components, and in multiple load-

4 Hausding et al.

bearing directions. The yarn can be easily positioned and its position easily reproduced. Furthermore, these two-dimensional reinforcements can be integrated into the composite as three-dimensional structures.

Reinforcing textiles should have an open structure and be non-deformable. The openness is necessary to guarantee a maximum perimeter of the yarn, thus ensuring the transfer of the load into the reinforcing component. The geometry of the textile depends on the maximum grain size, the necessary volumetric content of the fibers and the possibilities of the textile machine. The shape accuracy (depending on bending and displacement behavior) is fundamental for maximum fiber strength utilization and good handling.

That means that some textile manufacturing processes (for example warp knitting with reinforcing threads) are very well, and others (such as braiding with its closed surface) are not suited for this purpose. Besides warp knits (plain, circular or three-dimensional) fabrics commonly used for the reinforcement of concrete are adhesively bonded multiplies (plain or circular) and wovens [1].

At the ITB the stitch-bonding technology for the making of plain, mechanically bonded multiplies was chosen as the best method to produce textile reinforcements for concrete. It is a special version of the warp knitting technology. The decisive advantages are the high productivity, especially when producing high quantities (Figure 1) and the ideal orientation of the reinforcing layers. That means the threads can be arranged flexibly and drawn according to the expected load.

Multiplies are fabrics consisting of one or more parallel and drawn layers of threads that can have different orientations (EN 13473). Two layers form a bi-axial multi-ply; three or more layers a multi-axial multi-ply.

Multi-axial multiplies have versatile properties such as: drawn thread orientation, different angles between the layers, manifold layer composition and arbitrary mass. A stitch-bonded multi-axial multi-ply consists of several layers of reinforcing threads and a mesh structure – the warp knit. Up to eight layers can be combined with the orientation of the layers arranged as necessary (for example 0° , 90° , $+45^\circ$, -45° , Figure 2). The 0° orientation is called the warp system and corresponds to the work direction. The other layers are called weft systems.

TECHNOLOGICAL OPTIMIZATION

Structural stabilization

The most important challenge when using glass filament yarn or other high-performance fibers is to utilize the fiber strength as much as possible. It can be drastically reduced by processing filaments to yarns and yarns to fabrics. Since only the outer filaments of the yarn are connected with the cementitious matrix, the filaments are not stressed in equal measure. Therefore, it is most important to increase the cohesion between the filaments.

A means for increasing this cohesion and achieving the additional effect of better utilizing the filament strength could be applied either to the yarn or to the fabric. The textile characteristics of the yarn and fabric (especially the low flexural strength) however, must be maintained. Research has shown [3] that the tensile strength can be increased by applying a coating to the yarn before it is processed (Figure 3, left). But the flexural properties, and especially the resistance against lateral pressure (measured as ratio of loop tensile strength of uncoated and coated material, Figure 3, right) are thereby influenced in a way that processing on stitch-bonding machines becomes impossible. Due to this, coating should be applied not to the yarn but to the fabric.

A device for this purpose has been integrated into the multi-axial warp knitting machine. The stabilization must be accomplished at machine level while the multi-ply is still clamped. If the multi-ply was not fixed before being cut free, displacement would be unavoidable.

Based on a theoretical analysis of potential stabilization methods, the following selected techniques were examined outside of the machine: spray and dip coating with water based polymer dispersions, thermobonding with thermoplastic material and laminating with duromers [5].

Tension tests have shown that the tensile strength of the coated structures is clearly increased, whereas the thermally bonded structures display no such effect (Figure 4).

The results of the different stabilization methods can be clearly evaluated with a new bending test including vertical specimen arrangement (see below). The flexural strength of the spray coated and thermally bonded textiles is only slightly increased. Dip bonding causes a high increase in flexural strength and the laminated structures no longer possess any textile characteristics (Figure 5). The displacement test shows a large increase in deformation resistance with all stabilization methods (Figure 6). Considering the combination of the above mentioned properties (high tensile strength, good deformation resistance, acceptable increase in flexural strength), the coating technique proves to be the best method available to stabilize open grid reinforcing structures and to mobilize the filament strength in the fabric [6][7].

The coating is done on a roll-coater. An infrared heating device is used for effective drying [7][8]. The wave-length profile of the radiator is modified to fit the point of maximal absorption of water. This drying process is very well suited for integration into the textile manufacturing process due to its dynamic process control with extremely short temperature cycling stress. Thus, the optimal speed of the multi-axial warp knitting machine can be fully maintained.

The coating and drying devices have been integrated into the multi-axial warp knitting machine (Figure 7) and were adjusted and modified to fit the following parameters: precise dosing, constant and reproducible application on both fabric sides and over the width of the machine.

6 Hausding et al.

New testing methods

To evaluate the influence of an additional stabilization method on the fabric, it is necessary to develop and adopt testing methods for the quantitative characterization of shape accuracy.

To examine the bending behavior of the open grid structures a specially developed bending test with vertical specimen arrangement is used (Figure 8). The specimen is clamped perpendicularly, and the bending edge is situated in the center of rotation. The bending results from the rotation of the specimen against a fixed bar. The pressure load on the bar is measured as a turning moment. Any influence of gravity is practically avoided by this arrangement. According to Engler et al. 2004 [4] this new method can display the differences between open grid reinforcing textiles better than the usually applied Cantilever test (DIN 53362). To reduce as much outside influence as possible an electronically controlled testing device is currently being developed at the ITB.

Another possibility to measure the handling properties of reinforcing structures is the displacement test (Figure 9). This device provides for the two-dimensional shape of the textile. The clamping area is twisted against the textile fixed with pins [5]. The parameter measured is the turning moment at a certain angle of rotation.

Perspectives

The aim behind the current research on textile reinforcements is to create multi-pplies that meet the various demands of cementitious matrices. This also applies to handling on the construction site. A satisfactory compromise has to be found between flexural strength and deformation resistance on one hand and needed drapability on the other. This in addition to a high mobilization of the filament strength can be achieved by machine integrated stabilization. By determining and evaluating all influencing factors it will be possible to systematically and reproducibly manufacture multi-pplies with properties meeting exact requirements. Furthermore, the geometry will be improved to achieve even better composite characteristics.

EXAMPLES

Stitch-bonded multi-pplies as developed at the ITB can serve multiple purposes. The following examples of reconstruction, precast components and waterworks engineering are just a sampling.

Reconstruction

Masts made of prestressed and reinforced concrete are exposed to extreme weather conditions, but have to maintain their load-capacity for decades. However, many of these masts already show damages after about 15 years. While longitudinal cracks are less severe, the repair of damages caused by torsion makes high demands on the reconstruction method. By covering the masts with multi-axial stitch bonded multi-pplies and shotcrete (Figure

10), damages caused by both torsion and bending can be repaired reliably. The load-capacity is even increased by more than 80 % (Figure 11) whereas the ductility is also greatly improved. Repairing these masts is much cheaper than underground installation or erecting new masts [9].

Precast concrete parts

One example for the use of textile reinforcements in the construction of buildings is the balustrade panel developed at the TU Dresden that is integrated in the façade of parking garages (Figures 12, 13). The possibility of creating extremely thin concrete members by using textile reinforcements is best exploited by developing precast parts. Since the glass fibers are not corrosive and thus require no minimum concrete cover, it is possible to reduce the thickness of the concrete part by up to 75 % (Figure 14) and the weight by up to 80 %. Transportation and assembly costs are decidedly reduced. Furthermore, these precast components offer an aesthetic alternative for parking garages [10]. Transverse and bending loads were examined to determine the loading performance of the textile reinforcement plates of the dimension 1.5 m x 2.5 m or 4.9 x 8.2 ft (Figure 15, left). The results show that large pre-fabricated concrete parts with textile reinforcement have an adequate reinforcement value. Both bearing capacity and serviceability have been proved to be sufficient and adequate (Figure 15, right).

Hydroworks

Solid matters carried by streaming water cause high attrition and finally deterioration on hydroworks construction. An alternative to common protective layers made of special concrete are concrete layers reinforced with AR glass near the surface. Cracks are clearly reduced and the strength against other strains is increased. The protective layer can be integrated into new buildings or be subsequently applied for repair purposes [4]. Important advantages are achieved by combining the textile reinforcement with short fibers. The attrition is cleared reduced compared to concrete without reinforcement, as well as with textile reinforcement or short fibers alone (Figure 16). While the textile fabric carries the tensile load, the short fibers reduce the spread of cracks.

Another promising product are composite plastic tubes covered with textile reinforced concrete (Figure 17). By optimally dividing the functions, it is possible to use the advantages of plastic tubes; such as high resistance against aggressive media and good cost-performance ratio in high pressure applications and with large diameters. The combination of textile reinforcements and short fibers greatly increases the strength of the concrete layer (Figure 18) [11].

CONCLUSION

The usage of textiles for the reinforcement of concrete is a new, flexible and efficient technology. Based on its distinguished and versatile properties the textile reinforced concrete is suited for special as well as mass production. It offers a multitude of possibilities for light-weight construction, thereby reducing costs and allowing for new architectural

8 Hausding et al.

design. For the first time modern textile production methods are used that insert the reinforcing fibers in the quantity and structure according to the load. The machinery presented here permits low cost production with reproducible and predictable results. The assessment of both practical use and marketability confirms many possibilities for the use of textile reinforced concrete compared to steel or short fiber reinforcements. It can be used for repairing and strengthening existing structures, as well as for the production of load-bearing or non-load-bearing precast parts.

REFERENCES

Referenced Standards

DIN 53362, "Bestimmung der Biegesteifigkeit nach Cantilever," 2000, p. 3.

EN 13473, "Reinforcement – Specifications for Multi-Axial Multi-Ply Fabrics," 2001, p. 1-8.

Cited References

- [1] Offermann, P.; Engler, T.; Gries, T.; and Roye, A., 2004, "Technische Textilien zur Bewehrung von Betonbauteilen," *Beton-und Stahlbetonbau*, Vol. 99, No. 6, pp. 437-443
- [2] Abdkader, A.; Offermann, P.; Jesse, F.; and Curbach, M., 2003, "Textilbewehrter Beton mit AR-Glasfilamentgarnen," *Industrial Fabrics Bulletin*, Vol. 13, No. 3, pp. 50-54
- [3] Abdkader, A.; Engler, T.; Franzke, G.; and Offermann, P., 2004, "Processability of Coated AR Glass Filament Yarns," *ITB-Mitteilungen*, No. 2, pp. 9-15
- [4] Engler, T.; Franzke, G.; Horlacher, H.-B.; Offermann, P.; and Schmutterer, Ch., 2004, "Abrasionsverhalten textilbewehrter Feinbetonschichten," *Kettenwirk-Praxis*, Vol. 38, No. 2, pp. 17-20
- [5] Offermann, P.; Koeckritz, U.; Abdkader, A.; Engler, T.; and Waldmann, M., 2003, "Load-Adapted Textile Structures for Concrete Reinforcement," *Textile Reinforced Structures. Proceedings of the 2nd Colloquium on Textile Reinforced Structures (CTRS2), Dresden, Germany, 2003*, ed. Curbach, M., Technische Universitaet Dresden, pp. 15-28
- [6] Koeckritz, U.; Franzke, G.; Offermann, P.; and Waldmann, M., 2004, "Stabilisation of open grid structures in the warp knitting machine," *Proceedings of the 7th Dresden Textile Conference 2004, Dresden, Germany*

- [7] Koeckritz, U.; Franzke, G.; Offermann, P.; and Waldmann, M., 2004, "The Sustainable Structural Stabilisation of Open Grid Warp Knits," *11th International Conference on Composite / Nano Engineering (ICCE-11), Hilton Head Island, USA 2004*
- [8] Koeckritz, U.; Klug, P.; Offermann, P.; and Giessmann, A., 2004 "Drying of Textile Structures by Means of Convective Heat Flow," *Technical Textiles* Vol. 47, No. 4, pp. 202-206
- [9] Engler, Th.; Schierz, M.; Franzke, G.; and Offermann, P., 2002, "Standfest auch im Sturm durch multiaxiale Gelege," *Kettenwirk-Praxis*, Vol. 36, No. 4, pp. 22-23
- [10] Offermann, P. et al., 2003, "Textilbewehrte Bruestungselemente für Parkhaeuser," *Kettenwirk-Praxis*, Vol. 37, No. 2, pp. 20-22
- [11] Hausding, J. et al., 2005, "Textile reinforced multi-layer composite tubes for pressure line systems," *ICCM 15, Durban, South Africa, 2005*
- [12] Offermann, P.; Franzke, G.; Curbach, M.; and Hempel, R., 2001, "Flaechegebilde zur Sanierung von stahlbewehrten Betonelementen - Maste, Schalen, Platten," *Institut fuer Textil- und Bekleidungstechnik der TU Dresden, Institut fuer Tragwerke und Baustoffe der TU Dresden, Forschungsbericht zum AiF-Forschungsprojekt Nr. 11981 B*
- [13] Koeckritz, U.; Franzke, G.; and Offermann, P., 2005, "In-Situ Structural Stabilization of Open Grid Warp Knitted Fabrics," *The Textile Institute 84th Annual World Conference, Raleigh, USA, 2005*
- [14] Offermann, P., and Curbach, M., 2003, "Entwicklung einer großformatigen, duennwandigen, textilbewehrten Bruestungsplatte mit hoher Sichtflächenqualität einschließlich Herstellungstechnologie," *AiF-Forschungsbericht Nr. 4 ZBR/2, Technische Universitaet Dresden, Institut fuer Textil- und Bekleidungstechnik und Institut fuer Tragwerke und Baustoffe*
- [15] Offermann, P.; Franzke, G.; and Horlacher H.-B., 2003, Erhoehung der Abrasionsfestigkeit von duennen Moertelschichten durch textile Strukturen," *AiF-Forschungsbericht Nr. 12872 BR, Technische Universitaet Dresden, Institut fuer Textil- und Bekleidungstechnik und Institut fuer Wasserbau und Technische Hydromechanik*

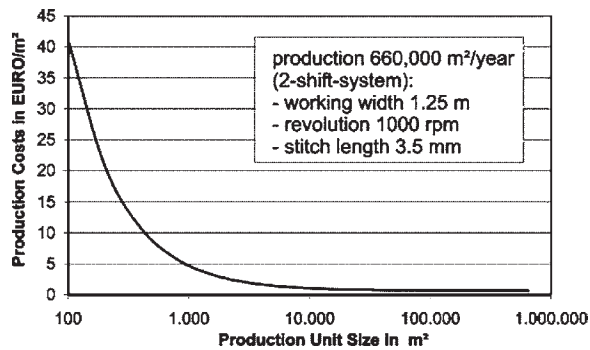


Fig. 1—Productivity of multi-axial warp knitting machine Malimo 14024. ^[12]
(1°€/m² ≈ 0.09°€/ft², 1 m² ≈ 0.09 ft², 1 m ≈ 3.28 ft, 1 mm ≈ 0.04 in.)

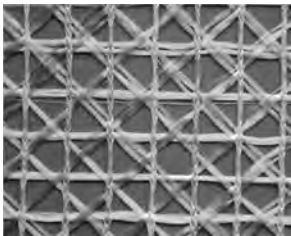


Fig. 2—Stitch-bonded multi-axial multi-ply.

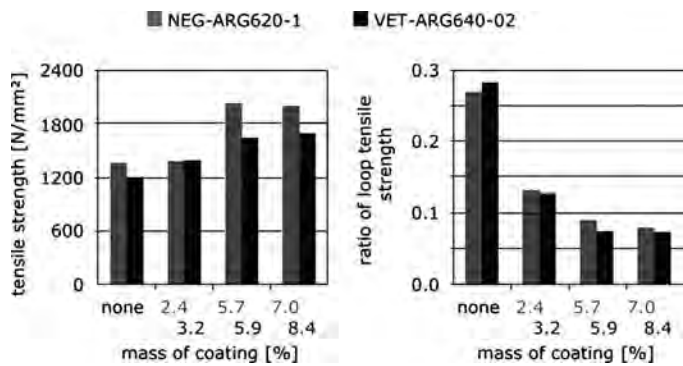


Fig. 3—Influence of mass of coating on tensile strength and loop tensile strength for two different types of AR glass yarn. ^[3] (1 N/mm² ≈ 0.15 ksi)

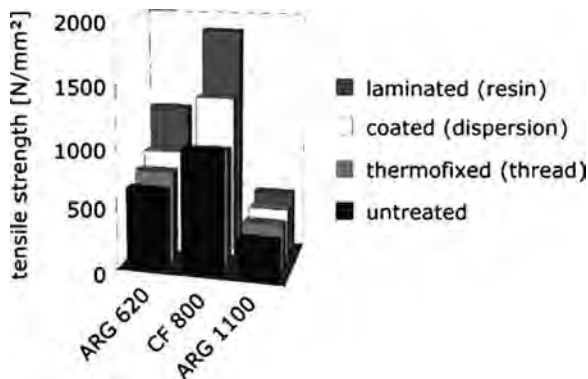


Fig. 4—Tensile strength of different multi-ply structures depending on the stabilization method.^[13] (1 N/mm² ≈ 0.15 ksi)

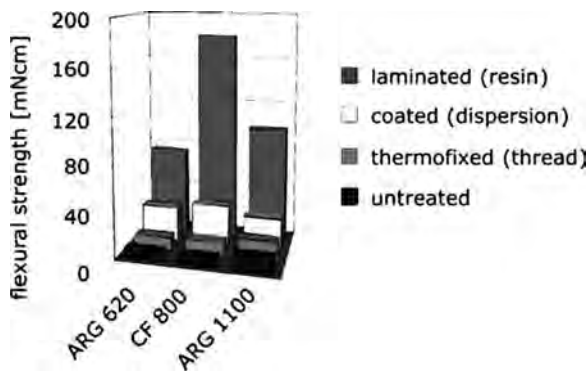


Fig. 5—Flexural strength of different multi-ply structures depending on the stabilization method.^[13] (1 mNcm ≈ 7.4e-6 lb ft)

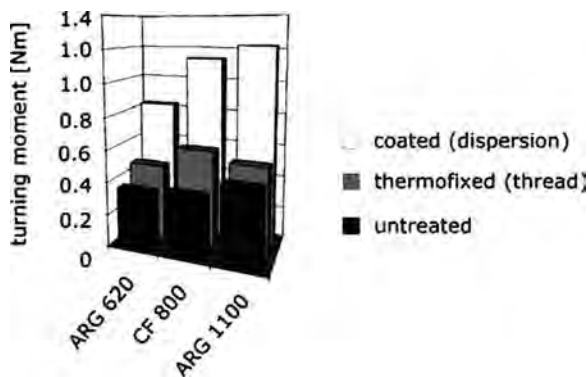


Fig. 6—Resistance against displacement of different multi-ply structures depending on the stabilization method.^[13] (1 Nm ≈ 0.74 lb ft)



Fig. 7—Drying and coating devices.



Fig. 8—Bending test with vertical specimen arrangement.^[14]



Fig. 9—Displacement test.^[14]

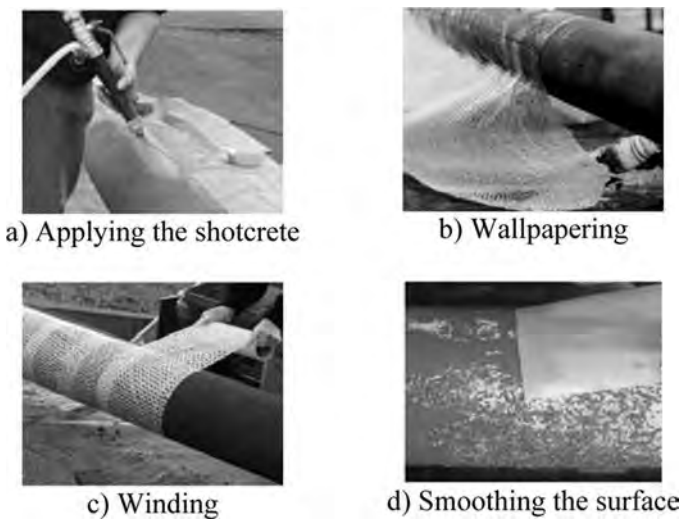


Fig. 10—Textile reinforcement of concrete masts.^[12]

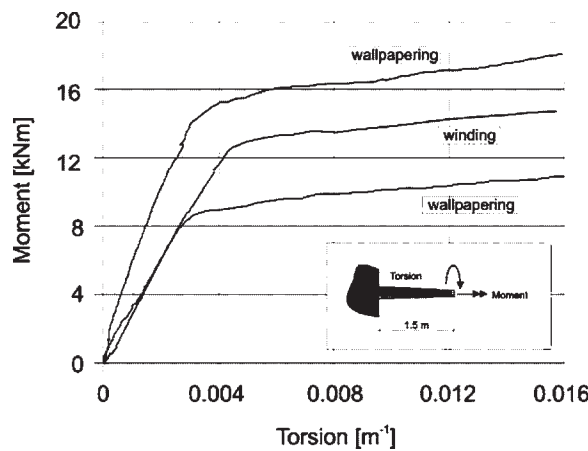


Fig. 11—Moment-torsion-performance of textile reinforced concrete mast.^[12]
(1 kNm $\approx$ 737.6 lb ft, 1 $m^{-1} \approx$ 3.28 ft^{-1})

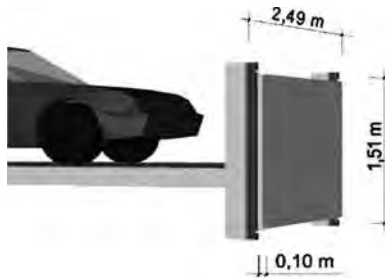


Fig. 12—Mounted ferro-concrete façade.^[14] (1 m ≈ 3.28 ft)

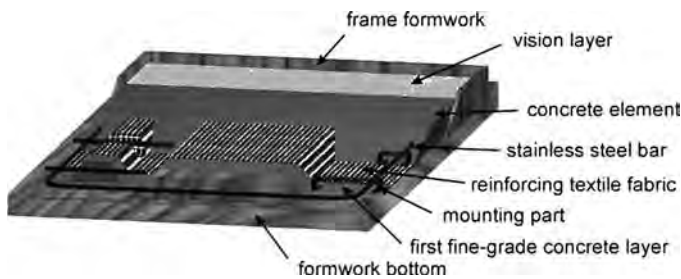


Fig. 13—Textile reinforced balustrade panel.^[14]

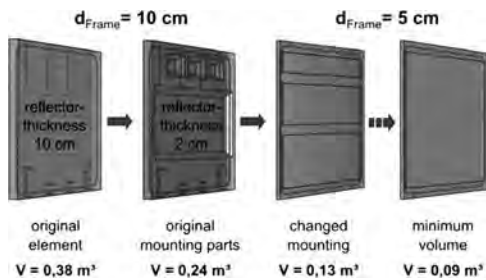


Fig. 14—Component development.^[14] (1 cm ≈ 0.39 in., 1 m³ ≈ 35.3 ft³)

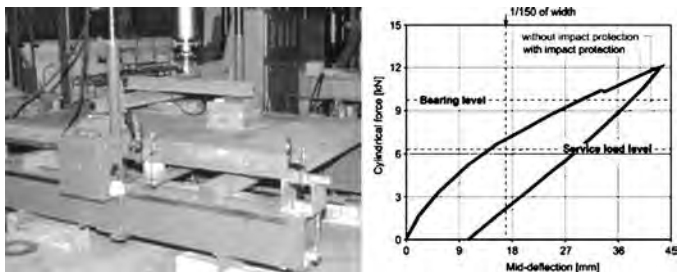


Fig. 15—Balustrade panel, test setup, and stress-strain behavior.^[14]
(1 kN ≈ 224.8 lb, 1 mm ≈ 0.04 in.)

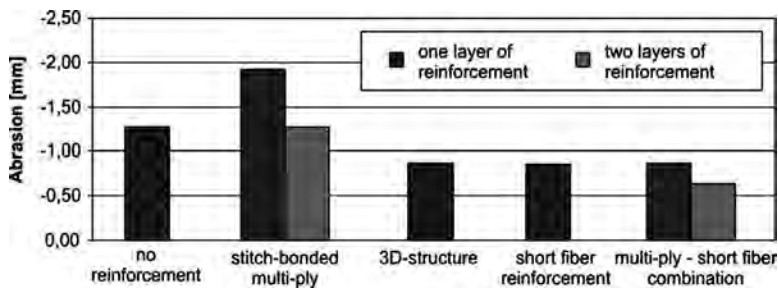


Fig. 16—Abrasion of concrete depending on the reinforcement.^[15] (1 mm ≈ 0.04 in.)

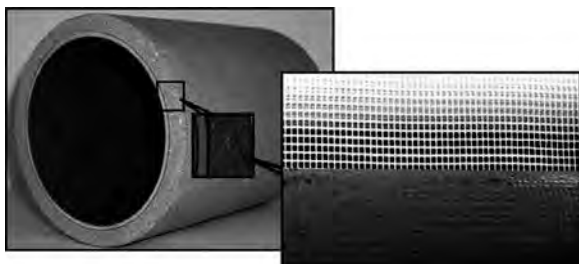


Fig. 17—Textile reinforced multi-layer composite tube.

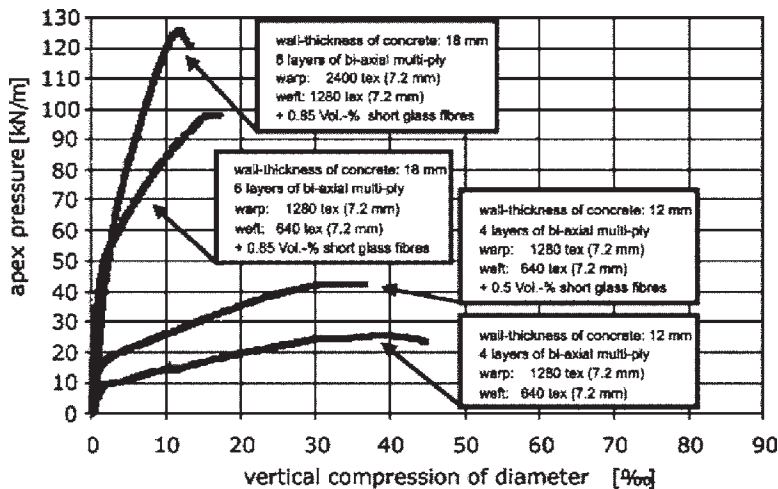


Fig.18—Apex pressure resistance of textile concrete composite tubes depending on number of reinforcing layers and short fiber amount.
(1 kN/m ≈ 68.5 lb/ft, 1 mm ≈ 0.04 in.)

Pull-out Characteristics of a Glass Yarn Embedded in a Cementitious Matrix

by B. Banholzer and W. Brameshuber

Synopsis: Although the bond of a multi-filament yarn in a cementitious matrix is controlled by the bond properties between filaments and matrix, more detailed information is needed to evaluate the failure mechanisms of such a complex system under a pull-out load and hence allow an analytical and numerical simulation of this composite. In this study innovative test methods are presented and used to identify the debonding process of a yarn as a result of the pull-out process, and ascertain the contact faces between the individual filaments and the matrix. Additionally, numerical procedures are proposed based on these findings and allow to establish a direct relationship between the load history of a pull-out test, and the failure process of an AR-glass yarn, by means of a mathematical function, defined as the active filaments versus displacement relation $NF(\Omega)$. Together with the load versus displacement relationship $P(\Omega)$ derived also during the pull-out test an analytical characterization and simulation of the bond between an AR-glass multi-filament yarn and a cement based matrix will be possible.

Keywords: bond; concrete; filament; model; pull-out test; simulation; yarn

18 Banholzer and Brameshuber

Björn Banholzer, Dr.-Ing.: Research assistant at the Institute of Building Materials Research at RWTH Aachen University, Germany. Graduate of RWTH Aachen University and of the Imperial College London (U.K.).

Wolfgang Brameshuber, Prof. Dr.-Ing.: Professor at the Department of Engineering and head of the Institute of Building Materials Research at RWTH Aachen University, Germany. Chairman of the RILEM committee "Textile reinforced concrete (TRC)". Former head of the international research laboratory of the construction company Bilfinger Berger.

INTRODUCTION

Concrete is relatively brittle, and its tensile strength is typically only approximately a tenth of its compressive strength. Regular concrete is therefore normally reinforced with steel reinforcing bars. Such reinforced concrete structures are used in almost every area of structural engineering. However, a replacement of the steel reinforcement in concrete structures with for example technical textiles (fabrics) is rapidly becoming an interesting option for constructed facilities. Placing multiple 2D fabrics made of alkali resistant glass (AR-glass) instead of the usual steel bars in the main load directions of the concrete might enable the engineer in the future to design and build light and slender structures with a high load carrying capacity if the basic load carrying mechanisms of this composite are known; one component is the bond mechanism between the yarns of a fabric and the surrounding matrix.

These bond properties also govern the load carrying capacity of the system during a pull-out test which is a typical test to determine the bond characteristics of a composite. Furthermore, they predominate the resulting failure mechanism which is quite complex because an AR-glass yarn represents an element of reinforcement quite different from other fibrous reinforcements used in cement based composites; especially steel fibers. In the present case the AR-glass yarn itself consists of several hundred randomly arranged individual filaments approximately 10 to 30 μm ($3.94 \cdot 10^{-4}$ to $1.18 \cdot 10^{-3}$ in.) in diameter. Fig. 1 shows a cross-section of such an AR-glass yarn embedded in a cementitious matrix. Obviously this non-uniform nature of the yarn and the random penetration of the concrete induce the inherently variable microstructure of this composite which in turn causes the substantial scatter in the force-displacement relationships determined in pull-out tests on yarn / matrix systems (Bartos 1982). So far only very limited data are available in regard to these microstructural properties, which strongly affect the transfer of shear forces between yarn and matrix and hence the composite's mechanical behavior. Because of this lack of information, the interpretation of experimental results even for the apparently simple pull-out test causes considerable difficulties since an analytical or numerical modeling of a yarn / matrix system is restricted.

Based on the limited available data, the main objective of this study is therefore to develop experimental tests and analytical tools to determine and evaluate the micromechanical and microstructural properties, which define the principal shear bonding characteristics of an AR-glass yarn / cement based matrix system. The aim is to subsequently derive an

analytical model which is capable of simulating the pull-out response of this composite. The presented work is part of the doctoral thesis by Banholzer (2004).

In order to achieve the objective, the following sub-problems are taken into consideration:

The principal shear bonding characteristics and mechanisms between AR-glass and a cementitious matrix are identified and evaluated.

Detailed information on how an AR-glass yarn in a cementitious matrix reacts under a pull-out load is gained and the dominating failure mechanisms are to be determined.

The load carrying cross-section of the yarn and the corresponding longitudinal contact area with the surrounding matrix are both qualitatively and quantitatively determined at each load step during the pull-out test.

The findings and solutions for each sub-problem listed above, and the relationships and principles discovered between these different domains are finally used to assemble a solution to the overall problem, which describes the shear force transmission and models the pull-out response of an AR-glass yarn / cementitious matrix system.

MATERIALS

Multi-filament yarn – All tests introduced in the following were carried out using Vetrotex Saint-Gobain 2400 tex alkali resistant glass yarns (production date 2001)¹. The unit tex thereby defines the linear weight of the yarn ($1 \text{ tex} = 1 \text{ g/km} = 3.55 \cdot 10^{-3} \text{ lb/mile}$). This yarn usually contains approximately $N_{F,m} = 1400$ filaments with an approximate diameter of $29 \mu\text{m}$ ($1.14 \cdot 10^{-3} \text{ in.}$). All filaments are assembled in the form of a flattened bundle. The tensile strength and the Young's modulus of a single filament have been determined in tension tests as $1,457 \text{ N/mm}^2$ (211.3 ksi) and $54,000 \text{ N/mm}^2$ (7,832 ksi) respectively (Banholzer and Brameshuber 2004).

Fine grained concrete – Within the collaborative research project SFB 532 "Textile reinforced concrete" undertaken at RWTH Aachen University, a fine grained binder system for textile reinforced elements was developed which meets special demands in regard to the production processes, the mechanical properties of the composite and the durability of the textile reinforcement (Brameshuber 2004). The matrix shows a high-flowable consistency which offers full penetration of the fabrics. These special properties are achieved by using a small maximum grain size ($d_{\text{max}} = 0.6 \text{ mm} = 2.36 \cdot 10^{-2} \text{ in.}$), high binder contents ($700 \text{ kg/m}^3 = 43.7 \text{ lb/ft}^3$), and by adding different pozzolanic additives. This leads to a more homogeneous and finer structure in comparison to ordinary concrete. The composition of the mixture PZ-0899-01 used for the presented experimental investigations is shown in Table 1. The Young's modulus has been determined in compressive tests as $35,000 \text{ N/mm}^2$ (5,076 ksi).

¹ <http://www.sgva.com>

BOND BETWEEN GLASS FILAMENTS AND A CEMENT BASED MATRIX

In civil engineering one of the most common tests to investigate the shear force transmission between e.g. a re-bar or a fiber and a cement based matrix is the so-called pull-out test. In this test a force P pulls a single, monolithic reinforcing element with diameter d out of a cuboid of matrix with dimensions $D \cdot D \cdot L$ while the corresponding displacement ω is recorded. The matrix is either fixed at the top (pull-push test) or fixed at the bottom (pull-pull test). Because an AR-glass yarn is made up of many single, cylindrical, monolithic structures in the form of filaments (Fig. 1), the pull-out test on a single filament is also feasible to investigate the shear bond characteristics between AR-glass and a cementitious matrix. Most of the single filament pull-out tests developed and carried out so far, however, are used to evaluate the bond between different types of resin and filaments. Some of the few studies found pertaining to pull-out tests on filament / cement based matrix systems are by (Katz, Li and Kazmer 1995). On the basis of this information a single filament pull-out test was developed and used for the experimental identification of load displacement relations $P(\omega)$ of a filament / matrix system (Banholzer and Brameshuber 2004).

The analytical approach introduced in (Banholzer, Brameshuber and Jung 2005) which is based on the principle of the cohesive interface model can be generally used to determine a bond stress versus slip relation (BSR) $\tau(s)$ on basis of experimental load displacement relations $P(\omega)$. Here ω defines the slip of the single filament at a location $x = L$. A N -piecewise linear $\tau(s)$ relation is adopted in this approach where the number N of the linear intervals assumed is not limited and thus if N is taken large, any possible bond law distribution can be approximated. Therefore, a general mathematical description of this relation is allowed. Because it is not possible to find a closed form analytical solution for this approach, a simple numerical procedure is used to evaluate the $\tau(s)$ for a given material combination. Since the proposed model could be verified on the basis of experimental steel fiber pull-out tests with different fiber radii and embedded lengths, it was used to derive the underlying BSR $\tau(s)$ defining the bond at an age of 28 days between a filament extracted from a 2400 tex Vetrotex yarn and a PZ-0899-01 concrete. Fig. 2 shows this analytically derived BSR $\tau(s)$. For more information see (Banholzer and Brameshuber 2004) and (Banholzer, Brameshuber and Jung 2005).

BOND BETWEEN GLASS YARNS AND A CEMENT BASED MATRIX

Various mechanical tests have been developed to date to determine the parameters of interfacial action and thus the principle bonding mechanisms between an AR-glass yarn and a cement based matrix. A detailed review is given in (Banholzer 2004). For the present study a one-sided pull-out test was chosen and modified in order to gain information on the pull-out response $P(\Omega)$ which is needed as one main input parameter for a subsequently carried out analytical modeling of the composite. In the present case Ω defines the slip of the yarn, i.e. the bundle of filaments, at a location $x = L$. However, the so determined $P(\Omega)$ relation is not sufficient to characterize the actual failure and break-down process of the yarn / cement based matrix system but other experimental techniques have to be applied to identify the onset and subsequent array failure of the reinforcing filaments.

Firstly the so called Confocal Laser Scanning Microscopy (LSM), mainly known from the measurement of cells (biology) or from the DNA analysis (medicine), combined with the Back Scattering Analysis (SEM) are used (Banholzer 2004). Together with the results of the pull-out tests it can be shown, that a causal relationship between the maximum pull-out load and the occurring damage as well as failure mechanism exists. Secondly a new technique is introduced in (Banholzer 2004), which uses the light transmission properties of glass filaments to set up a test scheme, which allows an online measurement of the failure mechanisms occurring during a yarn pull-out. Due to this background this test is called FILT test (Failure Investigation using Light Transmission properties). The specimen is exposed by light from the front (clamping range) and by using a small digital microscope the yarn can be identified on the rear of the specimen during the pull-out test due to its exposure and therefore bright appearance. The test set-up is presented in Fig. 3. Depending on the resolution it is possible to visualize every single filament. After a tensile failure a filament is no longer capable of transferring light, and therefore the bright spot vanishes in the image of the next load step. If a numerical image-analyzing routine is applied the optical image of the CCD-camera (charge-coupled device camera) can be analyzed and converted in a binarized image (black and white pixels). A subsequent numerical procedure allows the evaluation of these binarized images with regard to the number of white pixels the image contains. By using this computer routine it is possible to plot the number of pixels recorded versus the corresponding load and displacement from the pull-out test respectively. Since only an optical image of the CCD-camera visualizing the filaments is analyzed and converted in a binarized image outlining the filaments as white pixels, the number of these identified pixels can be directly related to the cross-sectional area of the yarn and thus to the number of filaments in a yarn. For detailed information see (Banholzer 2004). As a supplementary evaluation process, the binarized image of each load step is analyzed with regard to the number of white pixels $N_{p,c}$ in contact with surrounding black pixels, and hence the contact perimeter U_c of the load carrying filaments with the surrounding layer can be determined. Similar to the above described procedure the width and height of a pixel can be correlated to a real length by using a proportional parameter C which is evaluated as described in (Banholzer 2004).

Fig. 4A shows the recorded pull-out load versus displacement relations $P(\Omega)$ of four tests which were carried out with a 2400 tex Vetrotex yarn in combination with a PZ-0899-01 matrix after 28 days. In general the principal trend of a pull-out relation can be observed. The variability is quite acceptable for pull-out tests on yarns embedded in a cementitious matrix. Bartos (1982) experienced even more than 40 % scatter in his tests results, which is caused by the uncontrollable and random penetration of the matrix into the core of the yarn or by an unstable debonding caused by the “Poisson contraction” effect as described by Kelly and Zweben (1976).

The determined $N_F(\Omega)$ relations (number of filaments failed at a pull-out displacement Ω) are presented for the four specimens in Fig. 4B. In principle all progressions are characterized by a short almost horizontal line between $0 \leq \Omega \leq 0.12 \text{ mm}$ ($4.72 \cdot 10^{-3} \text{ in.}$) followed by an exponential decay; that means almost no filaments fail in tension before the maximum pull-out load is reached. A more detailed comparison of the presented

22 Banholzer and Brameshuber

active filament versus displacement diagrams reveals the varying breakdown of the filaments of the four yarns tested. Whereas the filaments of specimen B fail rapidly so that at a displacement of 0.5 mm ($1.97 \cdot 10^{-2}$ in.) only 23 % of the filaments are left undamaged, specimens A and D are left with 61 % of intact filaments at the same displacement. Specimen C retains about 40 % lying somewhere in between. The gradient of the $N_F(\Omega)$ relationship for specimen B decreases noticeably at the end of the pull-out test finally leaving about 6 % of filaments which have not failed in tension at a maximum displacement of approximately 1.7 mm ($6.69 \cdot 10^{-2}$ in.). Specimen A is left with the highest percentage (20 %) of unbroken filaments at the same introduced displacement. The overall scatter of the $N_F(\Omega)$ relations corresponds to the corresponding $P(\Omega)$ relations of the pull-out tests. More results and a more detailed discussion can be found in (Banholzer 2004).

For all of the specimens presented, the contact perimeter U_C steadily increases until a displacement of about 0.25 mm ($9.84 \cdot 10^{-3}$ in.) is reached (Fig. 4C). A subsequent decreasing stage follows. Specimen B starts out with the highest contact perimeter of 12.6 mm (0.496 in.), whereas U_C for specimen A and D is noticeably lower at about 8.2 mm (0.322 in.). The increase in percentage of the progression is about the same for all four specimens. However, the following almost linear drop from a contact perimeter of 15 mm (0.591 in.) to 8.2 mm (0.322 in.) within a displacement range of 0.18 mm ($7.09 \cdot 10^{-3}$ in.) is unique for specimen B although specimen C follows a similar but more gradual progression. In contrast the results of specimen A and D show a more steady decrease. At the final pull-out displacement of 1.7 mm ($6.69 \cdot 10^{-2}$ in.), specimen B is left with a contact perimeter of less than 4 mm (0.157 in.) whereas specimen C and D end up with a U_C of about 5 mm (0.197 in.), although they started with a considerably different initial value at the origin. Specimen A shows the highest value for U_C at $\Omega = 1.7$ mm ($6.69 \cdot 10^{-2}$ in.) with 8 mm (0.315 in.).

MODELING OF A YARN PULL-OUT

The fracture behavior of unidirectional fibrous composites - in the current case a yarn embedded in a cementitious matrix - has been tackled with several approaches over the years. One of the simplest approaches to idealize this system, the so-called one cylinder model (Fig. 5), is to assume a homogeneous and linear elastic yarn loaded under quasi-static conditions and further neglect matrix deformation. However, as has been shown in (Banholzer 2005), this simplification of the composite does not reflect the telescopic and staggered failure of the yarn in any way.

A somewhat more progressive approach had already been introduced some years beforehand by Ohno and Hannant (1994), who idealized the yarn / matrix system as a two ring model containing sleeve and core filaments (Fig. 5). However, since the bond stress between the different “rings” is assumed to be constant and no tensile failure is considered, this model also oversimplifies reality, but nevertheless, the principal idea of the ring structure is adopted in the following derivation.

Segment models as shown in Fig. 5 can likewise be found in a variety of studies, for example (Sejnoha and Zeman 2002). They proposed to use periodic unit cells (PUC) which

consist of N filaments statistically equivalent to the original microstructure. To achieve this, fundamental knowledge about the material's statistics is needed and the original microstructure has to be quantified, e.g. by using a collection of SEM images. Introducing an n -point probability function S_m defining the chance of finding a randomly placed filament located in the matrix, a PUC has to be determined with the help of stochastic optimization procedures which matches in its S_m function with the original microstructure. Hence the actual objective is to define the material statistics and properties of the PUC in accordance with the original composite. However, the bond between the filaments and the surrounding matrix is assumed as perfect, and the different failure mechanisms occurring during the yarn break down, that is debonding and tensile failure of the filaments, are not considered in this model. Thus for example the change in the number of active filaments $N_F(\Omega)$ (load carrying area of the yarn) is neglected and the staggered breakdown cannot be simulated.

Such a filament breakage and debonding of the filaments from the matrix as well as plasticity of the matrix are included in the lamina model proposed by Beyerlein and Phoenix (1997), who enhanced an idea introduced by Hedgepeth (1961) as early as in 1961. In this approach the stress distributions are analyzed in a sheet of parallel, high modulus filaments which carry normal loads and are embedded in a low modulus matrix which carries only shear. Unfortunately, the model implies that the load is introduced only by the filaments (tensional test) and hence this applied technique cannot easily be transferred to this study. However, the principal idea of the superposition techniques and summation procedures used in this approach will be considered in the following derivation of the analytical model.

Based on the evaluated results from the previous sections, that is the BSR $\tau(s)$ controls the bond between AR-glass filament and cementitious matrix, the load versus displacement relationship $P(\Omega)$ describing the pull-out response of a yarn / cement based matrix system, and the active filaments versus load relationship $N_F(\Omega)$ which characterizes the failure process of a yarn during this test,

a solution to the overall problem is proposed which analytically describes the pull-out behavior of a yarn in a cementitious matrix. A model is introduced which uses the above stated findings as main input parameters and yields an analytical simulation of the bond behavior between an AR-glass yarn and a cementitious matrix.

Analytical model

Generally it may be stated that if the pull-out response $p_i(\Omega)$ of every single filament i for $1 \leq i \leq N_{F,m}$ at every single load step is known, the resulting load displacement relationship and hence the overall response of the yarn $P(\Omega)$ can be calculated with a simple summation procedure similar to Hedgepeth (1961). Note, that $N_{F,m}$ corresponds to the number of filaments per yarn, ω to the displacement measured during a filament pull-out test and Ω to the displacement measured during a yarn pull-out test. In mathematical terms this yields

24 Banholzer and Brameshuber

$$P(\Omega) = \sum_{i=1}^{N_{F,m}} p_i(\Omega) \quad (1)$$

If the modeling of a ring structure (Ohno and Hannant 1994) is adopted which is justified by the telescopic failure visualized in the FILT test (Banholzer 2004), the composite may be idealized as a layered system made up of m layers with the number of $o(v)$ filaments per layer v for $1 \leq v \leq m$; see Fig. 6. Note, that o is dependent on v .

The number of filaments $o(v)$ in a layer v can be expressed as

$$o(v) = N_{F,v} - N_{F,v-1}, \quad N_{F,v} = \sum_{j=1}^v o(j) \quad (2)$$

and the corresponding layer pull-out response $p_v(\Omega)$ as $o(v)$ times the average pull-out response $p_{v,a}(\Omega)$ of all filaments of that layer. This yields

$$p_v(\Omega) = \frac{\sum_{i=N_{F,v-1}}^{N_{F,v}} p_i(\Omega)}{o(v)} \cdot o(v) = p_{v,a}(\Omega) \cdot o(v) \quad (3)$$

Hence Eq. (1) can be rewritten as

$$P(\Omega) = \sum_{v=1}^m p_v(\Omega) \quad (4)$$

Eq. (4) states that if all layer responses $p_v(\Omega)$ for $1 \leq v \leq m$ are known, the overall pull-out response of the yarn $P(\Omega)$ may be calculated.

The experimental results presented in (Banholzer 2004) state that the failure process of the yarn is generally predominated by a primary break down of the outer layer of filaments m followed by a successive failure of the adjacent layers until a core of filaments is finally pulled out. Under the assumption that the tensile force of layer v exceeds or equals the tensile strength of layer $v-1$ ($f_{t,v} \geq f_{t,v-1}$) this can be expressed by

$$p_v(\Omega) \geq p_{v-1}(\Omega) \quad (5)$$

Further on, if the filaments in the outer layer m reach their tensile strength and thus also their failure strain prior to the subsequent layers, it may be reasoned, that the average extensional stiffness is gradually decreasing from the outer to the inner layers. Assuming that

the filaments only carry normal loads,

the matrix which penetrated between the filaments only carries shear,

the bond between the single filaments and the matrix is basically characterized by the BSR $\tau(s)$, and

the BSR $\tau(s)$ is identical for all layers,

it may be stated, that the main parameter involving this stiffness gradient has to be the decreasing interlayer contact area $(L U_C)_v$ towards the core of the yarn. Note, L_v corresponds to the embedded length and $U_{C,v}$ to the contact perimeter of a layer v . Although this assumption is verified by the findings presented in (Banholzer 2004), it is so far still not possible to experimentally determine the exact values of these geometric parameters. It must also be pointed out that the contact perimeter $U_{C,v}$ determined with the FILT test (Fig. 4C) only gives a qualitative idea of this parameter since the computer routine only differentiates between white and black pixels, but cannot distinguish whether the black pixel refers to the matrix, voids or already failed filaments in the contact area.

In order to still allow an analytical modeling of the pull-out response of a yarn without adequate knowledge of the contact areas, the following proceeding is proposed under the assumptions that

the average pull-out response $p_{v,a}$ of a layer is described by Eq. (4),
 if matrix has penetrated into a layer v at a location i over a length $L_{v,i}$ all filaments in that layer are completely embedded in matrix over their circumference πd at that location over that length, and
 all individual embedded lengths $L_{v,i}$ of a layer may be summed up to a layer dependent embedded length L_v . Or vice versa, the filaments of a layer v are not embedded over the “free” length Ψ_v ; compare Fig. 7.

Note that only an embedded length of a couple of millimeters is needed to transfer all the forces a filament can carry into the surrounding matrix. This kind of idealization of the microstructure is also proposed in (Schorn 2003) and named “adhesion-bridge model”. Experimental results show (Banholzer 2004) that the layers and hence the filaments experience a staggered break down, i.e. the failure locations run from $x = L$ for the sleeve filaments to $x \ll L$ for filaments near the core. By assuming that the tensile strength of a filament does not vary over its length, it implies that the load transfer between filaments and matrix by shear stresses is negligible in the regions Ψ_v , where the filaments are not embedded.

Hence two major conclusions may be drawn:

The average pull-out force $p_{v,a}$ of a layer is summended only in the regions of embedment L_v .

The corresponding displacement Ω of a layer v consists of two components: (I) the slip ω of the filaments at $x = L$ and (II) the elongation Δ resulting from the deformation of the filaments over the free length Ψ_v .

This may be expressed in mathematical terms as

$$\Omega = \omega + \Delta \quad (6)$$

26 Banholzer and Brameshuber

As the stress versus strain relationship of a single filament is found to be linearly elastic (Banholzer and Brameshuber 2004), Δ is dependent on the layer force $p_v(\omega)$, the Young's modulus of the filaments E_F , the free length Ψ_v , and the cross-sectional area of the layer A_v which corresponds in turn to $o(v)$ times the area of a single filament A_F . If in addition the assumption holds that all filaments of a layer v do not interact, the average pull-out response $p_{v,a}(\omega)$ of a single filament in a layer v is either equivalent to the response of a filament in a single filament pull-out test $P(\omega)_v$, if the identical embedded length L_v is chosen, or is equivalent to the $P(\omega)_v$ relationship simulated on the basis of a given BSR $\tau(s)$ for the corresponding geometric arrangement (Fig. 8). Hence Eq. (6) yields

$$\Omega = \omega + \frac{P_v(\omega)}{E_F A_F \cdot o(v)} \Psi_v = \omega + \frac{P_{v,a}(\omega)}{E_F A_F} \Psi_v = \omega + \frac{P_v(\omega)}{E_F A_F} \Psi_v \quad (7)$$

after $p_v(\omega)$ is substituted according to Eq. (3).

Simulations show that the pull-out responses $P_v(\omega)$ of filaments embedded over different lengths L_v agree with each other as long as L_v is long enough to allow the filaments to reach their tensile strength f_t , at a corresponding pull-out displacement ω_f (Fig. 8). In addition a critical embedded length L_{crit} can be determined which is the maximum length at which the filaments do not reach their tensile strength; this is about 2.8 mm for the illustrated material combination in Fig. 8. The only real unknown constant parameter in Eq. (7) is the free length Ψ_v .

If $\Omega_{v,f}$ is defined as the critical displacement at the time of failure of the layer v where the filaments in that layer reach their tensile strength $f_{v,t}$ at a corresponding single filament pull-out displacement $\omega_{v,f}$, then Eq. (7) may be rewritten as follows

$$\Psi_v = \frac{(\Omega_{v,f} - \omega_{v,f}) \cdot E_F}{f_{v,t}} \quad (8)$$

$\Omega_{v,f}$ in Eq. 8 can be determined on the basis of the active filaments versus displacement relationship $N_F(\Omega)$. Assuming the numbers of filaments in each idealized layer to be equal, i.e. $o(v) = o$, the active filaments versus displacement relationship $N_F(\Omega)$ may be matched by a step function with a constant step height o as shown in Fig. 9 for specimen A of series 12. The number of steps used naturally corresponds to the number of layers assumed in the idealization; $m = N_{F,m} / o$.

The width of each step refers to the displacement range in which o filaments of the corresponding layer v fail. The displacements at the end of each step (black squares) are taken as average failure displacements, i.e. the layer v is assumed to fail in tension at a pull-out displacement $\Omega_{v,f}$. Using this information a free length Ψ_v can be calculated for each layer v . This yields for $p_v(\Omega)$

$$p_v(\Omega = \omega + \Delta) \stackrel{!}{=} P(\omega)_v \cdot o, \quad \Delta = \frac{P(\omega)_v}{E_F A_F} \frac{(\Omega_{v,f} - \omega_{v,f}) \cdot E_F}{f_{v,t}} \quad (9)$$

It was reasoned (Banholzer 2004), that in the interval $0 \leq \Omega \leq \Omega_{\text{NFL}}$ the failure of the layers is predominated by a pure tensile break down of the filaments without any prior pull-out, i.e. all layers v for $k < v \leq m$ fail in pure tension. Thus for $\Omega_{v,f} \leq \Omega_{\text{NFL}}$ the layer tensile strength $f_{v,t}$ in Eq. (9) corresponds to the tensile strength of a filament derived in a tensile test. Knowing $f_{v,t}$ the appropriate $\omega_{v,f}$ can be determined as well (Fig. 8). The $P_v(\omega)$ distribution can be evaluated with the direct boundary value problem proposed in (Banholzer, Brameshuber and Jung 2005) assuming a $L_v > L_{\text{crit}}$ and implying the BSR $\tau(s)$ determined (Fig. 2) for the investigated filament / cement based matrix combination.

As soon as $\Omega > \Omega_{\text{NFL}}$, the filaments are assumed to experience a pull-out accompanied by abrasion effects as well as a deterioration of the glass surface and fail consecutively in tension later on due to a reduced tensile strength, that is layers v for $j < v \leq k$ fail in tension after a prior pull-out. Hence the tensile strength $f_{v,t}$ of the layer v for $\Omega_{v,f} > \Omega_{\text{NFL}}$ may be seen as the product of the filament tensile strength f_t and a so-called “abrasion” factor k_A which considers the mentioned aggravation effects. Hence it can be stated:

$$\begin{aligned} f_{v,t} &= f_t, & \text{for } \Omega_{v,f} &\leq \Omega_{\text{NFL}} \\ f_{v,t} &= k_A f_t, & \text{for } \Omega_{v,f} &> \Omega_{\text{NFL}} \end{aligned} \quad (10)$$

Again the appropriate $\omega_{v,f}$ can be determined from Fig. 8. The pull-out response $P_v(\omega)$ can easily be calculated by choosing an embedded length $L_{\text{crit},ka}$ which results in a pull-out of the filament (compare Fig. 8) under consideration of a reduced tensile strength due to abrasion as stated in Eq. (10).

So far only those layers $j < v \leq m$ which failed in tension during the pull-out tests have been considered, regardless of whether they have experienced a pull-out beforehand or not. The core of inner filaments which is pulled out of the specimen without failing in tension, i.e. layers $1 \leq v \leq j$, has so far not been considered in the model. An additional simulation with the cohesive interface model can be carried out to calculate the response of the core layers if it is assumed that the pulled-out core filaments respond as a homogenous body, which is embedded over a length $L_{\text{crit},ka}$ and features a contact area of $U_{C,j}$ as well as a cross-sectional area of $A_F N_{F,j}$ determined with the FILT test (Fig. 4B/C).

For simplicity reasons it is further assumed, that the free length Ψ_v stays equal for all inner layers $1 \leq v \leq k$ and amounts to the free length derived for layer $k+1$. Substituting Eq. (9) in Eq. (4) yields

$$P(\Omega) = \sum_{v=1}^m p_v(\Omega = \omega + \Delta) \equiv \sum_{v=1}^m P_v(\omega) \cdot o, \quad \Delta = \frac{P_v(\omega) (\Omega_{v,f} - \omega_{v,f}) \cdot E_F}{E_F A_F f_{v,t}} \quad (11)$$

and thus a procedure to analytically describe the pull-out behavior of a yarn in a cementitious matrix under a pull-out load is derived.

28 Banholzer and Brameshuber

Results of Simulation

In the following, the results of the simulations carried out for specimens A to D are presented. To summarize and clarify the simulation procedure described above, a detailed illustration for the pull-out modeling of specimen A is presented subsequently.

For specimen A the FILT test results show (Fig. 4, Banholzer (2004)), that the failure process for $\Omega < \Omega_{NFL} = 0.38 \text{ mm}$ ($1.50 \cdot 10^{-2} \text{ in.}$) is predominated by a pure tensile break down of the outer layers. The tensile strength of these filaments has been determined as $1,473 \text{ N/mm}^2$ (213.6 ksi) (see before) with a coefficient of variation of 20.3 %. Due to a local lateral pressure of e.g. aggregates the tensile strength of a filament embedded in fine grained concrete is assumed at the lower end of the range of the standard deviation. Thus the tensile strength of a filament in a pull-out test is adopted as $1,200 \text{ N/mm}^2$ (174.0 ksi). This corresponds to a maximum filament force of approximately 0.78 N (0.175 lb) if a cross-sectional area $A_F = 660 \mu\text{m}^2$ ($1.023 \cdot 10^{-6} \text{ in.}^2$) is implied which is defined in turn by the average filament diameter $d_a = 29 \mu\text{m}$ ($1.14 \cdot 10^{-3} \text{ in.}$) (Banholzer 2004).

The Vetrotex 2400 tex yarn consists of approximately 1,400 filaments (see before). If the system is idealized as a 5 layer structure, the number of filaments for a single layer is found as $n \approx 280$. Thus the maximum force in the outer layers which fail in pure tension (for $\Omega < \Omega_{NFL} = 0.38 \text{ mm}$) ($1.50 \cdot 10^{-2} \text{ in.}$) is calculated as about 218 N (49.0 lb). The maximum layer force for all layers failing at an introduced displacement $\Omega > \Omega_{NFL} = 0.38 \text{ mm}$ ($1.50 \cdot 10^{-2} \text{ in.}$) can be determined as about 65 N (14.6 lb), if the “abrasion” factor k_A is presumed in a first estimation as 0.3, that is the tensile strength of a filament is reduced by 70 % due to weakening effects.

The bond between the filaments of the Vetrotex 2400 tex yarn and PZ-0899-01 matrix is defined by the BSR $\tau(s)$ as derived before and stated in Fig. 2. For the presented pull-out test on specimen A, about 280 filaments are left undamaged at the final displacement of 1.7 mm ($6.69 \cdot 10^{-2} \text{ in.}$) (Fig. 4B) featuring a contact perimeter U_C of about 8 mm (0.315 in.) (Fig. 4C). The corresponding critical embedded length is determined as about 2.8 mm (0.110 in.) (Fig. 8). All previously listed main input parameters are listed in Table 2 again.

From the stepwise adaptation of the active filaments versus displacement relation $N_F(\Omega)$ presented in Fig. 9 which refers to specimen A, the failure displacement $\Omega_{v,f}$ for the four layers failing in tension is found to be $\Omega_{5,f} = 0.19 \text{ mm}$ ($7.48 \cdot 10^{-3} \text{ in.}$), $\Omega_{4,f} = 0.38 \text{ mm}$ ($1.50 \cdot 10^{-2} \text{ in.}$), $\Omega_{3,f} = 0.67 \text{ mm}$ ($2.64 \cdot 10^{-2} \text{ in.}$), and $\Omega_{2,f} = 1.19 \text{ mm}$ ($4.69 \cdot 10^{-2} \text{ in.}$). Note, that layer 1 does not break down within the applied displacement but is pulled out. Adopting Eq. (9) and the $P(\omega)$ relationship presented in Fig. 9 together with the resulting $\omega_{f,v}$, the $p_v(\Omega)$ relationships can be plotted in a layer force versus displacement diagram which is presented in Fig. 10 for specimen A.

A summation of the individual $p_v(\Omega)$ responses according to Eq. (4) results in the simulated $P(\Omega)$ relation for a 5 layer idealization stated in the diagram on the left of Fig. 11.

Additionally the experimentally determined load versus displacement relationship $P(\Omega)$ is presented in the diagram as well. So far the system is idealized with five layers of 280 filaments each. Increasing now the number of layers to $v = 100$, the pull-out response can be simulated in more detail. Note, the higher the number of layers taken, that is the lower the number of filaments included in a single layer, the more the complex interaction between the individual filaments is considered due to the fact, that this information is hidden in the active filaments versus displacement relationship (Fig. 4).

In principle the simulation is in a good agreement with the experimentally determined load versus displacement relation of specimen A. The starting gradient is well mapped but the maximum pull-out force is overestimated by 12.5 %. The successive break down process, which is illustrated by the softening branch of the $P(\Omega)$ relationship, is also in a good agreement whereas the final pull-out force is underestimated by 7.5 %. The only “fitting parameter” included in the presented model is the so-called abrasion factor k_A , which was chosen for specimen A as 0.3. However, if the simulations of the remaining three tests show, that the factor is constant, it may well be assumed to be a material parameter as well. In a similar procedure the responses of specimen B, C, and D are simulated. To allow an easier comparison of the following simulations, the main input parameters for the analytical model are listed for specimen B, C, and D in Table 3.

The simulated overall pull-out response $P(\Omega)$ is presented for specimen B in the diagram on the right of Fig. 11 together with the experimentally determined load versus displacement graph. In general a good consistency between the analytical simulation and the experimental results is found, that is the starting gradient, the maximum pull-out force reached as well as the break down of the individual filaments are well met. The diagram on the left of Fig. 12 shows the outcome of the analytical simulation for specimen C. Again the starting gradient and the maximum pull-out force of experiment agree with the simulation. However, the failure process during softening of the yarn is underestimated. In some places the discrepancy is around 50 %. The end of the pull-out process then fits the experimental results again. Last of all the diagram on the right of Fig. 12 presents the experimental results of specimen D together with the simulated pull-out response. Again the “abrasion” factor k_A is chosen as 0.3 and therefore is identical for all simulations carried out. Similar to the previous results the starting gradient and the maximum pull-out force are well met but the failure process is overestimated by a certain degree although the discrepancy between simulation and experiment again reduces in the final frictional stage.

Discussion

The equations and procedures proposed in this study to simulate the pull-out process of a yarn embedded in a fine-grained concrete matrix involve a number of geometric and material parameters which have to be known in order to apply the analytical model.

The geometric and material parameters of the components, such as the cross-sectional area of the yarn, the number of filaments a yarn consists of and the tensile strength f_t as well as the Young's modulus E_F of the individual filaments can all be determined with an adequate accuracy (Banhölzer 2004).

30 Banholzer and Brameshuber

Conversely there are the interfacial properties employed in the model which are not so easy to determine: namely the bond stress versus slip relation $\tau(s)$ for the chosen material combination, the abrasion factor k_A , and lastly information on the interaction of neighboring filaments which has a huge influence on the pull-out response of a yarn / cementitious matrix system. Results stated in (Li, Grubb and Phoenix 1995) show that a pure summation of the individual responses may lead to an under- or overestimation of the expected load versus displacement response depending on whether the presence of neighboring filaments helps to prevent or accelerate the expected failure. In some cases neighboring filaments may even behave like a single filament with a larger diameter and corresponding contact circumference to the surrounding layer. However, such effects are not really considered in the model because it is assumed, that all filaments of a layer v do not interact. Nevertheless, the active filament versus displacement relationship $N_F(\Omega)$, which is used as a further main input parameter in the analytical model and differs for each investigated specimen, accounts for some of these effects. This experimentally derived relationship is further needed to deal with the problem that the actual unknown parameter Ψ_v in Eq. (7), which refers to the embedment and hence matrix penetration characteristics of the individual yarn layers v , can so far not be deduced in detail from the microstructural investigations carried out in (Banholzer 2004). A comparison between the microstructural investigations and the assumed distributions of the penetration depth, nonetheless, clearly outlines the similarities and confirms the assumption that the Ψ_v distribution in the model reflects the original microstructure of the specimen (Banholzer 2004).

In any case, a possible model adaptation is a subject for further research together with a supplementary experimental test method to check the regularity of the assumed $\Psi_v(v)$ relationship, for example, acoustic emission analysis (Große and Reinhardt 1994). However, a major technical effort and a subsequent elaborate analysis procedure are both required to gain this information and hence this technique was not applied in this study.

A further important input parameter, the “abrasion” factor k_A , is only assumed as a first estimation to be 0.3 with no actual experimental justification. However, as an identical k_A is used in the pull-out simulations of all three replications and these simulations are in good conformance with the experimental outcomes, the employed “abrasion” factor must have some physical meaning. Nevertheless, future investigation should clarify whether the tensile strength of a filament is really reduced by that factor due to abrasion or inflicted defects on the filament surface and what external influences cause these effects. It is also very likely, that this factor does not remain constant during the whole pull-out process, but changes the more the filaments are pulled out, that is the factor is greater for filaments nearer to the sleeve. In addition, k_A will also be material dependent.

The parameter U_{Cj} which refers to the contact area between the inner core and the surrounding system has been ascertained based on the FILT test results (Banholzer 2004), but this analysis does not take into account voids, broken filaments, matrix penetrated into the yarn, etc. and thus U_{Cj} may only be seen as a rough estimation of the real geometric parameter. Unfortunately microscopic analysis is also not feasible to determine this parameter as the system changes during the pull-out process.

CONCLUSION

In this study an analytical model has been introduced which uses the information gained from the pull-out test and the so-called FILT test to simulate the response of a yarn embedded in a fine-grained matrix under a pull-out load. However, since the active filaments versus displacement relationship from the FILT test is one of the main input parameters of the model, and this relationship is unique for each specimen tested, the proposed simulation procedure is so far only applicable for recalculating pull-out tests on yarn / cementitious matrix systems. The pull-out response for other geometric conditions can not be predicted so far. In order to ensure such a general applicability, the findings in regard to the microstructure have to be statistically evaluated as proposed in (Banholzer 2004) and implemented in the model. This also applies to the final contact area $U_{C,j}$ between core and surrounding system. Nevertheless, the four presented comparisons between the simulated $P(\Omega)$ responses and the experimental results mainly show a good consistency and support the general practicability of the proposed analytical model.

REFERENCES

- Banholzer, B. (2004): "Bond Behaviour of a Multi-Filament Yarn Embedded in a Cementitious Matrix". In: Schriftenreihe Aachener Beiträge zur Bauforschung, Institut für Bauforschung der RWTH Aachen, Nr. 12, (pdf file at: <http://www.bth.rwth-aachen.de>)
- Banholzer, B. and Brameshuber, W. (2004): "Tailoring of AR-Glass Filament / Cement Based Matrix Bond - Analytical and Experimental Techniques". In: Fibre-Reinforced Concretes (FRC), BEFIB 2004, Varenna, Italy, Vol. 2, pp. 1443-1452.
- Banholzer, B., Brameshuber, W. and Jung, W. (2005): "Analytical Simulation of Pull-Out-Tests - The Direct Problem" In: Cement and Concrete Composites 27, No. 1, pp. 93-101.
- Bartos, P. (1982): "Bond in Glass Reinforced Cements" In: Proceedings of the International Conference on Bond in Concrete, Paisley College of Technology, Scotland, pp. 60-72.
- Beyerlein, I.J. and Phoenix, S.L. (1997): "Stress profiles and energy release rates around fiber breaks in a lamina with propagating zone of matrix yielding and debonding" In: Composites Science and Technology 57, pp. 869-885.
- Brameshuber, W., Brockmann, T. and Banholzer, B. (2004): Textile Reinforced Ultra High Performance Concrete. In: Proceedings of the Intern. Symposium on Ultra High Performance Concrete, Kassel (Germany), pp. 511-522.

32 Banholzer and Brameshuber

Große, C.U. and Reinhardt, H.W. (1994): "Schallemissionsmessungen bei Pull-out-tests im Hinblick auf bruchmechanische Untersuchungen" In: Beiträge zum 30. Forschungskolloquium am 04. und 05. November (Universität Stuttgart), pp. 239-250.

Hedgepeth, J.M. (1961): "Stress Concentrations in Filementary Structures" Springfield : National Aeronautics and Space Administration.

Katz, A., Li, V.C. and Kazmer, A. (1995): "Bond Properties of Carbon Fibers in Cementitious Matrix" In: Journal of Materials in Civil Engineering 7, No. 2, pp. 125-128.

Li, Z.-F., Grubb, D.T. and Phoenix, S.L. (1995): "Fiber Interactions in the Mult-Fiber Composite Fragmentation Test" In: Composites Science and Technology 54, pp. 251-265.

Ohno, S. and Hannant, D.J. (1994): "Modelling the Stress-Strain Response of Continuous Fiber Reinforced Cement Composites" In: ACI Materials Journal 91, No. 3, pp. 306-312.

Schorn, H. (2003): "Ein Verbundmodell für Glasfaserbewehrung im Beton" In: Bautechnik. No. 80, pp. 174-180.

Sejnoha, M. and Zeman, J. (2002): "Micromechanical Analysis of Random Composites" In: CTU Reports 6, No. 1, Prague: Czech Technical University.

Table 1 – Fine-grained concrete PZ-0899-01 composition

Constituent	PZ-0899-01 Content kg/m ³ ¹⁾
<i>Binder</i>	
CEM I 52,5 N	490
Fly ash	175
Silica fume	35
<i>Admixtures</i>	
Superplasticizer	14
<i>Aggregates</i>	
Siliceous fine sand	499
Sand	714

¹⁾ 1 kg/m³ = 6.2426 · 10⁻² lb/ft³

Table 2 – Main input parameters in the analytical model for specimen A

Parameter	Specimen A
Tensile strength of filament f_t [N/mm ²] ¹⁾	1200
Young's modulus of filament E_f [N/mm ²]	53,336
BSR $\tau(s)$ [-]	Fig. 2
Critical embedded length L_{crit} [mm] ²⁾	2.8
"Abrasion" factor k_A [-]	0.3
Number of filaments in the yarn [-]	1400
Number of layers [-]	5
Critical pull-out displacement Ω_{NFL} [mm]	0.38
Intact filaments N_f at Ω_{max} [-]	280
Contact perimeter U_C at Ω_{max} [mm]	8.0

¹⁾ 1 N/mm² = 0.14504 ksi

²⁾ 1 mm = 3.937 · 10⁻² in.

Table 3 – Main input parameters in the analytical model for specimen B, C and D

Parameter	Specimen B	Specimen C	Specimen D
Tensile strength of filament f_t [N/mm ²] ¹⁾	1200	1200	1200
Young's modulus of filament E_f [N/mm ²]	53,336	53,336	53,336
BSR $\tau(s)$ [-]	Fig. 2	Fig. 2	Fig. 2
Critical embedded length L_{crit} [mm] ²⁾	2.8	2.8	2.8
"Abrasion" factor k_A [-]	0.30	0.30	0.30
Number of filaments in the yarn [-]	1400	1400	1400
Number of layers [-]	100	100	100
Critical pull-out displacement Ω_{NFL} [mm]	0.33	0.31	0.42
Intact filaments N_f at Ω_{max} [-]	83	121	222
Contact perimeter U_C at Ω_{max} [mm]	4.0	4.8	6.3

¹⁾ 1 N/mm² = 0.14504 ksi;

²⁾ 1 mm = 3.937 · 10⁻² in.

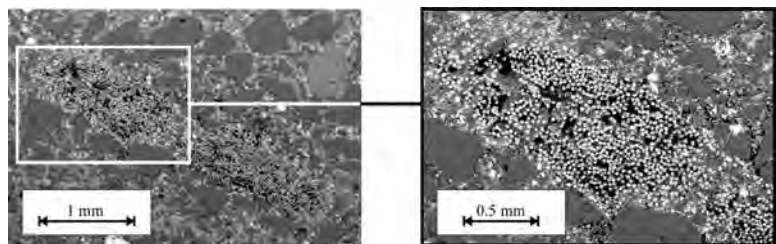


Fig. 1—SEM micrograph of a Vetrotex 2400 tex AR-glass yarn in a fine grained concrete (PZ-o899-1). (1 mm = $3.937 \cdot 10^{-2}$ in.)

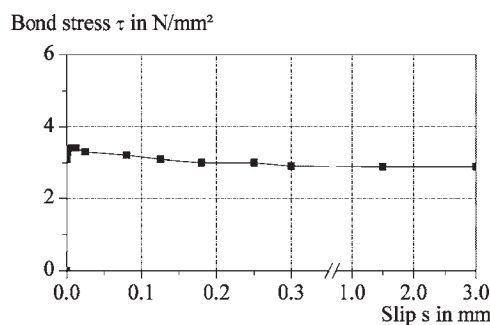


Fig. 2—Bond versus slip relation (BSR) $\tau(s)$ defining the bond between a filament extracted from a Vetrotex 2400 tex yarn and a fine grained concrete (PZ-o899-1). (1 N/mm² = 0.14504 ksi, 1 mm = $3.937 \cdot 10^{-2}$ in.)

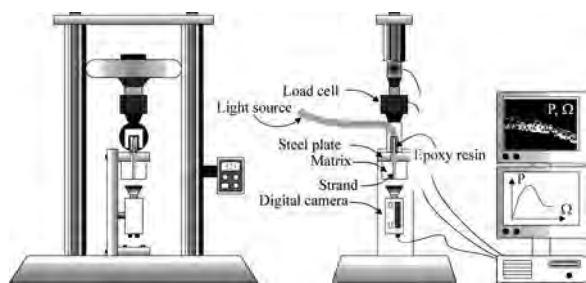


Fig. 3—Set-up of a pull-out test on a yarn.

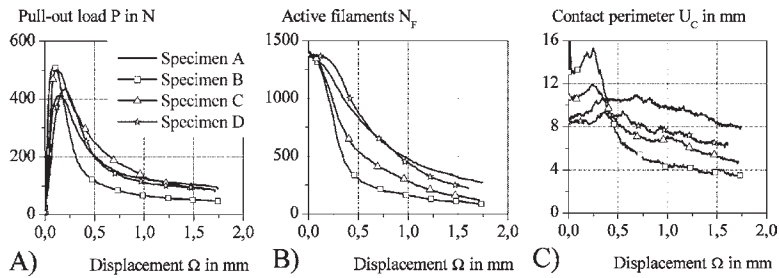


Fig. 4—Pull-out test results: A) Load versus displacement relation $P(\Omega)$; and B) Active filaments versus displacement relation $N_F(\Omega)$ (FILT-test).
(1 N = 0.2248 lb, 1 mm = $3.937 \cdot 10^{-2}$ in.)

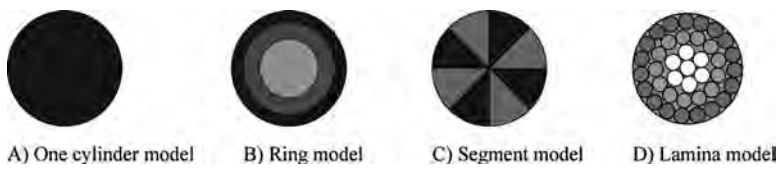


Fig. 5—Basic models to idealize a yarn in a matrix.

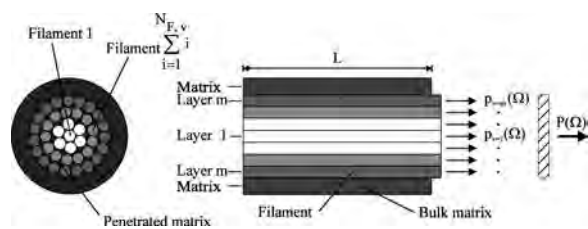


Fig. 6—Idealization of a yarn embedded in a matrix.

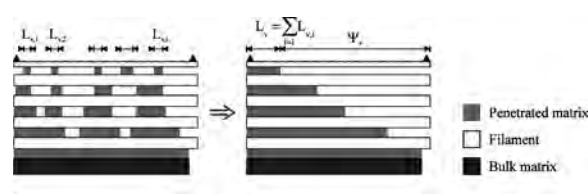


Fig. 7—Idealization of microstructural, geometric parameters.

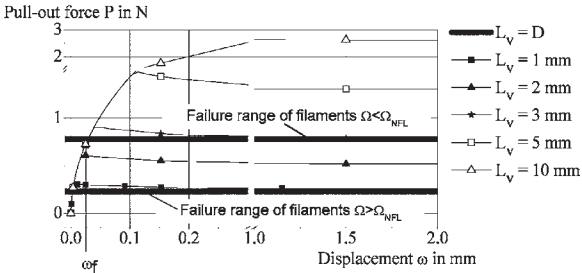


Fig. 8—Simulated responses of a filament in a single filament pull-out test with different embedded length L_v based on the material parameters of a filament extracted from a Vetrotex 2400 tex yarn and a PZ-0899-01 fine grained concrete. (1 N = 0.2248 lb, 1 mm = $3.937 \cdot 10^{-2}$ in.)

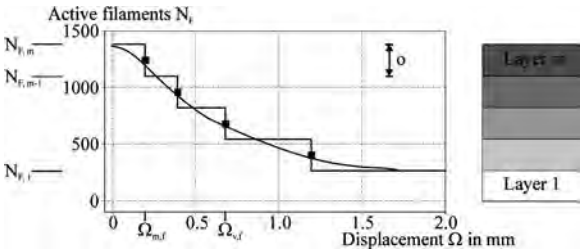


Fig. 9—Step-wise adaptation of the active filaments versus displacement relation $NF(\Omega)$. (1 mm = $3.937 \cdot 10^{-2}$ in.)

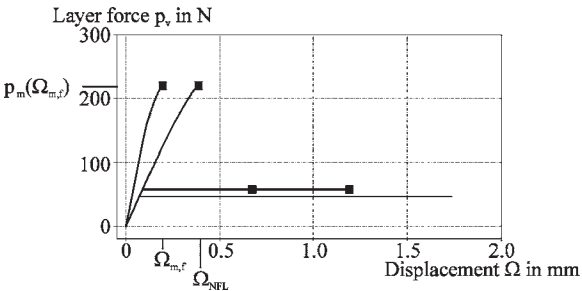


Fig. 10—Layer force displacement diagram $p_v(\Omega)$ for specimen A. (1 N = 0.2248 lb, 1 mm = $3.937 \cdot 10^{-2}$ in.)

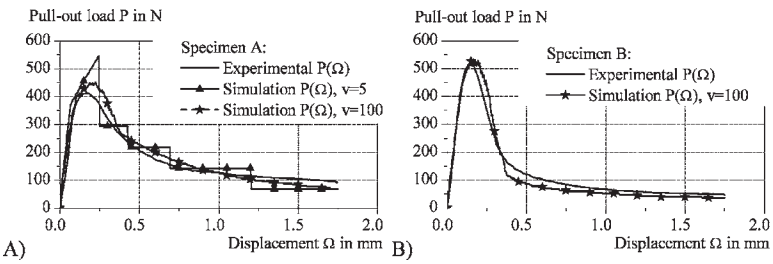


Fig. 11—Experimentally determined and analytically simulated pull-out responses.
A) For specimen A. Simulations with a 5 and 100 layer idealization respectively.
B) For specimen B. Simulation with a 100 layer idealization.
(1 N = 0.2248 lb, 1 mm = $3.937 \cdot 10^{-2}$ in.)

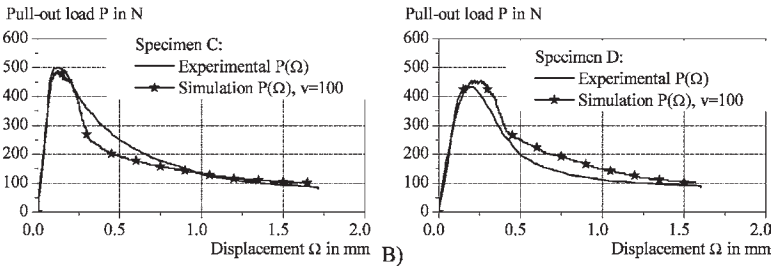


Fig. 12—Experimentally determined and analytically simulated pull-out responses.
A) For specimen C. Simulation with a 100 layer idealization. B) For specimen D.
Simulation with a 100 layer idealization. (1 N = 0.2248 lb, 1 mm = $3.937 \cdot 10^{-2}$ in.)

Numerical and Experimental Study of Imperfections in the Yarn and its Bond to Cementitious Matrix

by R. Chudoba, M. Konrad, M. Vořechovský, and A. Roye

Synopsis: This paper describes two models used in the modeling strategy for textile reinforced concrete. The modeling of multi-filament yarns and of the bond between yarn and matrix is focused on micromechanical aspects of the material behavior. The calibration procedure of the model is explained on an example of a detailed experimental and numerical study of pull-out specimen. We demonstrate the use of the model for numerical homogenization to derive effective parameters at the meso level. In parametric studies we analyze the influence of local imperfections in the microstructure arising in the production process on the meso- and macromechanical properties of the material.

Keywords: bond performance; material model; multi-filament yarn; size effect; textile reinforced concrete

Rostislav Chudoba is research assistant at the Chair of Structural Statics and Dynamics at RWTH Aachen University, Germany. He obtained his MSc. degree in 1990 and the Ph.D. degree in 1995 in the field of structural mechanics and computer science from the CTU Prague, Czech Republic.

Martin Konrad is research assistant at the Chair of Structural Statics and Dynamics at the RWTH Aachen University, Germany. He obtained his Diploma Degree in the field of structural statics from the RWTH Aachen University, Germany in 2002.

Miroslav Vořechovský is research assistant at the Chair of Structural Statics and Dynamics at RWTH Aachen University, Germany. He obtained his Diploma Degree in 2000 and the Ph.D. in 2004 in the field of structural mechanics and stochastic modeling of structures from Brno University of Technology, Czech Republic.

Andreas Roye is research assistant at the ITA at the Aachen University, Germany. He obtained his Diploma Degree in the field of mechanical engineering from the RWTH Aachen University, Germany in 2001.

RESEARCH SIGNIFICANCE

The textile reinforced concrete (TRC) has emerged in the last decade as a new composite material combining the textile reinforcement with cementitious matrix. Its appealing feature is the possibility to produce filigree high-performance structural elements that are not prone to corrosion as it is the case for steel reinforced concrete. In comparison with other composite materials, textile reinforced concrete exhibits a high degree of heterogeneity and imperfection that requires special treatment in the development of numerical models.

INTRODUCTION

The heterogeneous nature of both the matrix and the reinforcement introduces sources of randomness at overlapping scales of material structure that are not present in other types of composites. The material structure at the micro-scale exhibits high amount of irregularities and imperfections in the geometrical layout of the basic components with varying local properties and in the quality of local bindings between them. As an example, these imperfections may be represented by non-parallel orientation of filaments within the bundle or by varying bond quality between filaments and matrix across the bundle. As a result, the damage localization process of textile reinforced concrete exhibits interactions between elementary failure mechanisms in the matrix, in the reinforcement and in the bond. Due to the high amount of interactions between these mechanisms, existing models for concrete and composites are not directly applicable for the textile reinforced concrete.

Consistent numerical modeling of textile reinforced concrete requires the formulation of several models on different scales of resolution of the material structure (Fig. 1). At each scale, specific damage and failure mechanisms are being considered in the formulation of the model:

- micro-scale with the resolution of individual filaments and explicit distinction of

their interactions,

- meso-scale with an idealized structure of the yarn considered either homogeneous or decomposed into core and sleeve yarn fractions, discrete cracking of the matrix, and
- macro-scale with smeared representation of the textile as a layer within the idealized cross section of the composite and cracking of the matrix represented in form of smeared anisotropic damage.

MODELING STRATEGY

The mentioned aspects of the material behavior emphasize the special importance of two issues:

- hierarchical correspondence between the specified damage and failure mechanisms at the micro-, meso- and macroscopic scales,
- influence of irregularities in the material structure on the overall performance.

Fig. 2 shows the overall modeling strategy specifying the model components and the flow of material parameters between them. Starting from the microscopic scale we briefly describe the focus and purpose of each displayed model.

At the micro-scale, multi-filament bundles (A) are modeled using stochastic methods capturing the effects of spatially distributed imperfections in filaments and in the yarn structure (Chudoba et al. 2006; Vořechovský and Chudoba 2006). These models are calibrated and validated using the yarn tensile tests (Gries and Roye 2003) with varied length. The determined yarn characteristics are used in the modeling of the bond layer between yarn and matrix (B) introducing an additional source of randomness (Konrad and Chudoba 2004); in particular the irregular penetration of the matrix into the bundle. The bond layer model employs the local bond law between filament and matrix extracted from the filament pull-out test using the shear lag idealization with cohesive interface model (C) (Abrishami and Mitchell 1996; Banholzer 2004). These models are focused solely on the yarn and bond and they do not include the effect of crack evolution in the matrix.

The interaction between the crack evolution and the bonding behavior is studied at the meso level both in 1D and in 2D. First, the uni-axial aspects are reflected in the meso-level bond model (D) with the minimum resolution of the reinforcement into two subroving representing core and sleeve filaments (Hegger et al. 2004). The volume fractions of core and sleeve filaments and the corresponding effective bond law of the two-subroving model (D) are determined using the bond layer model (B). The obtained meso-level characteristics are validated using tensile tests on reinforced specimens. The comparison of experimentally and numerically obtained crack patterns (number of cracks and average crack distances) is included in the validation of the model parameters. Two-dimensional aspects of the crack-bond interaction are investigated using the small-scale reinforced plates in connection with the discrete crack propagation model (E). The effective properties obtained using this model are used in the smeared two- (F) and three-dimensional (G) anisotropic model of textile reinforced concrete (Hegger2005).

In the present paper we shall focus on the description of the models (A) multi-filament

yarn and (B) bond layer in order to evaluate the influence of local imperfection on their performance in quasi-ductile cementitious composites. The development of the two models with fine resolution of the material structure is motivated by two advantages:

- in combination with carefully designed experiments they make it possible to trace the changes in the material structure at the micro- and meso scale during the loading process and, thus, provide very detailed interpretation of the experimental data,
- they can be used for the purpose of numerical homogenization delivering effective material parameters of modified composite structures required for the meso- and macroscopic resolution of the material structure.

The paper presents several parametric studies using the described models both of the yarn and of the bond behavior. Special attention will be paid to the statistical size effect. Further, the applied homogenization of the response at the micro scale with the goal to obtain the effective characteristics for the use at the meso and macro scale will be presented.

MULTI-FILAMENT YARN IN A TENSILE TEST

The importance of the correct description of the local effects in the multifilament yarn is documented in Fig. 3. The yarn performance measured in the tensile test with $L_{test} \approx 0.1$ m (≈ 3.9 in.) must be extrapolated to application-relevant effective lengths, namely to the effective length of a crack bridge $L_{bridge} \approx 0.0001$ m (≈ 0.039 in.) and to the length of the structure $L_{struct} > 1$ m (≈ 39 in.). Obviously, the irregularity of the bundle structure affects the yarn behavior especially on extremely short length as is the case of crack bridges (see Fig. 3 right). Therefore, the application of data obtained for length L_{test} is questionable.

The influence of irregularities can be indirectly observed using the yarn tensile test without further complex experimental equipment. The following experimental and numerical analysis is focused on the evaluation of

- the amount of friction in the filament bundle
- non parallel ordering of filaments (waviness)
- distribution of flaws and variation of strength and stiffness along and across the bundle

Experimental evidence

By targeted variation of the parameters of the tensile test (Gries and Roye 2003), namely the specimen length and loading rate and by thorough analysis of the corresponding quantitative and qualitative changes of the load-strain diagram we could make conclusions about the significance of the particular sources of imperfection in the studied bundle. As an example consider the two response surfaces shown in Fig. 4. They display the peak loads normalized with the maximum peak load measured on yarns with three testing lengths (50 - 250 - 450 [mm] $\approx 2.0 - 9.8 - 17.7$ [in.]) and three loading rates (1 - 20 - 40 [%/min]). The two diagrams show the test results for a) Vetrotex AR-glass rovings with 2400 tex and for b) Tenax carbon rovings with 1600 tex. We note that although the tendencies are generally the same, i. e. reduced strength with increased length and slow

loading rate, the shape of their response surface differs. Considering the length-dependent performance first we see that both yarns exhibit a reduced bundle strength with an increasing specimen length. This well known effect usually referred to as statistical size effect is due to the distribution of flaws along the filaments. In case of AR-glass, this effect is more pronounced at low loading rates. On the other hand, in case of carbon, stronger size effect is observed at high loading rates.

The explanation of this behavior is possible with the help of the corresponding load-strain diagrams (see Fig. 5). The post peak behavior reveals a very low level of transmitted force for AR-glass. On the other hand the force transmitted by friction is significantly higher for carbon. Obviously its level increases with the increasing specimen length. As a conclusion, a filament break may be recovered by the neighboring filaments if the bundle length is sufficiently large. In other words, high amount of friction between filaments (local load sharing) can drown the effect of flaws along the yarn. In our opinion, this provides a plausible explanation for the different shapes of response surfaces in Fig. 4. This conclusion is supported by the parametric studies in (Vořechovský and Chudoba 2006) showing that only for low level of friction between filaments (global load sharing) the shape of the statistical size effect is independent of the number of filaments in the bundle.

Fiber bundle model

From this study we may conclude at which range of lengths the internal friction becomes significant. Since the amount of friction is negligible for AR-glass, even for the specimen length $l = 450 \text{ mm}$ ($\approx 17.7 \text{ in.}$), it can be disregarded in the modeling of the bundle and of the bond layer at the effective length of a crack bridge. This assumption substantially simplifies the construction of the fiber bundle model (FBM) that is necessary to extract the further information about the yarn structure from the tensile test data. The statistical strain based fiber bundle models have been introduced by Phoenix (Phoenix and Taylor 1973; Phoenix 1978). These models provide an explicit formula for the mean load strain diagram of the bundle μ_θ for a given cumulative probability distribution G_θ of random filament parameter(s) θ and a load strain relation $q_e(e; \theta)$

$$\theta = \{A, E, f', \theta, \lambda\} \quad (1)$$

$$\mu_\theta(e) = \int_0^e q_e(e; \theta) dG_\theta(\theta) \quad (2)$$

where A is the bundle cross section, E is the Young's modulus, f' is the filament strength θ is the slack and λ represents the relative differences in clamping distance of individual filaments [3]. The constitutive law $q_e(e; \theta)$ is assumed as linear elastic and brittle.

In particular the fiber bundle model has been used to evaluate the effect of non parallel ordering of filaments causing their delayed activation (slack). The effect of slack has been first studied by (Phoenix 1974) using a continuous analytical bundle model. This model has been refined with a more precise kinematic hypothesis (Chudoba 2006) allowing us to simulate the bundle response even for extremely short bundle lengths, a case that is not correctly covered by the model of Phoenix. The distribution of slack across the bundle may be derived from the evolution of stiffness in the initial stages of loading. As can be seen on the response of the 30 mm ($\approx 1.2 \text{ in.}$) long AR-glass bundle (Fig. 6) the

full bundle stiffness is attained only at some strain level ϵ . With an increasing specimen length, the relative differences in slack become negligible and this effect vanishes (compare the load strain curve for the test with the length 500 mm (≈ 19.7 in.)). Using the discrete numerical bundle model we were able to calibrate the parameters of slack distribution from the data obtained in the tests on AR-glass bundles with varied length.

With the experience gathered from the thorough testing program and with the use of the numerical bundle model we have reproduced the complex statistical size effect in terms of local statistical distributions of slack, filament strength and filament stiffness (Vořechovský and Chudoba 2006). The resulting size effect curve can be decomposed with respect to contributions of the individual sources of imperfections.

In Fig. 7 we qualitatively sketch the proportions of bundle strength reduction depending on the bundle length (size effect). It can be seen that the scatter of fiber clamping lengths and slack lengths reduce the bundle strength force especially for extremely short lengths. On the other hand, spatial variation/randomness of local filament strength/flaws reduces the bundle strength for very long yarns. If we model the strength along filament length by an autocorrelated random field, the size effect disappears for lengths shorter than the autocorrelation length. This and other results have been thoroughly explained in (Vořechovský and Chudoba 2006). The lowest curve in Fig. 7 illustrates the interaction of aforementioned sources of imperfection that can be observed experimentally.

The conclusions that can be drawn from the described experimental and numerical studies are important for the construction of the crack bridge models in general:

- In order to reflect the true yarn performance in a crack bridge, it is necessary to include the effects of varying filament length and slack. The ambition is to find statistical distribution of free filament length and slack as objective material parameters, so that they represent the distribution of material in any cross section of a yarn embedded in the cementitious matrix.
- Friction between filament surfaces can be considered negligible in the range of effective filament lengths occurring in a crack bridge. However, it must be taken into account at the length scale of the structure, especially in the boundary zones with a long range of stress transfer and relatively large slip between filaments.

MULTI-FILAMENT YARN EMBEDDED IN A TENSILE TEST

Bond layer model

The prerequisite for correct modeling of the bonding behavior is the proper representation of the damage process in the crack bridges. Due to the varying penetration profile along the yarn, the length on which the individual filament is embedded in the matrix and the quality of this embedding exhibits high amount of scatter. Regarding a representative bundle cross section we can make the following assumptions: The average bond quality diminishes from the outside of the yarn to the inside while the average length on which the filament is not bonded increases.

The described irregularities are reflected by assumed profiles (Fig. 8b) of

- bond quality $\varphi(\xi)$, diminishing from the outside to the inside of the yarn,
- bond free length $\ell(\xi)$ increasing from the outside to the inside of the yarn,
- delayed activation $\theta(\xi)$ of filaments within the bond free length,

varying across the bundle with the parametric coordinate $\xi \in \langle 0, 1 \rangle$. $\xi = 0$ is identical with an idealized center of the bundle, $\xi = 1$ coincides with the outer layer of the bundle. For the purpose of numerical studies we approximate the introduced profiles by the following polynomial functions:

$$\varphi(\xi) = (k_{\varphi,0} + k_{\varphi,1} - 2)\xi^3 - (3 - 2k_{\varphi,0} - k_{\varphi,1})\xi^2 + k_{\varphi,0}\xi \quad (3)$$

$$\ell(\xi) = \ell_{\max} + (\ell_{\min} - \ell_{\max})\xi \quad (4)$$

$$\theta(\xi) = (2\theta_{\max} - k_{\theta,1})\xi^3 + (2k_{\theta,1} - 3\theta_{\max})\xi^2 - k_{\theta,1}\xi + \theta_{\max} \quad (5)$$

This choice of the profiles is based on the expertise gathered in the interpretation of experimental data. We note that these profiles do not represent the material structure in a statistical sense and there is a functional dependency between them. However, this representation of the material structure is sufficient to show the important effects in the damage process on the selected example.

As emphasized earlier the effect of the introduced imperfections gets amplified in a case of a crack bridge that can be regarded as tensile test on a yarn with extremely short length extended with a shear-lag-like clamping of filaments (Stang et al. 1990).

With the assumption of uniform distribution of imperfections in the bond and yarn structure along the specimen the effect of imperfection on the performance of each crack bridge can be considered the same. Thus, the quantification of this effect can be performed with an isolated analysis of a pull-out experiment in connection with the bond layer model shown in Fig. 9. As can be seen in the figure the profiles of heterogeneity are directly used for discrete representation of the crack bridge. We emphasize that the fine resolution of the material structure further away from the crack bridge is not needed due to the increasingly homogeneous stress profile.

In this way we construct the discrete bond layer model (B) with the interface layer between the yarn and the matrix represented by a set of laminas. Each lamina interacts with the matrix through a given bond law. It represents a subset of filaments with the same characteristics and is coupled with the matrix using zero thickness interface elements (Kaliakin and Li 1995).

In (Banholzer 2004) filament matrix bond laws for perfectly embedded filaments have been derived as multi linear functions $\tau_1(s)$ (with s representing the slip) using the filament pull-out test and the cohesive interface model (C). In the particular case of the Vetrotex AR-glass roving with 2400 tex and a portland cement matrix the derived function shows that no adhesional bond is developing and thus the interfacial properties are predominated by friction. Therefore $\tau_1(s)$ can be represented in the following bilinear form:

$$\tau_1(s) = \tau_{fr} \cdot \begin{cases} s / s_{crit} & \text{for } 0 \leq s \leq s_{crit} \\ 1 & \text{for } s_{crit} \leq s \end{cases} \quad (6)$$

with $\tau_{fr} = 3.38 \text{ MPa} \approx 490 \text{ psi}$, $s_{crit} = 0.0004 \text{ mm} \approx 0.000016 \text{ in.}$

The bond law distributed over the bond layer is then constructed as:

$$\tau(s, \xi) = \tau_1(s(\xi)) \cdot \varphi(\xi) \quad (7)$$

Parameter identification

Equipped with the boundary conditions of a pull-out test the calibration (Chudoba et al. 2003) of the model is performed both using the load-displacement curve and the curve representing the instantaneous fraction of the unbroken filaments during the loading process. The latter is obtained experimentally using the FILT test (Failure Investigation using Light Transmission properties) by optical recording of the light transmission through the unbroken filaments (Banholzer 2004) (Fig. 10).

The result of the calibration of the model with a single experiment is exemplified in Fig. 11. for the Vetrotex AR-glass roving with 2400 tex (approximately 1600 filaments) and fine grained portland cement matrix. The best match has been achieved for profiles of irregularity (Eqn. 5-7) with the following parameters:

$$\begin{aligned} k_{\varphi,0} &= 2.69, \quad k_{\varphi,1} = 1.89 \\ \varphi(\xi) &= 2.58 \xi^3 - 4.27 \xi^2 + 2.69 \xi \end{aligned} \quad (8)$$

$$\begin{aligned} \ell_{\max} &= 16.25, \quad \ell_{\min} = 1.31 \\ \ell(\xi) &= 16.25 - 14.94 \xi \end{aligned} \quad (9)$$

$$\begin{aligned} \theta_{\max} &= 0.0637, \quad k_{\theta,1} = 0.302 \\ \theta(\xi) &= -0.175 \xi^3 + 0.413 \xi^2 + 0.302 \xi + 0.0637 \end{aligned} \quad (10)$$

The parameters describing the profiles have been obtained using the calibration framework of automated calibration procedures based on evolutionary strategies to avoid convergence to local minima (Chudoba et al. 2003). The found minimum was unique. The present example demonstrates the methodology for obtaining objective material parameters. In order to get statistically representative results an extensive test program is currently being contemplated.

APPLICATIONS OF THE MODEL

Effective bond law for the meso level

The calibrated profiles of bond quality, bond free length and delayed activation provide

the basis for further modeling on the meso- and macro-level. For the smeared representation of the bond properties as it is used in the two-subroving model (D), the fractions of core and sleeve filaments and the corresponding effective bond parameters are derived with regard to their dependence on the crack distance. This is performed by numerical homogenization of the calibrated profiles to effective bond characteristics (Hegger et al. 2005). Simply speaking, the homogenization is performed by fitting the response of the two-subroving model to the response of the more detailed bond layer model exposed to the boundary conditions of a crack bridge. By systematic variation of the micromechanical characteristics of the bond layer model it is possible to construct a response surface capturing the functional correspondence between the micromechanical and mesomechanical representation of the material structure. An example of such a response surface is shown in (Fig. 12) describing the influence of delayed activation and bond free length profiles on the critical slip in the two-subroving model (D).

Improving the performance of TRC

Using the described models, it is possible to identify auspicious parameter combinations for yarns, textiles, and their bond to the matrix leading to improved performance of textile reinforced concrete. One promising possibility is the combination of two different yarn materials with balanced properties. Fig. 13a illustrates that by combining AR-glass and carbon yarns in balanced volume fractions a noticeably more ductile pull-out behavior can be achieved, as that is impossible with only one material. Fig. 13b exemplifies that this behavior is obtained by adjusting the failure process of the two filament groups. This tendency predicted with the combined use of the models at the micro and meso level has been qualitatively confirmed in bending tests (Hegger 2005).

Parametric studies

The qualitative influences of the characteristics of the basic material components on the peak force in the pull-out simulation have been on the peak force analyzed in several parametric studies. In (Konrad and Chudoba 2004) the impact of the local bond quality represented by τ_{fr} on the pull-out behavior has been investigated. The parametric study emphasizes the significance of the non parallel orientation of the filaments in the bundle and exemplifies how it reverses the intended improvement of the pull-out performance. Fig. 14a illustrates that for an improved local bond quality the peak load of the pull-out test decreases.

The reduction of the peak load with increasing local bond strength can be explained using Fig. 15. The two diagrams show the cumulative pull-out response (thick curve) and the pull-out curves for each lamina separately. For the lower level of frictional stress ($\tau_{fr} = 0.5 \text{ MPa} \approx 72.5 \text{ psi}$) it is possible to activate more filaments simultaneously (left diagram). At the peak load there are 95% of filaments active and at the end of the loading only 15% of filaments got broken while all the rest remains intact (they have been pulled out).

On the other hand, for the yarn with a higher level of friction ($\tau_{fr} = 6 \text{ MPa} \approx 870 \text{ psi}$) and with the same profiles of irregularity ($\varphi(\xi)$, $\ell(\xi)$, $\theta(\xi)$) there are only 55% of fila-

ments active at the maximum pull-out force (30% are still inactive and 15 % are already broken). At the end of the loading all the filaments are broken. Thus, even though the inner filaments could transfer a higher amount of force to the matrix, the resulting pull-out force has been reduced due to the non-uniformity of the transfer.

In general terms this conclusion is in agreement with the results presented by (Phoenix 1974) saying that isolated improvement of a single material component can lead to reduced overall performance of the composite with presence of significant amount of imperfections.

SUMMARY

A specific feature of the textile reinforced concrete is the high degree of heterogeneity of the reinforcement and of the matrix on similar scales of the material structure. The complex damage and failure process calls for an application of stochastic and micromechanical models that can reflect the heterogeneity.

Tensile tests on AR-glass and carbon multi-filament yarns show a complex length- and loading rate dependent performance. The stochastic modeling of the multi-filament yarn using the numerical bundle model is able to reproduce the complex statistical size effect observed in the testing program in terms of statistical distributions of slack, filament strength and filament stiffness. The comparison of the load-strain diagrams of AR-glass and carbon revealed that the different loading rate dependency is a result of different levels of friction transferred between the filaments.

The described qualitative studies of the bond-layer emphasize the influence of heterogeneity represented by the varying bond-free length, delayed activation and spatial variations in the bond quality. The improvement of the local bond performance is counterproductive if the failure process and the activation rate of the filaments are not balanced. On the other hand the delayed activation can be utilized to improve the material performance by a convenient combination of different materials.

The final message of this paper can be put as follows: In the design of cementitious composites reinforced with multi-filament yarns the issue of disorder must be carefully analyzed. Only with a good knowledge of the phenomena in the microstructure it is possible to balance the performance of the individual components of the material structure to obtain an optimum performance of the composite.

ACKNOWLEDGEMENTS

The authors thank the German research foundation (DFG) in context of the Collaborative Research Center 532 for their financial support.

REFERENCES

- Abrihami, H.H.; Mitchell, D., "Analysis of Bond Stress Distributions in Pull-out Specimens", *Journal of Structural Engineering* 122(3), 1996, p. 255-261.
- Banhölzer, B, *Bond Behaviour of a Multi-Filament Yarn Embedded in a Cementitious Matrix*, Schriftenreihe Aachener Beiträge zur Bauforschung, Institut für Bauforschung der RWTH – Aachen, PhD thesis, 2004.
- Chudoba, R.; Vořechovský, M.; Konrad, M., "Stochastic modeling of multifilament yarns I: random properties within the cross section and size effect", *Int. Journal of Solids and Structures*, 43, 3-4, 2006, p. 413-434.
- Chudoba, R.; Butenweg, C.; Peiffer, F., "Technical Information System for Collaborative Material Research," *Advances in Engineering Software*, 35, 2004, p. 747-756.
- Gries, T. and Roye, A.: Three-Dimensional Reinforcement Structures for Thin Walled Components, *proceedings: 2nd Colloquium on Textile Reinforced Structures CTRS2*, Dresden, 2003, p. 513-524.
- Hegger, J.; Will, N.; Bruckermann, O.; Voss, S., "Load Bearing Behavior and Applications of Textile Reinforced Concrete", *Materials and Structures*, submitted for publication, 2005.
- Hegger, J., Voss, S., Bruckermann, O., "AR-Glass and Carbon Fibers for Textile Reinforced Concrete – Simulation and Design", *ACI Spring Convention*, New York 2005.
- Hegger, J., Arbeits- und Ergebnisbericht zum Sonderforschungsbereich 532 "Textilbewehrter Beton – Grundlagen für die Entwicklung einer neuen Technologie " für die Periode II/2002 bis I/2005. *Tech. Rep. SFB 532*, RWTH Aachen University.
- Hegger, J.; Bruckermann, O.; Chudoba, R., "A Smeared Bond-Slip Relation for Multi-Filament Yarns Embedded in Fine Concrete." *Sixth International RILEM Symposium on Fibre-Reinforced Concretes (FRC) BEFIB 2004*, Editor: M. di Prisco et al., Varenna, Italy, 2004, p. 1453-1462.
- Kaliakin, V. N. and Li, J., "Insight Into Deficiencies Associated with Commonly Used Zero-Thickness Interface Elements", *Computers and Geotechnics*, 17(2), 1995, p. 225-252.
- Konrad, M. and Chudoba, R.: "The Influence of Disorder in Multifilament Yarns on the Bond Performance in Textile Reinforced Concrete", *Acta Polytechnica*, 44(5-6), 2004, p. 186-193.
- Phoenix, S. L., "Probabilistic Strength Analysis of Fibre Bundle Structures", *Fibre Science and Technology* 7, 1974, p. 15-31.
- Phoenix, S. L. and Taylor, H. M., "The Asymptotic Strength Distribution of a General Fiber Bundle", *Advances in Applied Probability* 5, 1973, p. 200-216.

Phoenix, S. L., “The Random Strength of Series-Parallel Structures with Load Sharing among Members”, *Probabilistic Mechanics*, 1978, p. 91-95.

Stang, H.; Li, Z.; Shah, S.P. “Pullout Problem: Stress Versus Fracture Mechanical Approach”, *Journal of Engineering Mechanics* 116(10), 1990, p. 2136-2150.

Vořechovský, M., Chudoba, R., “Stochastic Modeling of Multifilament Yarns II: Random Properties Over the Length and Size Effect”, *Int. Journal of Solids and Structures*, 43(3-4), 2006, p. 435-458.

LIST OF NOTATIONS

A	=	bundle cross section
E	=	Young's modulus
G_θ	=	cumulative probability distribution of random filament parameter(s)
L_{test}	=	length of s yarn tensile test specimen
L_{bridge}	=	length of a crack bridge
L_{struct}	=	length of a structure
e	=	bundle strain;
f^t	=	tensile filament strength
$k_{\varphi,0}$	=	gradient of the profile of the bond quality in the center of the roving
$k_{\varphi,1}$	=	gradient of the profile of the bond quality at the border of the roving
$k_{\theta,1}$	=	gradient of the profile of the delayed activation at the border of the roving
$\ell(\xi)$	=	profile of the bond free length
ℓ_{max}	=	maximum of the bond free length
ℓ_{min}	=	maximum of the bond free length
l	=	nominal length of the test specimen
$q_e(e; \theta)$	=	load strain relation
s	=	slip
$\varphi(\xi)$	=	profile of the bond quality
λ	=	relative differences in clamping distance of individual filaments
$\mu_\theta(e)$	=	mean load-strain function of the bundle
θ	=	delayed activation (slack)
$\theta(\xi)$	=	profile of the delayed activation
θ_{max}	=	
θ	=	Vector of random filament parameter(s)
τ_{fr}	=	local bond quality
$\tau_1(s)$	=	bond law filament matrix for a perfectly embedded filament
$\tau(s, \xi)$	=	bond law distributed over the bond layer
ξ	=	parametric coordinate