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

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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 innova-tive 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 con-crete components."

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

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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.

SUITABLE HIGH PERFORMANCE FIBERS

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/dm^3 (175 lb/ft^3), good adhesion to concrete and a good cost-performance ratio with an average price of 24 €/dm^3 (680 €/ft^3) [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 und 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) und 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/dm^3 (110 lb/ft^3), 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 €/dm^3 or 1130 €/ft^3) 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-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 transference 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 multi-plies (plain or circular) and wovens [1].

At the ITB the stitch-bonding technology for the making of plain, mechanically bonded multi-plies 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.

Multi-plies 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 multi-plies 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°, -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.

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-plies 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-plies with properties meeting exact requirements. Furthermore, the geometry will be improved to achieve even better composite characteristics.

EXAMPLES

Stitch-bonded multi-plies 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-plies 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 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.

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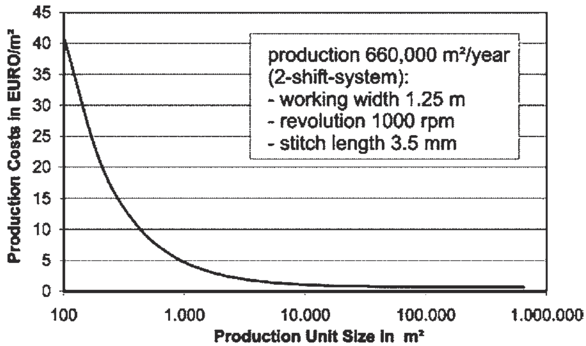

Fig. 1—Productivity of multi-axial warp knitting machine Malimo 14024.[12] (1°€/m² ≈ 0.09°€/ft², 1 m² ≈ 0.09 ft², 1 m ≈ 3.28 ft, 1 mm ≈ 0.04 in.)

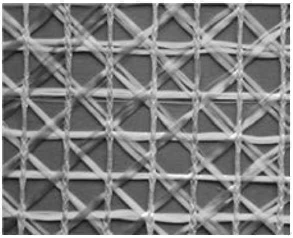

Fig. 2—Stitch-bonded multi-axial multi-ply.

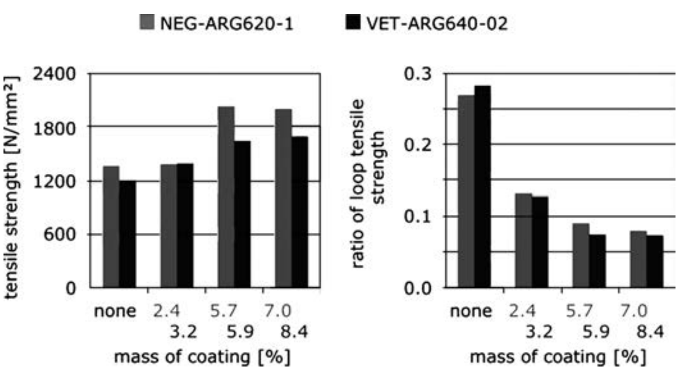

Fig. 3—Influence of mass of coating on tensile strength and loop tensile strength for two different types of AR glass yarn.[3] (1 N/mm² ≈ 0.15 ksi)