DIMENSIONING OF TRC WITH APPLICATION TO VENTILATED FAÇADE SYSTEMS

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ABSTRACT: Textile Reinforced Concrete (TRC) is a new composite material consisting of non-corroding fibre meshes embedded in a fine grained concrete matrix. The textile reinforcement is a 2-D or 3-D mesh made of multifilament yarns (rovings), bundles of hundreds to thousands of single fibers. As no concrete cover is required to protect the textile fabrics against corrosion, the utilisation of TRC enables the production of thin, lightweight structural concrete components. In this paper the capability of the design and application of TRC is exemplified with a presentation of ventilated large-sized façade elements. The paper describes the development of suitable materials for the panels, the structural design, the experimental testing of the structure and the design and dimensioning of the façade elements.

1 INTRODUCTION

Textile Reinforced Concrete (TRC) is a new composite material consisting of non-corroding fibre meshes embedded in a fine grained concrete matrix. It combines the advantages of ordinary steel reinforced concrete and short fibre concrete. As no concrete cover is required to protect the textile fabrics against corrosion, it is possible to create thin, lightweight structural components from TRC and thus to expand the fields of application of concrete structures.

Since its initiation in 1998, the Collaborative Research Center Project No. 532 (CRC 532) at Aachen University has been investigating the basic principles of textile reinforced concrete. Since then several projects have been conducted that show the high potential and the advantages of textile reinforced concrete.

In this paper the design of textile reinforced concrete and its latest transformation into practical application are explained. Therefore an industrial research project is presented where a large-sized façade panel was developed in cooperation of two institutes at RWTH Aachen University (IMB: Institute of Structural Concrete; Ibac: Institute of Building Materials Research) and the company Hering Group (Burbach), a supplier for precast industrial concrete. The aim of the project was the development of a façade panel with an area of more than 12 m² due to economic reasons. Afterwards the results of the project were applied in the scope of a pilot project, where the large-sized TRC façade panels were used for the cladding of the new laboratory hall of the Institute of Structural Concrete. The building and the façade was designed by the architects "Weiss + Schätzke" (Aachen).

The paper summarizes the development of suitable materials for the panels, the structural analysis, the experimental testing of the composite structure and the dimensioning and design of the façade elements.
2 MATERIALS

The new composite material TRC consists of a textile reinforcement embedded in a fine grained concrete matrix. Usually for the construction of flat, two-dimensional structural elements 2D-textile reinforcements are applied with fabrics produced of AR glass or carbon.

2.1 Fine-grained concrete matrix

Within the scope of CRC 532 a standard concrete matrix with a maximum grain size of 0.6 mm (concrete A, Table 2.1) was developed at the Institute of Building Materials Research (IBAC) at RWTH Aachen University, specially adapted to the application of textile reinforced concrete.

One important task in the research project “large-size façade elements” was the development and production of a new fine-grained concrete matrix that is still workable under realistic conditions in practice, i.e. with building site and without laboratory conditions. In close collaboration and cooperation between IBAC and Hering Group a new concrete with an increased grain size of 5 mm was developed (concrete B). Selected material properties of these two concretes are presented in Table 2.1.

Table 2.1. Concrete properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Concrete A (standard concrete matrix of CRC 532)</th>
<th>Concrete B (concrete matrix for large-sized façade panels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum grain-size</td>
<td>mm</td>
<td>0.6</td>
<td>5.0</td>
</tr>
<tr>
<td>Compression strength</td>
<td>MPa</td>
<td>67.1</td>
<td>70.9</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>MPa</td>
<td>4.1</td>
<td>4.0</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>MPa</td>
<td>33100</td>
<td>35700</td>
</tr>
</tbody>
</table>

2.2 Textile reinforcement

Within the research of CRC 532 different materials for the textile reinforcement have been investigated, such as AR-glass (alkali-resistant glass), carbon or aramid, whereas AR-glass is the most common and most used material in TRC-applications today.

The first step in the production process of a textile structure is the twisting and bundling of several hundreds to thousands of single filaments to rovings, which, in turn, are processed to an open mesh-like reinforcement structure. For the application of concrete A with a maximum grain-size of 0.6 mm, suitable textile structures with roving distances of about 8 mm were developed in CRC 532 (textile A, Fig. 2.1).

Due to the larger maximum grain size of 5 mm of concrete B the closed-meshed reinforcement of textile A could not be used as reinforcement for this purpose. For an easy cast of the concrete through the mesh, the openings in the textile are chosen to be at least
three times bigger than the grain size, otherwise the aggregates are not able to penetrate through the reinforcement mesh, which then acts like a separation layer for the concrete components.

Thus, several feasible variations of textiles with increased roving distance were investigated and textile B (Fig. 2.1) produced the best results regarding load-bearing behaviour.

![Textile A](image1.png) ![Textile B](image2.png)

**Fig. 2.1.** Textile structures: a) standard textile of CRC 532; b) specially developed textile used for the large-sized façade panels.

To increase the tensile strength of the textile in the composite structure, to enhance the stability for handling and to avoid deformations of the textile, textile B was impregnated with an epoxy resin coating after production.

Table 2.2 presents the material properties of the two textiles as well as the results from tensile tests on specimens reinforced with textile A and textile B.

### Table 2.2. Textile properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Textile A (standard matrix, standard textile of CRC 532)</th>
<th>Textile B (large-sized façade panels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roving</td>
<td>-</td>
<td>OCV\textsuperscript{TM} Reinforcements</td>
<td></td>
</tr>
<tr>
<td>Denotation</td>
<td>-</td>
<td>LTR 5325</td>
<td></td>
</tr>
<tr>
<td>Titer</td>
<td>tex</td>
<td>2400</td>
<td>1200 + 2400</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>MPa</td>
<td>64800</td>
<td></td>
</tr>
<tr>
<td>Roving distance</td>
<td>mm</td>
<td>8.2</td>
<td>8.2 / 16.8</td>
</tr>
<tr>
<td>Tensile strength 1</td>
<td>MPa</td>
<td>1700</td>
<td></td>
</tr>
<tr>
<td>Impregnation</td>
<td>-</td>
<td>-</td>
<td>epoxy resin</td>
</tr>
<tr>
<td>Cross-section</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0°</td>
<td>mm\textsuperscript{2}/m</td>
<td>108</td>
<td>108</td>
</tr>
<tr>
<td>90°</td>
<td>mm\textsuperscript{2}/m</td>
<td>108</td>
<td>75</td>
</tr>
<tr>
<td>Tensile strength 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0°</td>
<td>MPa</td>
<td>489</td>
<td>1160</td>
</tr>
<tr>
<td>90°</td>
<td>MPa</td>
<td>619</td>
<td>1390</td>
</tr>
</tbody>
</table>

1 Tensile strength of the filaments (without concrete) (manufacturer information)
2 Tensile strength of the reinforcement in concrete (mean values)
It is obvious that because of its epoxy resin coating textile B achieves a much higher tensile strength (about 1400 MPa in 90°-direction) than textile B without coating. The lower tensile strength in 0°-direction compared to the higher value in 90°-direction is caused by the production process of the textile: Due to the knitting-yarn wound around the rovings in 0°-direction these rovings are strongly compacted. Thus, the resin cannot penetrate as easily into the inner roving as compared to the 90°-direction and the inner filaments are not completely activated for the load transfer.

3 DIMENSIONING OF TRC: TENSILE STRENGTH AND BENDING CAPACITY

For the structural design the knowledge of the tensile capacity of the construction material is important. Previous investigations [Ban04], [Ohn94] have shown that the tensile strength of the filaments cannot be fully utilised within the composite material TRC. The main reason is the decreasing bond performance from the outer filaments towards the inner core of the roving. Based on the results of tensile tests on textile reinforced concrete elements, a factor $k_1$ for the fibre efficiency can be determined [Heg07]. This factor is calculated as the ratio between the measured average strength of the reinforcement embedded in the concrete $\sigma_{\text{max}}$ and the tensile strength of the filament $f_{\text{fil}}$:

$$k_1 = \frac{\sigma_{\text{max}}}{f_{\text{fil}}} \quad (3.1)$$

The efficiency of a fabric is influenced by the geometry of the roving and the penetration of the concrete matrix into the roving. The decisive parameters are the bond properties of the roving, the filament’s diameter, the roving thickness and the existence of a polymer coating of the textile as these parameters affect the roving geometry and the penetration of the matrix into the roving. In table 3.1 the factor $k_1$ is given as a mean value of at least six single tests. When coated with an epoxy resin, the load-bearing capacity of the AR-glass-fabric can be significantly increased and the average strength of the composite material rises to 65-70 % of its filament strength.

<table>
<thead>
<tr>
<th>Textile</th>
<th>$k_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Textile A (uncoated)</td>
<td>0.288</td>
</tr>
<tr>
<td>Textile B (coated)</td>
<td>0.682</td>
</tr>
</tbody>
</table>

The tensile strength of the component is furthermore influenced by lateral tensile stresses as shown in biaxial tensile tests on textile reinforced concrete discs [Vos08]. The cracking of the concrete along the reinforcement leads to damages of the rovings and causes a decreasing strength of the component. Another very important effect is the orientation of the reinforcement in respect to the load direction. The deviating directions of loading and reinforcement lead to significant losses of tensile strength. The main effects responsible for this loss of strength are the lateral pressure and the bending stresses of the filaments at the crack edges as the fibres are diverged (Fig. 3.1).
A detailed description of these effects is given in [Heg06]. Based on these results the assumption was derived that the tensile strength of the reinforcement decreases linearly with an increasing angle $\alpha$ between the direction of tensile force and the direction of alignment of the rovings. This relationship is represented by the factor $k_{0,\alpha}$:

$$k_{0,\alpha} = 1 - \frac{\alpha}{90^\circ}$$  \hfill (3.2)

Results of other investigations concerning the effects of alignment of the rovings with higher loss of strength are described in [Jes05].

Considering the described effects the tensile strength of the textile reinforced component $F_{ctu}$ can be calculated as

$$F_{ctu} = A_t \cdot f_{fil} \cdot k_1 \cdot k_{0,\alpha} \cdot k_2$$  \hfill (3.3)

where

- $A_t$ cross-sectional area of the reinforcement [mm$^2$]
- $f_{fil}$ tensile strength of the filament [MPa]
- $k_1$ efficiency factor [-]
- $k_{0,\alpha}$ factor for orientation of the reinforcement [-] (according to equation (3.2))
- $k_2$ factor for biaxial loading [-] (derived in [Vos08]).

In accordance to steel reinforced concrete the bending capacity of TRC elements can be calculated with the knowledge of the tensile strength of the reinforcement $F_{ctu}$ and the inner lever arm $z$:

$$M_u = F_{ctu} \cdot z$$  \hfill (3.4)

where

- $F_{ctu}$ according to equation (3.3) [kN]
- $z$ inner lever arm [mm].
4 DIMENSIONING OF THE LARGE-SIZED FACADE PANELS

4.1 General Remarks

The aim of the project was the development of a façade panel with an area of more than 12 m² to reduce costs for the transport and installation of the elements. Thus, panel dimensions of 2.51 m x 4.88 m were chosen while the slab thickness was only 30 mm with an additional structuring of 5 mm, which was not taken into account in the structural analysis.

The results of the research project were applied in the scope of a pilot project, where the large-sized TRC façade panels were used for the new laboratory hall of the Institute of Structural Concrete (Fig. 4.1).

Due to the thin slab thickness of 30 mm a bracing system had to be arranged on the backside of the slab. While small sized façade panels are normally stiffened by metal stud-frame systems, it was also an aim of this research project to use a monolithic solution of the bracing system. Thus, two concrete webs were arranged, which also accommodated the fixing devices (Fig. 4.2, left): On the top of the slab, the webs width was enlarged to place the precast panel anchor and the spacer bolt properly. On the under part, wind anchors were placed to bear the forces due to wind suction.

The position of the concrete webs was determined in the way that under a uniform loading the hogging moment at the support and the sagging moment in the field were equal. By designing the cross-section in this way, it is possible to reinforce the slab with only one textile layer in the center of the cross-section, which is utilized evenly (Fig. 4.2, right).

4.2 Structural analysis

The deformations, stresses and internal forces under loads were determined by a finite-element (FE) model using the program "InfoCAD" version 7.0, Infograph, Fig. 4.3, a). Typical loads for façades have been applied, e.g. self-weight (25 kN/m²), wind pressure and wind suction (+0.45 resp. -0.50 kN/m²). The load cases "temperature" and "concrete

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**Fig. 4.1.** Pilot project: a) View of the new laboratory hall, b) dimensions, c) detail of the TRC façade.
shrinkage” were also considered, but do not cause internal forces due to the statically determined supporting situation.

**Fig. 4.2.** Backside of the large-sized façade panel with concrete webs; cross-section with bending moments

**Fig. 4.3.** Structural system (a) and detail of supporting (b); FE-model, "InfoCAD” version 7.0, Infograph
In Fig. 4.3 b) the detailed model of the fixing devices is shown. The precast panel anchor bears the self-weight of the panel in vertical direction. Spacer bolts and wind anchors were used to carry the horizontal wind loads. Restraint forces due to shrinkage and temperature were reduced significantly by using a small diameter of the wind anchor, thus, the panel can deform easily in vertical direction. By choosing this arrangement of the fixing devices, the façade panel is supported statically determined.

At first, the load-bearing behaviour in transversal direction of the panel is considered, i.e. the analysis of a slab cross-section. In Fig. 4.4 a) the location of the reinforcement is shown. Due to a thin slab-thickness of only 30 mm, the reinforcement-layer is located in the center of the 3 cm thick cross-section to avoid an upper and lower layer as it is known from ordinary steel-reinforced concrete slabs. The concreting is much easier with only one layer, but due to a low inner lever arm \( z \), the area of the textile has to be increased to bear the tensile force \( F_t \).

Then the load-bearing behaviour in longitudinal direction of the panel is considered, i.e. the analysis of the web. In Fig. 4.4 b) the arrangement of the adequate reinforcement is shown. By impregnating the textiles with an epoxy resin and curing them in a mold, it is possible to produce the shaped and inherently stable reinforcement structure for the web reinforcement as depicted in Fig. 4.4 b). Details on the production process are explained in [Heg09]. To avoid a second layer on the bottom of the web, two FRP-bars were arranged.

### 4.3 Experimental test results

As textile-reinforced concrete is not regulated in any standard today, for each construction project an individual approval is required in Germany. In the approval process, all assumptions made in the static calculation have to be verified within the scope of a wide-range testing program.

According to the load-bearing behaviour in longitudinal and transversal direction, both the cross-section of the slab as well as of the T-beam had to be considered in the experimental test program. The fixing devices were tested as well, but are not explained in detail in this paper. Bending tests on 3 cm thick specimen reflected the load-bearing behaviour in
transversal direction. Fig. 4.5 a) shows the test-setup and Fig. 4.5 b) the textile stress-deflection diagram, where the deflection is related to the span.

In the serviceability limit state (SLS), defined by initial crack formation, the deflections are very small and not visible to the naked eye. In contrast to this, in the ultimate limit state (ULS) the deformations are very high and indicate the failure of the structure. Due to the impregnation of the textile with an epoxy resin, tensile stresses of about 1400 MPa (medium value) were achieved [Rau06].

**Fig. 4.5.** Load-bearing behaviour of the slab: a) test setup, b) textile stress-deflection diagram

In Fig. 4.6 the test setup of bending tests on T-beams is shown to represent the load-bearing behaviour in longitudinal direction. In that case the cross-section was tested in two different positions to examine the behaviour under wind pressure (positive bending moment) as well as under wind suction (negative bending moment).

**Fig. 4.6.** T-beam: a) test setup, b) different positions of the cross-section in the test.
The T-beam tests demonstrated that TRC members have a distinctive ductile behaviour: The stress-deflection diagram in Fig. 4.7 a) reveals high deflections (L/23 - L/19) in the ULS and small deflections in the SLS. Fig. 4.7 b) depicts a T-beam member with a well-developed, stabilized crack pattern (in Fig. 4.7 b) the cracks are highlighted). Here, the high deformations of the member are well recognizable.

![Stress-Deflection Diagram](image)

**Fig. 4.7.** T-beam (negative moment): a) stress-deflection diagram, b) crack pattern

### 5 Conclusions

The load bearing behaviour of TRC is significantly influenced by the mechanical properties and the bond performance of the textile reinforcement, thus efficiency factors are introduced for dimensioning TRC members. The comparison of the test results of uncoated AR-glass fibres and AR-glass fibres coated with an epoxy resin show that the impregnation of the rovings significantly influences the bond performance, i.e. the inner bond of the filaments, as well as the effectiveness of the reinforcement in the concrete.

The composite material TRC broadens the application of concrete constructions in the field of façade engineering. For structural members without planar geometry tailor-made reinforcements with high load-bearing capacities are possible. With the development of these structures, an important step for building almost any section with TRC has been performed.

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REFERENCES


