APPLICATION POTENTIAL OF TEXTILE REINFORCED CONCRETE

Josef Hegger (1), Ali Shams (1), Christian Kulas (1) and Michael Horstmann (1)

(1) Institut of Structural Concrete, RWTH Aachen University, Germany

Abstract

The innovative composite material Textile Reinforced Concrete (TRC) takes into account the advantages of high-strength fine-grained concretes and open-meshed textile reinforcements, which are mainly made of alkali-resistant glass (AR-glass) or carbon fibers. Due to the non-corrosive behavior of the textiles, the required concrete covers can be minimized resulting in filigree and lightweight concrete structures with minimum thicknesses of 15 mm. This paper presents selected TRC applications in the field of façade- and bridge-construction which have been realized within the last three years.

1. INTRODUCTION

Structural members made of concrete are usually reinforced with steel. To prevent the steel from corrosion, concrete covers of about 35 mm have to comply with current design codes [1], [2], [3]. The use of non-corrodible technical textiles reduces concrete cover significantly and enables the realization of light-weight as well as slender structures. In the scope of this paper three different applications are presented: self-supporting sandwich façade (ITA, Aachen, Germany), ventilated façade structure (Community College Leiden, The Netherland) and a pedestrian bridge (Albstadt, Germany).

2. APPLIED MATERIALS

2.1 Textile reinforcement

The currently used materials for TRC applications are filaments made of alkali-resistant glass (AR-glass, filament diameter 14-27 μm) or carbon (filament diameter 7 μm). Hundreds or thousands of those filaments are bundled to rovings, which, again finished to a laid-scrim, i.e. a mesh-like reinforcement structure (Figure 1a).

2.2 Concrete mixtures

The selection of concrete mixtures is very important for the structural behavior. Special attention is paid to the mechanical properties of the concrete and the alkali-silica reaction. The mixtures are mainly selected for their workability and resistance against alkali-silica reaction in the long term.

2.3 Materials of façade- and bridge-construction

Facade structures (Figure 2a) are usually made of cementitious composites with a thickness of about 15 mm. The materials are mainly selected for their low weight and special properties such as sound reduction. Bridge-constructions (Figure 2b) are mostly made of reinforced concrete. The tensile forces are mainly transferred by the TRC and the steel reinforcement.

2.4 Reinforcement in concrete structures

In concrete structures, the reinforcement is mostly made of steel. The use of TRC allows for a reduced reinforcement, which results in a lower material cost and a lower weight of the structure.

2.5 Durability

The durability of concrete structures is mainly influenced by the alkali-silica reaction. The use of AR-glass fibers reduces the risk of this reaction, which results in a longer service life of the structure.

2.6 Costs

The costs of TRC are mainly influenced by the costs of the textile reinforcement. The use of AR-glass filaments is more expensive than carbon filaments. However, the reduced concrete cover results in a lower total cost of the structure.

3. RESULTS

The results of the TRC applications are presented in the following sections. The structural behavior is mainly influenced by the mechanical properties of the concrete and the textile reinforcement.

4. CONCLUSIONS

The use of TRC allows for the realization of light-weight and slender structures. The selected applications show the potential of TRC in the field of façade- and bridge-construction.
Finally, the textiles are impregnated with e.g. an epoxy-resin. Raupach et al. [4] describe the advantages of impregnated textiles in comparison to those which are not impregnated. Since the filaments have diameters of some micrometers, and therefore small space between the single filaments, the concrete matrix is not able to penetrate into the inner rovings. Thus, the core filaments are not activated for load transfer. In contrast, the resin has the ability to penetrate into the roving and connect the filaments. The result is a homogenous cross-section, where nearly all filaments are activated for load transfer. Furthermore, the tensile strength can be more than doubled in comparison to an uncoated roving.

Only the impregnation and curing process, described in [5], allows for inherently stable reinforcement structures in any arbitrary shape, Figure 1b. These textile reinforcements offer a good handling and workability, which is necessary for using them for large-scale members under practical conditions in precast concrete factories. The main properties of the textiles used in the projects in this article are specified in Table 1.

### Table 1: Properties of the textile reinforcements

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Textile 1</th>
<th>Textile 2</th>
<th>Textile 3</th>
<th>Textile 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project</td>
<td>-</td>
<td>Sandwich panels</td>
<td>Community College Leiden, The Netherlands</td>
<td>Pedestrian Bridge Albstadt, Germany</td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>-</td>
<td>AR-glass</td>
<td>AR-glass</td>
<td>Carbon</td>
<td>AR-glass</td>
</tr>
<tr>
<td>Roving: 0°/90°</td>
<td>tex</td>
<td>OCV&lt;sup&gt;TM&lt;/sup&gt; 2400 / 2400</td>
<td>OCV&lt;sup&gt;TM&lt;/sup&gt; 2x1200 / 1200</td>
<td>Chomarat North America 3000 / 3000</td>
<td>OCV&lt;sup&gt;TM&lt;/sup&gt; Reinforcement 3600 / 3600</td>
</tr>
<tr>
<td>Impregnation</td>
<td>-</td>
<td>Epoxy resin</td>
<td>Uncoated</td>
<td>Epoxy resin</td>
<td>Epoxy resin</td>
</tr>
<tr>
<td>Roving distances&lt;sup&gt;1)&lt;/sup&gt;</td>
<td>mm</td>
<td>8.4 / 8.4</td>
<td>12.5 / 12.6</td>
<td>46.741</td>
<td>5.15 / 7.5,15</td>
</tr>
<tr>
<td>Cross-section&lt;sup&gt;1)&lt;/sup&gt;</td>
<td>mm&lt;sup&gt;2&lt;/sup&gt;/m</td>
<td>108 / 108</td>
<td>71.5 / 53</td>
<td>38.42</td>
<td>134 / 119</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>MPa</td>
<td>1227 / -</td>
<td>2267 / -</td>
<td>87.1&lt;sup&gt;1)&lt;/sup&gt;</td>
<td></td>
</tr>
</tbody>
</table>

<sup>1)</sup> Designation in direction of textile: 0° / 90°<sup>1)</sup> Designation in main direction of load transfer

### 2.2 Fine-grained concrete

The properties of the textile reinforcement involve special demands on the concrete mixture. To enable the concrete to penetrate through the fabric mesh, the maximum grain size is adjusted to the openings of the textiles. Furthermore, a high flowability is necessary to achieve a proper workability. The main properties of the hardened concrete are summarized in Table 2.

### Table 2: Properties of applied concrete (mean values after 28d)

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Concrete 1</th>
<th>Concrete 2</th>
<th>Concrete 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project</td>
<td>-</td>
<td>Sandwich panels</td>
<td>Community College Leiden, The Netherlands</td>
<td>Pedestrian Bridge Albstadt, Germany</td>
</tr>
<tr>
<td>Max. grain-size</td>
<td>mm</td>
<td>2</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>MPa</td>
<td>68.7&lt;sup&gt;1)&lt;/sup&gt; / 65.1&lt;sup&gt;1)&lt;/sup&gt;</td>
<td>64.4&lt;sup&gt;1)&lt;/sup&gt;</td>
<td>87.1&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>MPa</td>
<td>4.0</td>
<td>4.8</td>
<td>4.7</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>MPa</td>
<td>37000</td>
<td>not determined</td>
<td>33600</td>
</tr>
</tbody>
</table>

<sup>1)</sup>Cube, “Cylinder,” Prism 40x40x160mm
2.3 Rigid foam core

Rigid Polyurethane (PU) foam is a suitable material for producing sandwich panels with a high stiffness and load-bearing capacity with low thermal conductivity and excellent insulating properties. With increasing density of the PU foam the stiffness and the strength of sandwich panels are enlarging whereas the sound and heat insulation of the panel are decreasing. For the production of self-supporting sandwich panels, PU foam with a core density of 50 kg/m$^3$ was chosen which provides a good agreement of load-bearing behavior and structural-physical properties. The foams were gained from large block rigid foams and the surface was notched and pressed into the freshly cast facings to provide good bond characteristics. The properties of the foam core material are listed in Table 3.

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Polyurethane ($\rho = 50$ kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength / Elastic modulus</td>
<td>MPa</td>
<td>0.38 / 10-16</td>
</tr>
<tr>
<td>Tensile strength / Elastic modulus</td>
<td>MPa</td>
<td>0.23 / 14-16</td>
</tr>
<tr>
<td>Shear strength / Shear modulus</td>
<td>MPa</td>
<td>0.225 / 3-4</td>
</tr>
</tbody>
</table>

3. APPLICATIONS

3.1 Self-supporting sandwich façades

In a research project funded by the European Union (Life INSU-SHELL) an innovative modular system for self-supporting sandwich panels made of TRC have been developed and applied for the façade of the new laboratory building of the “Institute für Textiltechnik (ITA)”, RWTH Aachen University, Figure 2.

Figure 2: View of the INSU-SHELL TRC façade (Source ITA, RWTH Aachen University)

The maximum dimensions of the panels are $L \times H \times T = 3.425 \times 0.975 \times 0.18$ m$^3$, Figure 3. The sandwich section consists of a rigid polyurethane foam core (section 2.3) and two thin TRC facings with a principal thickness of 15 mm. The thickness is enlarged to 40 mm at the ending frames in which stainless steel connectors are located to connect inner and outer facing properly. The larger thickness both benefits the panel stiffness and the anchorage depth of the connectors. The thin mid parts are reinforced with two layers of the uncoated textile 2
(Table 20) whereas in the narrow and highly stressed frame additional stripes of the coated textile 1 (Table 20) are located, Figure 3.

Figure 3: Structural system of self-supporting sandwich panels

The design of the panels is based on test results and a calculation model presented in [6], [7]. According to the theory of the elastic composite, shear forces induced by transverse loads are borne mainly by the core whose stiffness also dominates the load-deflection behavior of the panel. To ensure a durable sandwich action, eight ductile pin connectors with a diameter of 4 mm have been designed to relieve stresses perpendicular to the joints of core and facing induced by temperature, shrinkage and wind suction. The panels dead load is transferred to two vertical supports while the wind loads are borne by four horizontal supports. All supports are located at the inner TRC facing transferring the loads to the backing main load-bearing steel frame structure. The weight of the front facing is directly transmitted to the upper horizontal supports with two diagonal steel ties at both ends of the panel.

Ten prototype elements were tested in four-point bending tests under static and cyclic loading to determine the load-bearing behavior and capacity. The results of three representative bending tests are depicted in Figure 4.

Figure 4: Results of prototype tests and influence of joint quality on shear capacity
Due to the high load-bearing capacity of the TRC facings all sandwich panels failed by shear rupture of the core. After shear failure the residual load-bearing capacity equaled 50% of the maximum load was still larger than the design limit multiplied with the partial safety factor for the polyurethane material. Due to the deliberately chosen core strength, a large reserve is remaining given that the layers are connected by perfect joints. Panel 2 and 3 failed at a much lower load level due to some large areas of poor bond quality leading to a concentrated and inhomogeneous shear flow in areas with good bond. Furthermore, a significant influence of the cyclic loads on the shear capacity of the foam did not become evident from the performed tests. Tests on panel 2 and 3 with poor bond areas have proven that the pin connectors and the surrounding concrete frame at the panel edges allow for secondary shear transfer mechanisms like friction or principle positive locking. Thus, panels 2 and 3 also exceeded the demanded design values in ultimate limit state (ULS).

The chopped fibers and textile fabrics effectively reduced cracking of the concrete facings. In SLS no cracks were observed and even in ULS only a few cracks were visually noticed.

3.2 Ventilated façade structures

Hegger et al. presented in [8] one of the first ventilated TRC façade, which was developed within the scope of an industrial research project. The panel has dimensions of 2.685 m x 0.325 m (A = 0.87 m²) and a thickness of 25 mm. Its applicability was demonstrated in a pilot project, where a façade with an area of 200 m² was cladded. Based on this industrial research project, an imposing example of a TRC façade was applied to the 10,000 m² large façade of the Community College in Leiden (The Netherlands). Here, the largest elements have dimensions of 1.780 m x 0.642 m (A = 1.14 m²) while the slab is only 30 mm thick, Figure 5.

Figure 5: Elevation and cross-section of a small-sized façade panel

Since the building has a total height of approximately 50 m and is located near the North Sea coast, the façade panels have to carry high wind loads up to 3.0 kN/m² (characteristic value). Thus, a heavy-duty material as reinforcement has to be chosen like the carbon textile 3 in Table 20. By impregnating this grid with an epoxy resin, an ultimate tensile strength of 2267 MPa was achieved, which is the mean value of the textile embedded in concrete.

The fact that TRC is not regulated in standards so far necessitates the assessment of the load-bearing behavior by tests. In the scope of this project, the bending-behavior of the slab and the punching-behavior of the supporting have to be assessed. The bending-behavior, which is exemplarily presented in the scope of this paper, was determined by four-point
bending tests on specimens with the dimensions of 700 mm x 150 mm x 30 mm (Figure 6a). The test results are depicted in Figure 47b, where the moment is plotted over the deflection.

![Figure 6: Bending-behavior of the slab: a) test-setup; b) moment-deflection diagram](image)

Out of those test results the characteristic value (k) is determined on the basis of the European standard DIN EN 1990 [9]. Under consideration of partial safety factor $\gamma_R = 1.50$ (textile failure) the design values (d) can be calculated for the resistant bending moment (R). In Figure 6b these values are compared with those of the acting internal bending moment (E). All in all, a global safety factor of $\eta_{\text{global}} = 4.84$ is achieved, which is higher than the required factor of 2.25.

### 3.3 Pedestrian bridge construction

Next to applications for façade structures, TRC is also applicable for constructions like bridges. One example is the 97 m long pedestrian bridge (opened in November 2010) over a state road in Albstadt, Germany (Figure 7a). Since the concrete superstructure is produced in a precast concrete factory, the construction is subdivided in six prefabricated parts, with a maximum length of 17.20 m. The aim of the design of this bridge is a slender fair-faced concrete superstructure fulfilling demands on a durable construction, especially frost resistance. Thus, TRC (textile 4 in Table 20) was chosen as construction material instead of the commonly used steel reinforcement. By using non-corrodirble textiles, the concrete covers can be minimized to 15 mm and only the combination of TRC and a post-tensioning system makes it possible to realize such an extreme slender superstructure. Since the maximum span is $L = 15.05$ m and the height of the superstructure is $H = 0.435$ m the bridge has a slenderness ratio of only $H:L = 1:35$ (Figure 7b).
A wide range testing program was carried out to assess the load-bearing behavior in longitudinal and transversal bridge direction [10]. Exemplarily, in this paper the results of a shear-test in longitudinal direction are presented, Figure 8a.

The specimen remained all uncracked in serviceability limit state (SLS), which fulfilled the requirements of the bridges owner, who required a maximum crack width of 0.3 mm. As the load increased, a distinctive crack pattern was observed, i.e. small crack distances and widths, which are typical for TRC members. The ultimate limit state was characterized by the collapsing of the compression zone, which is due to the high reinforcement area in the tension zone (textiles, GFRP-bars and single-strand cables). High deformations in ULS of about 1/200 to 1/150 and a stabilized crack pattern signalize the collapsing of the member, thus, no sudden failure was observed. All in all, the tests showed a global safety factor $\eta_{\text{global}} = 5.0$ (Figure 8b).
4. SUMMARY AND CONCLUSIONS

The applicability of the innovative composite material textile reinforced concrete (TRC) was demonstrated on several projects. It was shown, that TRC can be used for fair-faced structures. The facings of sandwich elements can be made of TRC and thus, the overall wall thickness can be halved. Ventilated façade structures with slab-thicknesses of only 30 mm can be applied even in highly stressed regions. By using TRC for (pedestrian) bridges, an extreme slenderness ratio of only $H:L = 1:35$ was achieved, which leads into a new age of concrete bridge construction.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation), which financed the Collaborative Research Centre at RWTH Aachen University (SFB 532) “Textile Reinforced Concrete – Development of a new technology” and the funding of the project “INSU-SHELL” within the European Union’s LIFE program. Furthermore, thanks are also given to Hering Group (ventilated façade structures) and Groz-Beckert Group as well as the City of Albstadt (pedestrian bridge).

REFERENCES