Textile Reinforced Concrete – Realization in applications

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ABSTRACT: Textile Reinforced Concrete (TRC) is a composite material made of open-meshed textile structures and a fine-grained concrete. Comparable to steel reinforcement the textile fabric bears the tensile forces released by the cracking of the concrete. Only a minimal concrete cover is required for the bond of the textile fabrics. Thus, the application of TRC leads to the design of filigree and lightweight concrete structures with high durability and high quality surfaces. In recent years, TRC has been successfully employed for the production of ventilated façade systems. Current investigations enlarge the application range of TRC to façade systems with large spans and load-bearing structures. In this paper, the investigations on self-supporting and structural sandwich panels regarding production methods, results of bending and shear tests, tests on sound insulation and fire resistance as well as first prototypes of slender frames and shell elements are presented.

1 INTRODUCTION

Structural concrete has been an economic and often used building material for façade constructions and load-bearing structures in recent decades. The insufficient architectural design range, the clumsy appearance and corrosion damages have led to a decreasing acceptance of the material in regard to façades for clients and architects.

Thus, non-corrosive reinforcement materials have gained importance in the last 3 decades to achieve the goal of precast, filigree and lightweight concrete structures with high durability, high quality surfaces and a wide-spread design range. Glassfibre Reinforced Concrete (GRC) has been widely used for years for the production of non-structural building elements either of complex shape produced in manual spray techniques or for plain elements with additional one-dimensional long-fiber reinforcements manufactured in production lines.

The development and application of Textile Reinforced Concrete (TRC) incorporates the advantages of GRC adding a structural load-bearing capacity in arbitrary directions. The used textile fabrics can be customized as 2D or 3D reinforcements to the production method and load-bearing behavior of the structure. Thus, TRC complements and broadens the design and application range opened up by GRC.

2 VENTILATED FAÇADE SYSTEMS

TRC allows economic savings in terms of material, transport and anchorage costs and thus has been severally used for thin-walled and light-weight ventilated façade systems in recent years (Hegger et al. 2006, Brameshuber 2006). At present, small panel sizes of 0.5–3 m\(^2\) are state-of-the-art in application of TRC in Germany. Panel sizes of up to 7 m\(^2\) can only be realized in combination with bracing stud-frame systems (Engberts 2006).

Due to the missing design codes the application of TRC façade elements in Germany requires either an individual approval for each construction or a general approval for defined boundary conditions of the German building inspection (DIBt 2004).

3 SELF SUPPORTING SANDWICH ELEMENTS

The application of sandwich panels for façades of factory and industrial buildings has gained importance in the past 50 years due to the prefabrication irrespective the weather conditions as well as the reduced time effort during mounting.

Common structural sandwich elements consist of a structural, load-bearing layer ($h = 10–14$ cm), a heat insulation layer and an outer facing ($h \sim 7$ cm). Although in standard non-composite action panels the outer facing has no structural function, a steel reinforcement is necessary to bear constraint forces caused by constricted deformations induced by temperature and shrinkage. In load-bearing structures as well as in façades a concrete cover of about 35 mm complying with current design codes (DIN 1045-1, MC 90) has to be provided to avoid corrosion of the steel reinforcement. If the massive outer layer of usual structural concrete panels is replaced by a thin-walled TRC-layer,
the overall thickness of the panel can be reduced about 5–6 cm and the number of connectors between the concrete layers diminishes. In case the inside facing is also produced with TRC in combination with a sustainable, heat-insulating rigid polyurethane (PU) foam light-weight sandwich structures with large spans can be obtained.

3.1 Load-bearing behaviour

The load-bearing behaviour of sandwich panels with rigid facings depends primarily on the thicknesses of the layers, the overall height and the (shear) stiffness of the core (Stamm & Witte 1974).

In contrast to panels with flexible facings the concrete facings are not only stressed by diaphragm forces but also by bending and shear forces according to their flexural stiffness related to the panel stiffness (Fig. 1). The magnitude of the flexural and diaphragm forces follows the theory of the elastic composite. Facings connected by a core with a low stiffness react decoupled to the loading (non-composite action, NCA, Seeber 1997). The relative shear deformations of the layers cause large deformations and thus a non-validity of the Bernoulli-Hypothesis and large deformations (Fig. 2).

With an increasing shear modulus of the core the composite action of the upper and lower facing is more activated. This leads to decreasing deformations and for an infinite core stiffness to full composite action (FCA, Seeber 1997). The relating stress and strain distributions for both NCA and FCA panels is illustrated in Figure 2.

3.2 Production methods

For the experimental program prefabricated PU rigid foams \( (h_c = 150 \text{ mm}) \) were used as a core being attached to the TRC-facings \( (h_f = 15 \text{ mm}) \) either by gluing or by pressing a notched core into a fresh concrete layer (Fig. 3). The notches were oriented perpendicular to the beam axis with an interspace of 5 cm. The concrete facings were produced in a lamination process where concrete and three fabrics are alternately placed in the formwork.

3.3 Result of bending tests

In four-point-bending tests on sandwich panels with spans of 1.90 m and 4.90 m (Fig. 4) a satisfactory load-bearing behavior was determined which mainly depends on the (shear) stiffness of the core and the joint quality between core and facings.

All cores were cut out of slabstocks and a fine dust of PU-cells covered the cutting edges. The dust could not be removed with compressed air nor be brushed off the surfaces. If the core was pressed into the fresh concrete the particles were easily bounded and showed no noticeable influence on the bond quality. Compared to panels with direct bond, the inferior joint quality resulted in at least 30% lower ultimate loads (Fig. 5, Table 1).

The ultimate load in the tests was determined by a brittle shear failure of the core except for panel P3 with a high density core which failed by tensile rupture of the textile reinforcement in the lower facing.
Table 1. Selected results of test on sandwich beams.

<table>
<thead>
<tr>
<th>Panel</th>
<th>Core</th>
<th>Interface</th>
<th>Span (m)</th>
<th>Failure Load $F_u$ (kN/m)</th>
<th>Deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>PU 32</td>
<td>Notched</td>
<td>1.9</td>
<td>27.6</td>
<td>43.0</td>
</tr>
<tr>
<td>P2</td>
<td>PU 32</td>
<td>Glued</td>
<td>1.9</td>
<td>18.1</td>
<td>29.2</td>
</tr>
<tr>
<td>P3</td>
<td>PU 200</td>
<td>Notched</td>
<td>1.9</td>
<td>151.2</td>
<td>28.0</td>
</tr>
<tr>
<td>P4</td>
<td>PU 40</td>
<td>Notched</td>
<td>4.9</td>
<td>23.2</td>
<td>99.8</td>
</tr>
</tbody>
</table>

$^{1)}$ tensile failure of fabrics in lower facing.

For the panels P1 to P4 no connectors were used. The sandwich action was only established by the bond between the foam and the concrete layers. A suitable calculation model for sandwich panels is given in Hegger, Horstmann & Scholzen (2007).

For a durable load-bearing capacity producitable connectors between the concrete layers are required, which, on the one hand reduce the stresses normal to the bond joint due to shrinkage and temperature, and on the other hand avoid constraint stresses. Convenient devices adapted to the low anchorage length in the thin-walled TRC layers are currently developed.

3.4 Fire resistance and sound/heat insulation

A first examination of the fire resistance of the sandwich panels was conducted with a SBI (single burning item) test according to DIN EN 13823 (2002). The panels were categorized in the second highest class according to DIN EN 13501-1 (2002) as $A_2/B, S1, d0$ making them suitable for façades of office buildings and factory floors. The airborne sound insulation was determined in a testing facility according to DIN EN 140-3 (2005). The measured sound reduction index of $R'_w = 43$ dB is sufficient for factory floors and office buildings. The heat transfer coefficient $U$ for the homogeneous section was assessed to $0.22$ W/m²K which complies with the limit ($U = 0.35$ W/m²K) of the current German Energy Saving Regulation (EnEV 2001).

4 SANDWICH PANELS FOR MODULAR BUILDINGS

The advantages of the sandwich technology are also applied to the design study of a modular building consisting of load-bearing and demountable sandwich panels for walls and roofing. Based on a basic grid of 1 m wall (clear height: 2.82 m) and roof elements (span 4.73 m) are assembled to a small demonstration building (Fig. 6).

4.1 Design of modular panels

The sandwich panels were designed with the theory of the elastic composite and a comparative finite element analysis. The inner TRC layer of the roof elements was profiled and a PU foam density of 50 kg/m³ was chosen to reduce the shear portion and the thus induced creep deformations of the visco-elastic core material (Fig. 7).

The section of the inner layers of the wall elements was designed similar to the roof elements but forming a hutch with additional horizontal beams at the top and the bottom. In the horizontal beams cast-in channels connecting the wall elements to the foundation and the roof elements were integrated.

The sides of the vertical webs of the inner layers were profiled as tongue and groove for both roof and wall elements.

4.2 Tailoring of 3D textile reinforcement

For a simple cast process a capable and rigid 3D AR-glass reinforcement was tailored. The fabrics were laminated with a resin and cured on a metal form in an oven to shape them to e.g. rectangular reinforcement cages. These were fixed to the cnc-milled cores and in the knee points the transverse rovings of the crossing cages were removed to enable a penetration of the
longitudinal rovings (Fig. 8). Additionally placed textile gussets supported a sufficient frame knee action in the vertexes.

The element was cast upside down in a three step production method: (1) lamination of the upper plain layer with GRC and one fabric, (2) positioning of core assembled with the tailored reinforcement and the lateral formwork and (3) casting of the lower profiled layer without short-fibers.

4.3 Bending tests on roof and wall elements

In Figure 9 the setup of the bending tests on a roof element (P5) and a wall element (P6) is illustrated.

The roof element was tested with a positive flexural load and supported true-to-detail, the wall element was loaded by a negative flexural load and supported on the horizontal beam of the inner hutch. The outside concrete facing thus was shortened and able to deform without any constraint.

Table 2 and Figure 10 show the results obtained by the bending tests on panels P5 and P6.

In comparison to panel P4 the profiled inner concrete layer and the slightly higher core density led to a much stiffer load-deflection curve (Fig. 10) of panels P5 and P6. The ultimate load of the roof element calculated in the design stage was exceeded.
due to a shear block action caused by a vault and the compressive stresses at the supports.

Panels P5 and P6 both failed due to shear rupture of the core leading to a subsequent delamination between concrete facings and the core (Fig. 11).

The sustainability of the sandwich bond was ensured by discrete stainless steel pins ($\varnothing = 3\,\text{mm}$) bearing peeling stresses normal to the bond joints owing to shrinkage, temperature and wind suction. The calculation model presented in Hegger, Horstmann & Scholzen (2007) is currently upgraded regarding the load-bearing portion of discrete connectors.

5 RHOMBIC LATTICE-GRID

Diamond-shaped lattice frameworks have already been applied for the construction of arched halls for more than one century by now. The structural principle has originally been developed by Friedrich Zollinger in 1905 and was used for the construction of wooden arched halls (Winter 1992). The original principle of the constructive form “Zollinger” is a geometrical expression of closely spaced timber arches intersecting with each other diagonally. This way large spanning structures can be assembled from small and slender single components.

Due to the relatively large concrete cover accompanied by a large wall thickness, the high dead load as well as the complex production process the application potential for the construction of frameworks made of concrete with ordinary steel reinforcement has diminished. The diamond-lattice grid principle together with Textile Reinforced Concrete provides an excellent opportunity to prefabricate extremely slender and lightweight, diamond-shaped components. Therefore, the use of slender TRC elements results in a fine spun appearance that has not been associated with concrete yet.

Within the scope of a collaborative research project at RWTH University a diamond-shaped lattice arch consisting of a textile (carbon) reinforcement embedded in a fine-grained high strength concrete matrix has been produced and erected in February 2005 (Fig. 12, Schneider et al. 2006a, Hegger et al. 2007).

The construction consisted of 36 single rhombic elements jointed in 3 parallel rows with 12 elements each. The total span of the arc was 10 m, the height was 3 m and width 1.8 m. The single rhombic elements with the dimensions $1000 \times 600 \times 160\,\text{mm}$ have been prefabricated in a cnc-milled formwork. The concrete wall thickness was 25 mm and the complete structure consisting of the single elements bolted together had a total weight of 23 kg.

6 BARREL-SHELL STRUCTURES

Due to its material properties Textile Reinforced Concrete is very well suited for the production of complex geometries, e.g. for roof constructions. The bearing capacity can be improved especially by the formation (bending or folding) of two-dimensional building components. The easy forming of the textiles enables a simple realization of curved surfaces as e.g. the barrel shell elements in Figure 13.

Even in reinforced concrete structures, simple channel-section folded beams belong to the most economical types of construction. The shell effect of thin concrete elements can be very effective in the case of barrel-shell roofs. With a material thickness of 25 mm in textile-reinforced concrete the structure is extremely light-weight and the shell is rigid in both the longitudinal and lateral direction. A structural depth of about 500 mm and a span of up to 8 m generate interesting forms of applications for this type of TRC structure.
e.g. in smaller and medium-sized halls. The utilization of shotcrete is the easiest production method for textile reinforced concrete shells with the placement of concrete and reinforcement in alternating layers. The manufacturing of such a barrel shell was successfully tested on a 1.5 m long segment at the Institute of Buildings Materials Research (ibac), RWTH Aachen University.

7 SUMMARY AND CONCLUSION

The presented investigations proved TRC to be a proper and capable construction material with a high adaptivity to the requirements of light-weight and filigree building components. The potential of TRC compliments the utilization of GRC and broadens the application of load-bearing structures of complex geometry. In addition to simple joining techniques and static dimensioning models the basis is formed for the development of future constructions with optimized concrete sections, sharp edges and excellent concrete surfaces. Combined with the manufacturing as precast element and the entailed simple assembly and disassembly of buildings also the demand for a sustainable method of construction is fulfilled.

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