Applications for TRC

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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. No concrete cover is required to protect the fabrics against corrosion. 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 become an attractive choice for architects and engineers for the production of ventilated façade systems. Current investigations are looking at the possibility of using TRC for façade systems with large spans and for load-bearing structures. In this paper, the state of the art of ventilated façades, investigations into the production methods of self-supporting and structural sandwich panels, results of bending and shear tests, tests on sound insulation and fire resistance as well as the first prototypes of slender frames and shell elements are presented.

Keywords: textile-reinforced concrete, application, polyurethane foam, sandwich panel, load-bearing structures, diamond-lattice grid, barrel shell

Introduction

In recent decades, structural concrete has been an economic and often-used building material for façade constructions and load-bearing structures. For clients and architects, the limited architectural design range, clumsy appearance and corrosion damage have led to a decreasing acceptance of the material for use on façades. Consequently, non-corrosive reinforcement materials have grown in importance over the last 30 years for achieving precast, filigree and lightweight concrete structures with high durability, high-quality surfaces and a broad design range. Glassfibre-reinforced concrete (GRC) has been widely used for years, either for the production of non-structural building elements of complex shape produced by manual spray techniques or for structural plain elements with additional one-dimensional long-fibre reinforcements manufactured in ingenious production lines.

The development and application of textile-reinforced concrete (TRC) has all the advantages of GRC but with the added bonus of a structural load-bearing capacity in arbitrary directions. The textile fabrics used bear the tensile forces released by the cracking in a way comparable to steel reinforcements and are customised as 2D or 3D reinforcements in accordance with the production method and load-bearing behaviour of the structure. Thus, TRC complements and broadens the design and application range opened up by GRC.

Non-structural façade systems made of TRC

Ventilated façade panels

TRC allows economic savings in terms of material, transport and anchorage costs and in recent years has become an attractive material for thin-walled and lightweight ventilated façade systems[1, 2].

One of the first applications of TRC for the cladding of a building was the ventilated façade of the extension to the laboratory hall of the Institute of Structural Concrete at RWTH Aachen University in 2002. Here the upper part of the façade is clad with 2.68 × 325 × 25 mm panels (Fig. 1) consisting of a fine-grained high-strength concrete and two layers of alkali-resistant (AR-)glassfibre near the concrete surface. The panels were cast in a lamination process in horizontal position. The main disadvantages of this very simple yet labour-intensive production process are difficulties in the exact positioning of the textile-reinforcement layer.

Figure 1: Ventilated TRC façade of the laboratory hall of the Structural Institute of Concrete, RWTH Aachen University

The dimensions of the panels (0.87 m²) and the concrete tensile strength were adjusted to prevent crack initiation under service loads. Due to the low mass per unit area (57.5 kg/m²), the panels were fixed to the wall with standard loop and aluminium fixing devices at four anchorage points each.

Currently, state-of-the-art application of TRC in Germany employs small panel sizes of 0.5–3.0 m² (Fig. 2). Due to the low stiffness of the filigree sections and the low Young's modulus of the favoured AR-glassfibre, panel sizes of up to 7 m² can only be realised in combination with stud-frame systems. As there are yet no design codes for TRC, the application of TRC façade elements requires either an individual approval for each construction or a general approval for defined boundary conditions from the German building inspection authorities.

Figure 2: Ventilated and generally approved betoshell®-façade elements[3] with photograph of concrete at the Marien-Hospital in Hamburg, Germany (left) and large-sized façade of a multi-storey building in Arnheim, the Netherlands (right)[4]

Within the scope of a current research project, large-sized TRC façade elements with dimensions of up to 12 m² and an integrated monolithic bracing structure, are developed and produced for the cladding of the second extension building to the laboratory hall of the Institute of Structural Concrete.

Self-supporting sandwich elements for façades

Advantages and load-bearing behaviour of sandwich façades

The use of sandwich panels for the façades of factory and industrial buildings has grown in popularity over the past 50 years thanks to the advantages of prefabrication (which eliminates problems associated with working in inclement weather) and time savings during mounting operations. Favoured materials for the facings of current sandwich types are metals or structural concrete. Prefabricated concrete panels in mulit-storey constructions also stand up successfully to vertical loads as well as exposure to the rigours of wind and temperature; they also serve the purpose of bracing the overall structure.

Common structural sandwich elements consist of a structural, load-bearing layer (*d* = 10–14 cm), a heat insulation layer and an outer facing (*d* ~ 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[5–7] 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 by about 5–6 cm and the number of connectors between the concrete layers diminishes. In cases where the inside facing is also produced from TRC in combination with a sustainable, heat-insulating rigid polyurethane (PU) foam, light-weight sandwich structures with large spans can be obtained.

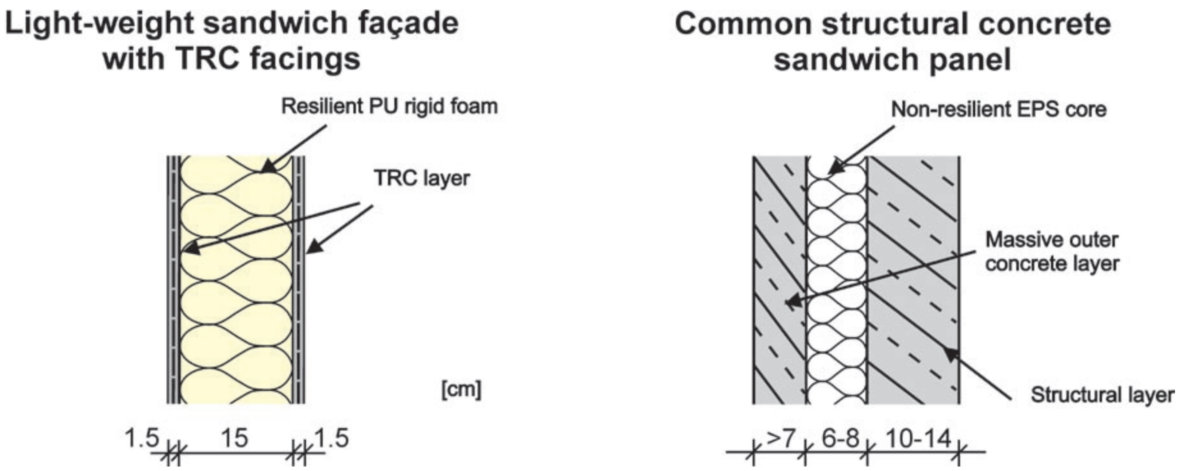

Figure 3: Comparison of sandwich panels with facings made of TRC and structural concrete

The load-bearing behaviour of a sandwich panel with perfect bond between the layers depends primarily on the layer thicknesses, the overall height and the (shear) stiffness of the core[8]. In contrast to panels with flexible facings, the concrete layers are not only stressed by diaphragm forces but also by bending and shear loads according to the flexural stiffness of the facing related to the overall panel stiffness (Fig. 4).

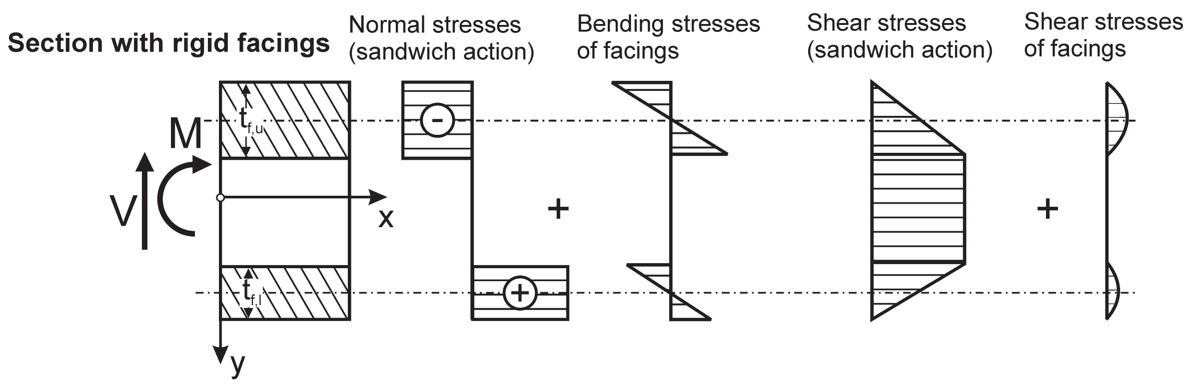

Figure 4: Stress distribution in sandwich panels with rigid facings[8]

The magnitude of the bending, shear and diaphragm forces follows the theory of the elastic composite. Facings connected by a core with a low stiffness react as decoupled from the loading (non-composite action, NCA)[9]. The relative shear deformations of the concrete layers create non-validity of the Bernoulli hypothesis (Fig. 5) and large deformations. Therefore, the total vertical deflection is equal to the summation of a bending and a shear component. With an increasing shear modulus of the core, the composite action of the upper and lower facing becomes more accentuated. This leads to decreasing deformations and, for an infinite core stiffness, to a fully composite action (FCA)[9]. Panels with a partial composite action (PCA) range in between the limits described above.

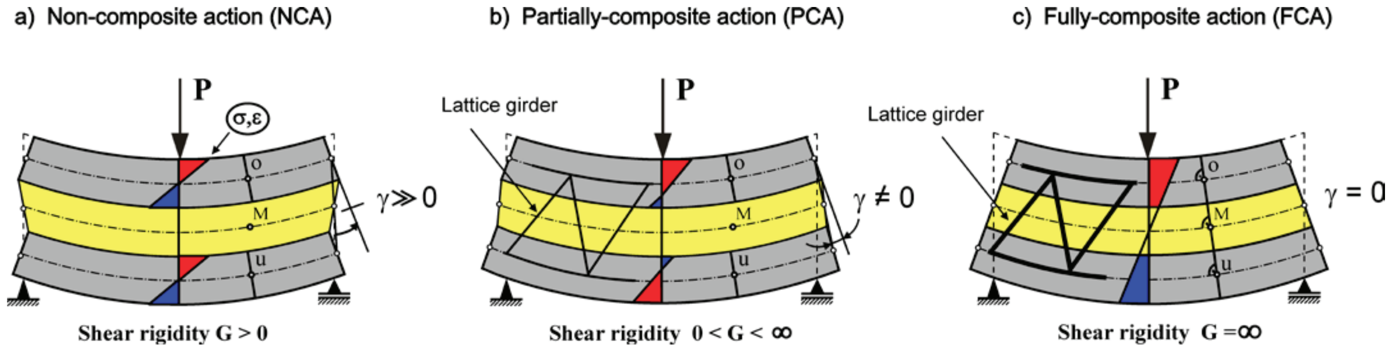

Figure 5: Composite action of sandwich panels subjected to core stiffness

Production methods and test results

For the experimental programme prefabricated PU rigid foams (h_c = 150 mm) were used as a core, being attached to the TRC facings (h_f = 15 mm) either by gluing or by pressing a notched core into a fresh concrete layer (Fig. 6). 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.

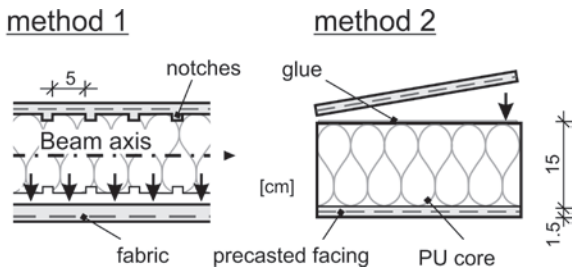

Figure 6: Production methods of sandwich interface

In four-point bending and shear tests on sandwich panels with spans of 1.90 m and 4.90 m (Fig. 7), a satisfying load-bearing behaviour was determined which mainly depends on the (shear) stiffness of the core and the joint quality between core and facings.

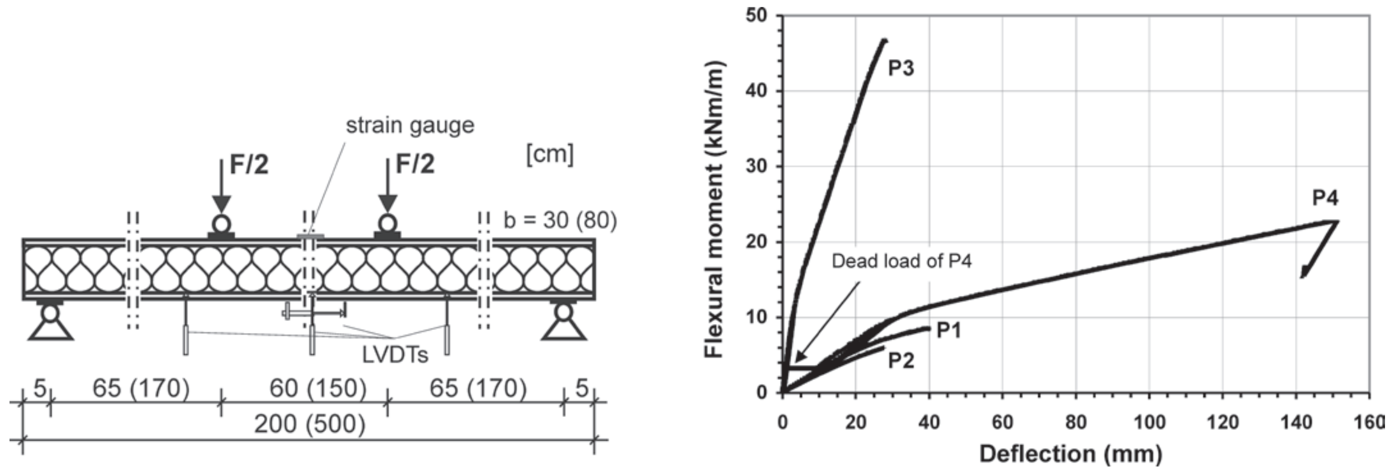

Figure 7: Set-up and load–deflection curves of sandwich panels (l_s = 1.90/4.90 m) of four-point bending tests

As 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 bound and had no noticeable influence on bond quality. Compared to panels with direct bond, the inferior joint quality gave rise to a minimum of 30% lower ultimate load (Table 1).

Panel	Core	Interface	Span (m)	Failure load F_u (kN/m)	Deflection (mm)
P1	PU 32	Notched	1.9	27.6	43.0
P2	PU 32	Glued	1.9	18.1	29.2
P3	PU 200	Notched	1.9	151.2[1]	28.0
P4	PU 40	Notched	4.9	23.2	99.8

1. tensile failure of fabrics in lower facing

Table 1: Selected results of test on sandwich beams

The ultimate load in the tests was determined by a brittle shear failure of the core (Fig. 8) except for panel P3 with a high density core which failed by tensile rupture of the textile reinforcement in the lower facing.

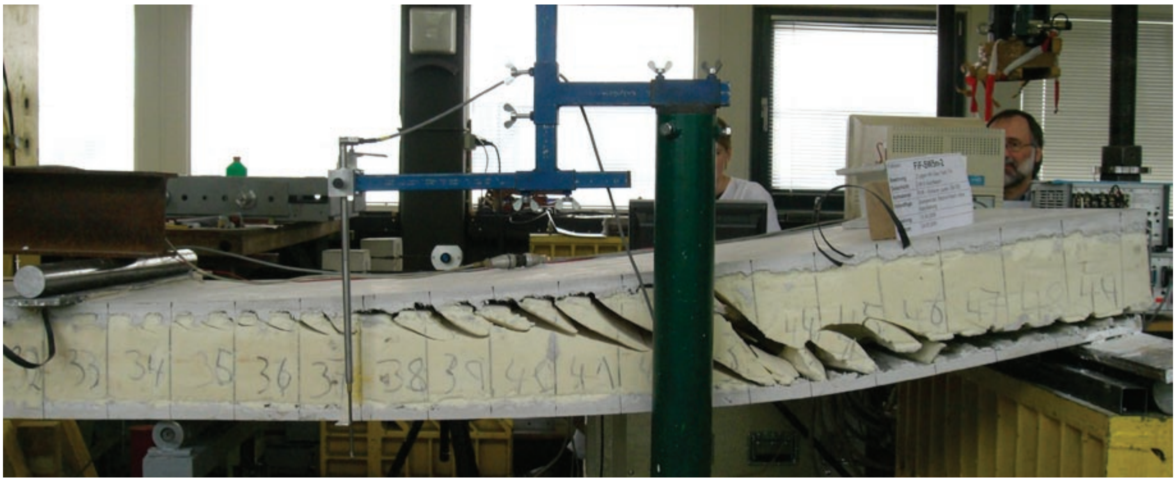

Figure 8: Shear failure of panel P4

For panels P1 to P4, no connectors were used. The sandwich action was only established by the bond between the foam and concrete layers. For a durable load-bearing capacity, 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 owing to a sufficient deformability of the connector. Convenient devices adapted to the low anchorage length in the thin-walled TRC layers are currently being developed. A resilient foam core akin to the tested PU foam reduces the number of connecting devices to a minimum.

Fire resistance and sound/heat insulation

An initial examination of the fire resistance of the sandwich panels was undertaken by SBI (single burning item) test according to DIN EN 13823[10]. For a period of 20 minutes, a fire burning in the corner of a room was simulated. The release of energy, smoke and temperature was measured in the chimney above the fire. Element joints were placed in the centre of the diffusion flame. Due to the fire resistance of the TRC facings and the well-detailed joints, smoke and energy emissions were negligible. Thus, the panels were categorised in the second highest class according to DIN EN 13501-1[11], i.e. as A2/B, S1, d0 – a great improvement on most panels with metal facings, which are categorised as class D or lower (in a class range of A1, A2, B, C, D, E, F). Therefore, the panels are suitable for façades of office buildings and factory floors.

The airborne sound insulation was determined in a testing facility according to DIN EN ISO 140-3[12]. Due to the low dynamic rigidity and the thickness of the light core (PU 32), the facings were acoustically decoupled. 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 as 0.22 W/m²K which is well within the limit (U = 0.35 W/m²K) of the current German Energy Saving Regulation (EnEV)[13].

Application

Based on the presented investigations, sandwich panels with TRC facings will be used for the cladding of a university work floor ($H \times B \times L$: 12 × 27 × 108 [m]) within the project INSUSHELL funded by the European Union within the framework of the LIFE programme.

Load-bearing building envelopes

Sandwich elements for modular buildings

The advantages of sandwich constructions were 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, 14 wall (height 2.82 m) and four roof elements with a length of 4.9 m were assembled to form a small demonstration building (Fig. 10).

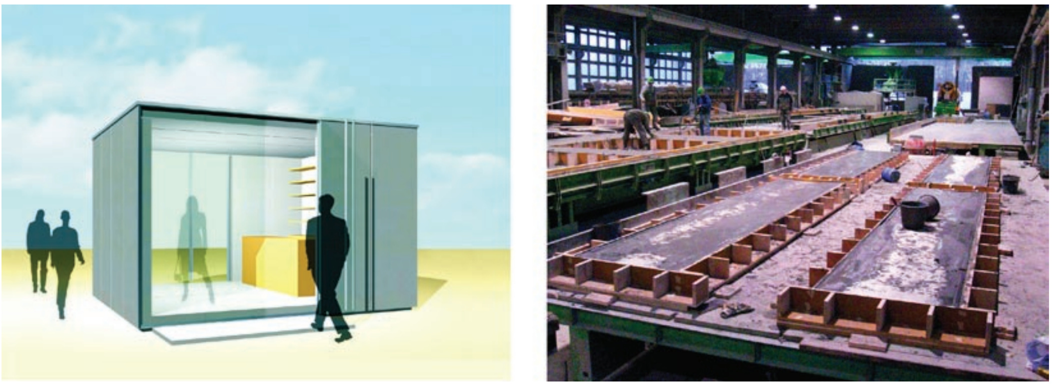

Figure 9: Architectural design of modular sandwich building and production of roof elements in precast company

The sandwich panels were designed according to the theory of the elastic composite and a comparative finite-element analysis using linear elastic material properties. The inner TRC layer of the roof elements was profiled as a U-shape and a PU foam density of 50 kg/m^3 was chosen to reduce the shear portion and the induced creep deformations of the visco-elastic core material. The inner layer of the wall elements was formed like a hutch to integrate cast-in channels connecting the elements to the foundation and the roof elements (Fig. 10). The sides of the vertical webs of the inner layers were profiled as tongue and groove.

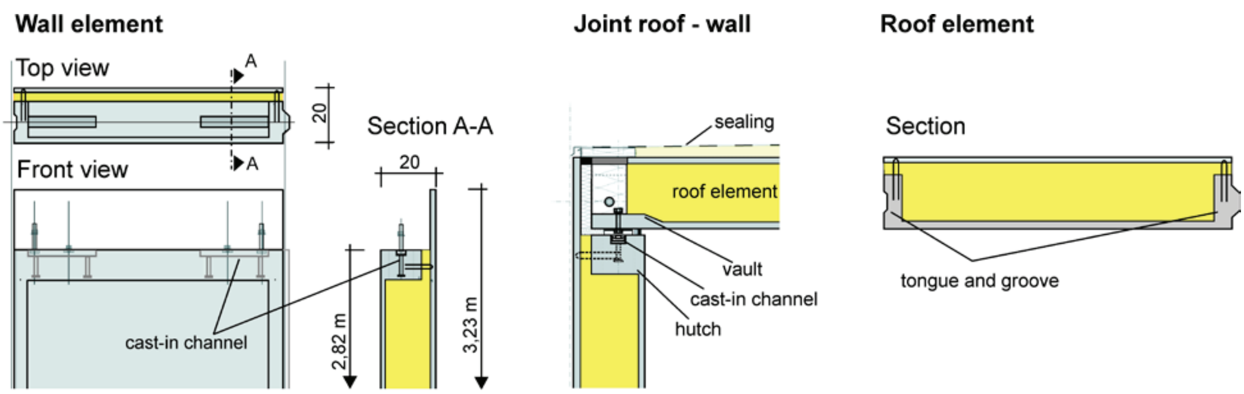

Figure 10: Sections and connections of modular wall and roof elements

The durability of the sandwich action was secured by the configuration of discrete connecting pins (Ø = 3 mm, stainless steel) which bear peeling stresses normal to the bond joints due to shrinkage, temperature and wind suction.

In addition to the research into the mounting devices, the tailoring of the 3D AR-glassfibre reinforcement has been of special interest. The fabrics were laminated with a resin and cured on a metal form in an oven to shape them into, for example, rectangular stirrups. In the frame knees of the hutch, the inner transverse reinforcements of the horizontal and vertical textile stirrups were removed, allowing penetration of the longitudinal reinforcements to enable a frame knee action. The ultimate strength of the laminated textiles was determined as 1400 MPa. The reinforcement was fixed to the core before casting the element upside down in a three-step production method: (a) lamination of the upper plain layer with GRC and one reinforcement layer; (b) positioning of the core and the lateral formwork; and (c) casting of the lower profiled layer without short fibres.

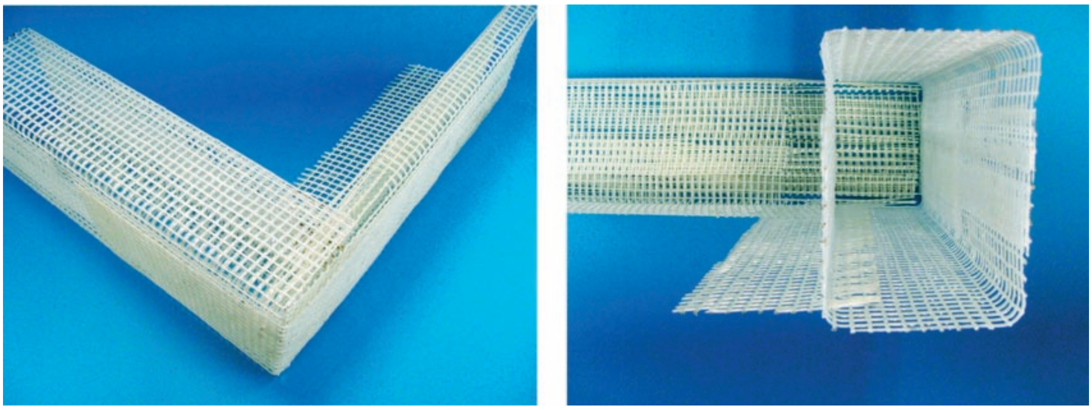

Figure 11: Details of tailored AR-glassfibre reinforcement for frame knees

In Table 2 and Fig. 12 the test set-up and the results of a bending test on a roof element (P5) with a span of 4.73 m are depicted. In comparison to panel P4 the profiled lower concrete layer and the slightly higher core density led to a much stiffer load–deflection curve. The ultimate load calculated in the design stage was exceeded due to a shear block action caused by a vault and the compressive stresses at the supports.

Panel	Core	Interface	Span (m)	Failure load F_u (kN/m)	Deflection (mm)
P5	PU 50	Direct bond / notched	4.73	28.0	108

Table 2: Results of bending test on sandwich roof panel P5

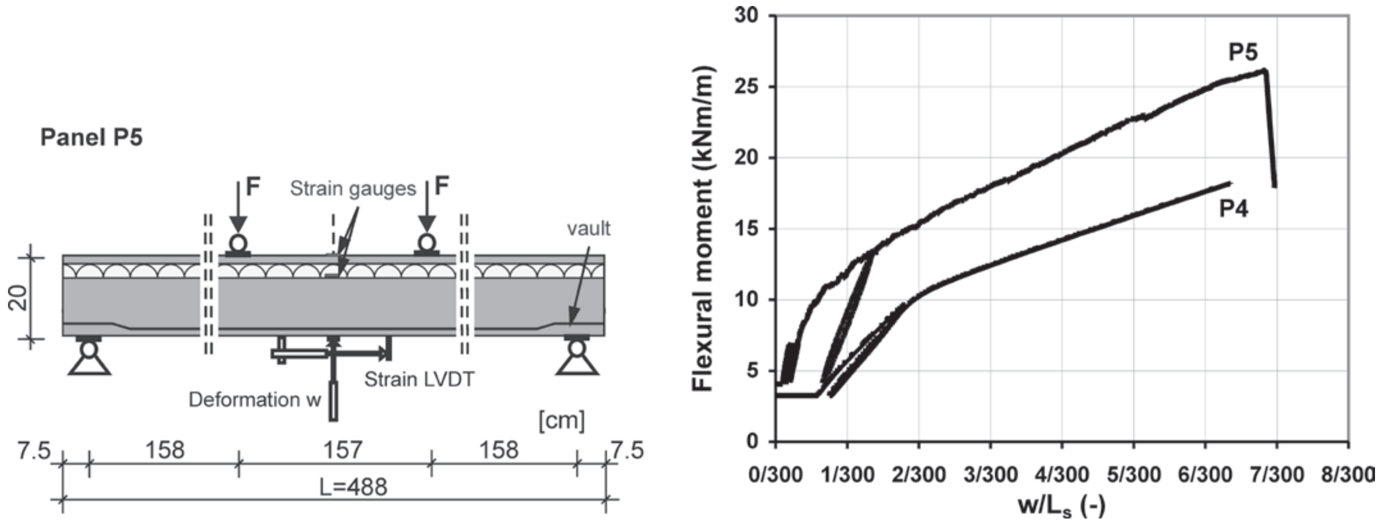

Figure 12: Set-up and load–deflection curve of four-point bending test on roof element

Load-bearing frames and shell structures

Rhombic lattice-grid

Diamond-shaped lattice frameworks have been used for the construction of arched halls for over a century. The structural principle was originally developed by Friedrich Zollinger in 1905 and was used for the construction of wooden arched halls. The original principle of the Zollinger construction form is a geometrical expression of closely spaced timber arches intersecting each other diagonally[2]. In this way large-spanning structures can be assembled from small and slender single components.

Due to the relatively large concrete cover together with large wall thickness, high dead load and complex production process, the suitability of frameworks made of concrete with ordinary steel reinforcement for construction work is reduced. The diamond-lattice grid principle together with TRC provides an excellent opportunity to prefabricate extremely slender, lightweight, diamond-shaped components. Therefore the use of slender TRC elements results in a fine-spun appearance that has hitherto not been associated with concrete (Fig. 13).

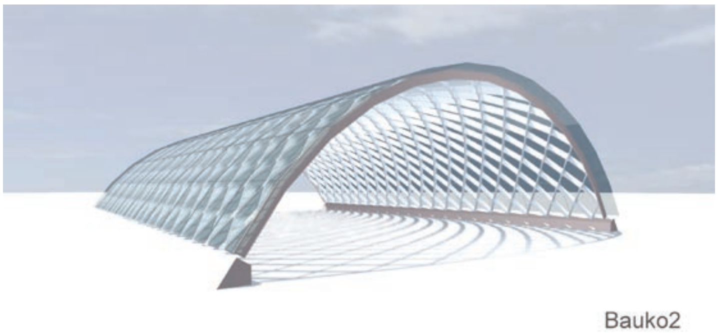

Figure 13: Diamond-lattice grid

The diagonal arrangement of the single rhombic members has a stiffening effect in the longitudinal direction of the building. In Zollinger's original constructional system, three linear elements meet at the nodes; in other diamond-lattice grid systems there are usually four; and in hexagonal geometries there may even be six elements that have to be joined at these points. The often complex details at the points of intersection of the members may be regarded as a disadvantage; however, as a single rhomboid, TRC elements are prefabricated before assembly, and the complexity of the joined nodes of the whole structure is significantly reduced.

The interaction with the low dead-weight of the elements and the possibility of bolting the members together permits the construction of arched structures with spans of short and medium length from 8 to 15 m to be realised in a very simple manner. Within the scope of a collaborative research project at RWTH University, a diamond-shaped lattice arch was produced and erected in February 2005 (Fig. 14).

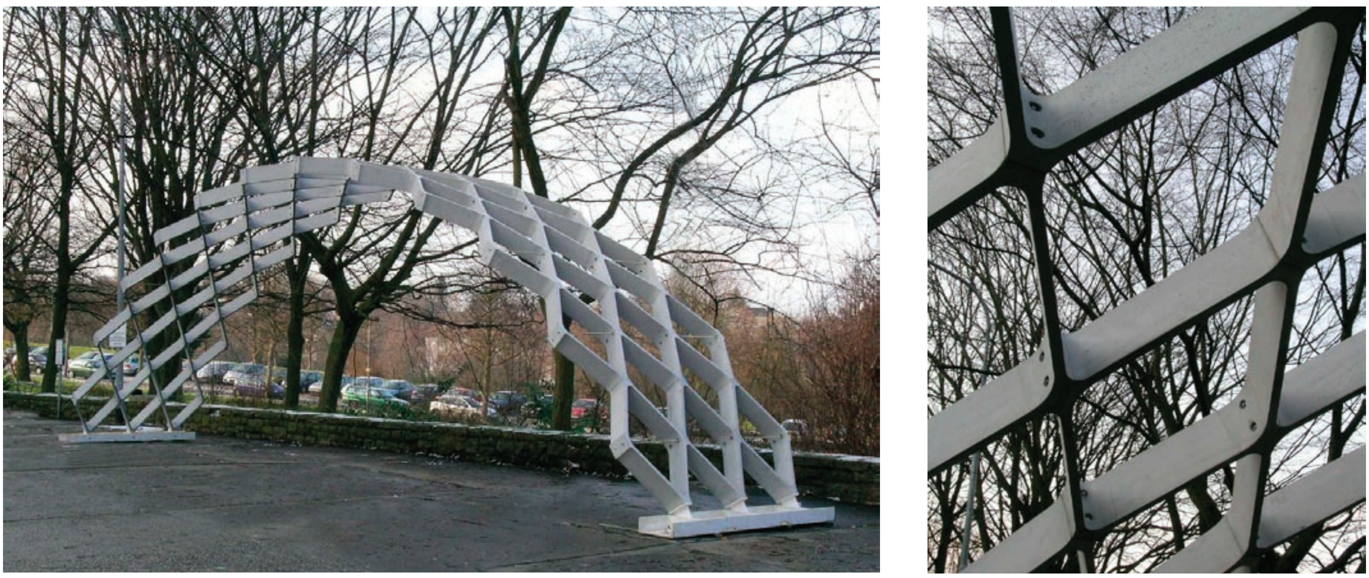

Figure 14: Prototype (left) and constructional detail (right) of a diamond-shaped lattice grid from textile reinforced concrete

The construction consisted of 36 single rhombic elements jointed in three parallel rows with 12 elements each. The total span of the arc was 10 m (32.8 ft); it was 3 m high and 1.8 m wide. The single rhombic elements with dimensions 1000 × 600 × 160 mm were prefabricated in a cnc-milled formwork. The concrete wall thickness was 25 mm and the complete structure had a total weight of 23 kg.

Self-consolidating, fine-grained high-strength concrete was used, reinforced with carbon fabrics. The manufacturing process of the prototype, including production of formwork for the elements, provision of textile fabrics and arrangement in the formwork, casting of the concrete matrix and assembly of the prefabricated elements, demonstrated that it is possible to produce sharp-edged TRC elements and implement them into the construction of arched load-bearing structures with spans of several metres. The bolted joints have been verified as an effective and stable connecting device.

Barrel shell structures

Due to its material properties, TRC 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 realisation of curved surfaces as, for example, the barrel shell elements in Fig. 15.

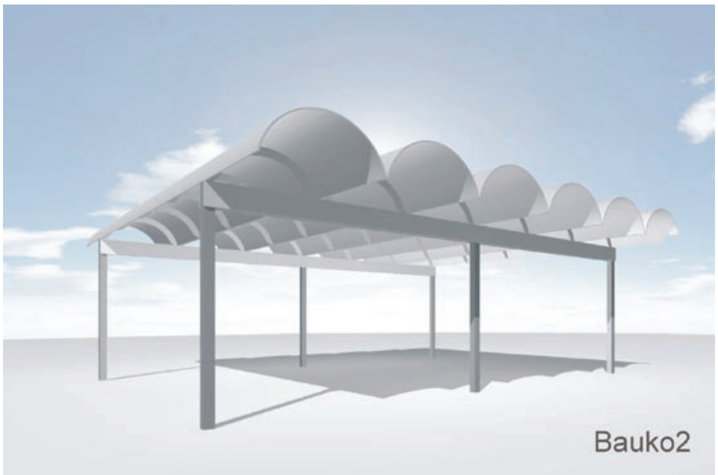

Figure 15: Design of barrel shells made of textile reinforced concrete

Even in reinforced-concrete work, simple channel-section folded beams belong to the most economical types of construction. The shell effect of thin concrete structures can be very effective in the case of barrel-shell roofs. With a material thickness of 25 mm in TRC, the structure is extremely lightweight 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 application for this type of TRC structure, e.g. in smaller and medium-sized halls.

The use of shotcrete is the easiest production method for TRC shells, with the placement of concrete and reinforcement in alternating layers. The manufacturing of such a barrel shell was first successfully tested on a 1.5 m long segment at the Institute of Buildings Materials Research (ibac), RWTH Aachen University (Fig. 16).

Future innovations, including the development of double-curved shell structures and the production of further prototypes, will broaden the range of roof structures and highlight the requirements for further research.

Figure 16: Prototype of the barrel shell made of TRC (ibac)

Summary and conclusion

The investigations described in this paper have proved TRC to be an acceptable and capable construction material which is highly adaptable to the requirements of lightweight and filigree building components. The potential of TRC complements the use of GRC and broadens the application of load-bearing structures of complex geometry. The textile fabrics employed are no longer used only as 2D reinforcements for plain structures but are also customised for the requirements of complex 3D structures.

In addition to simple joining techniques and static dimensioning models, the foundation has now been laid for the development of future constructions with optimised concrete sections, sharp edges and excellent concrete surfaces. Together with the fact that it is manufactured as a precast element, which facilitates the simple assembly and disassembly of buildings, TRC also fulfils the demand for a sustainable method of construction.

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