Thin-walled shell structure made of textile reinforced concrete Part I structural design and realization

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Part I: Structural design and construction

At RWTH Aachen University recently, a pavilion was constructed with a roof shell made of textile-reinforced concrete (TRC), a composite material consisting of a fine-grained concrete and high-strength, non-corroding textile reinforcement in the form of carbon fibres. The thin-walled TRC shell structure demonstrates impressively the loadbearing capacity of this innovative composite material. The present paper discusses the practical issues concerning the construction, such as the fabrication of the TRC shells using shotcrete, the concepts developed for the arrangement of the textile reinforcement and the erection of the shells on top of the precast concrete columns. The issues concerning the design, assessment and numerical simulation of the loadbearing behaviour of TRC shells are presented in the companion paper (Part II).

Keywords: cementitious composites, textile-reinforced concrete, hyperbolic paraboloid, finite element simulation, manufacturing technology, shotcrete, carbon fabrics, industrial textiles

1 Introduction

During the last decades, intensive research has been conducted on cementitious composites, leading to the development of strain hardening materials with high compressive and tensile strengths and better ductility and energy absorption capacity. The ductile tensile response of the composite required for applications with a load-carrying function in civil engineering structures can be achieved by combining continuous fabrics and short-fibre reinforcement with a fine-grained matrix [1]. Based on advances in the characterization and modelling methods, e.g. [2, 3, 4], a wide range of applications demonstrating the design possibilities of these high-performance composites have emerged. Examples include a slim TRC footbridge [5, 6], façades of large TRC elements [7] and sandwich panels [8]. Further, textile reinforced concrete has been successfully used in many cases as a retrofitting system for existing steel reinforced concrete structures, such as in the renovation of a heritage-listed barrel-shaped roof [9]. A detailed review of applications of textile-reinforced concrete recently carried out in Germany is given in [10].

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The present paper describes in detail the structural design and construction of a pavilion with an ambitious roof structure made of textile-reinforced concrete recently built on the campus of RWTH Aachen University. Once glazed on all sides, the pavilion will be used as a room for seminars and events (Fig. 1). The design by the Institute of Building Construction of RWTH Aachen University (bauko 2) uses umbrella-like shells as basic elements, each of which consists of an addition of four surfaces in double curvature, known as hyperbolic paraboloids (hypar surfaces).

This shape refers to designs by the Spanish architect *Félix Candela* (1910–1997) who, especially in the 1950s and 1960s, created many buildings in Mexico which are based on variations of such hypar shells [11] (Fig. 2).

Such shell structures made of reinforced concrete have almost completely vanished from the current construction scene because of the corrosion problems of steel reinforced concrete and because of the labour-intensive fabrication of the complex in situ formwork. Here, TRC with non-corroding textile reinforcement provides new possibilities for the efficient realization of loadbearing systems with a small cross-sectional thickness. Owing to their low weight, such filigree loadbearing structures are particularly suitable for economical prefabricated construction

Fig. 1. Roof structure consisting of four large precast TRC shells (photo: bauko 2, RWTH Aachen University)

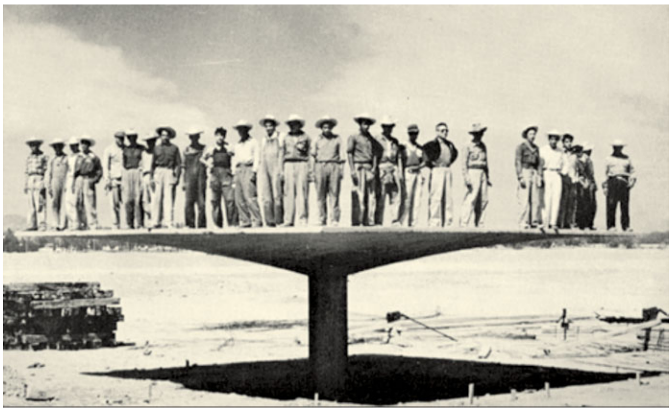

Fig. 2. Experimental shell structure by the Spanish architect *Félix Candela*, Las Aduanas, Mexico, 1953 [11]

and segmentation. In contrast to conventional reinforced concrete shells, which require elaborate falsework and formwork, the spectrum of questions to be addressed for textile-reinforced loadbearing structures shifts to issues of assembly, alignment and joining of the individual finished parts.

The present paper significantly extends the previous publication in the German language [12]. The structural design of TRC shells is discussed in section 2, dealing with the description and analysis of the loadbearing structure within the preliminary design, resulting in the chosen cross-sectional layout of the TRC shell structure. The spatial arrangement of the textile reinforcement within the shell to reflect the stress flow is described in section 2.4. Section 3 covers the issues concerning fabrication of TRC shells using shotcrete technology as well as the erection of the precast structural elements.

The ultimate limit state assessment of a TRC shell structure as well as the underlying design approach are described in detail in the companion paper [13]. That paper also addresses the issue of the loadbearing reserves due to the quasi-ductile behaviour and the associated stress redistribution within the TRC shell.

2 Structural design

2.1 Description of the loadbearing structure

The loadbearing structure of the pavilion is composed of four TRC shells, each of which is supported at its centre by a steel-reinforced concrete column. Each shell is 7 × 7 m on plan and is 6 cm thick. At the centre of the shell the thickness increases to 31 cm in order to ensure a sufficient cross-sectional capacity for transferring the loads from the shell to the reinforced concrete column (Fig. 3) [14].

Arranging the four umbrellas in a 2 × 2 layout results in overall plan dimensions of 14 × 14 m and a structure height of 4 m. The basic geometric shape of the TRC shells leads, in particular, to straight shell boundaries, facilitating flush alignment between the individual umbrellas and a simple connection to the façade. The TRC shells were produced as precast parts. The rigid connection between TRC shell and reinforced concrete column as well as the connections between each column and its pad foundation were achieved using prestressed bolts (Fig. 3). Construction planning was carried out in collaboration with the Institute for Steel Construction of RWTH Aachen University.

The four TRC umbrellas were subsequently joined by cylindrical steel hinges, significantly increasing the rigidity of the overall system with respect to wind-induced horizontal loads. The coupling prevents vertical displacement between adjacent umbrellas and reduces vertical as well as horizontal edge displacements in the transition to the façade (see Fig. 4). In addition, it is no longer necessary to absorb asymmetrical loads solely by bending moments at the fixed column bases, which would have required larger column cross-sections. By coupling the umbrellas, the moment load in the column bases is considerably decreased because the normal forces in the total loadbearing structure are activated. It was therefore also possible to reduce

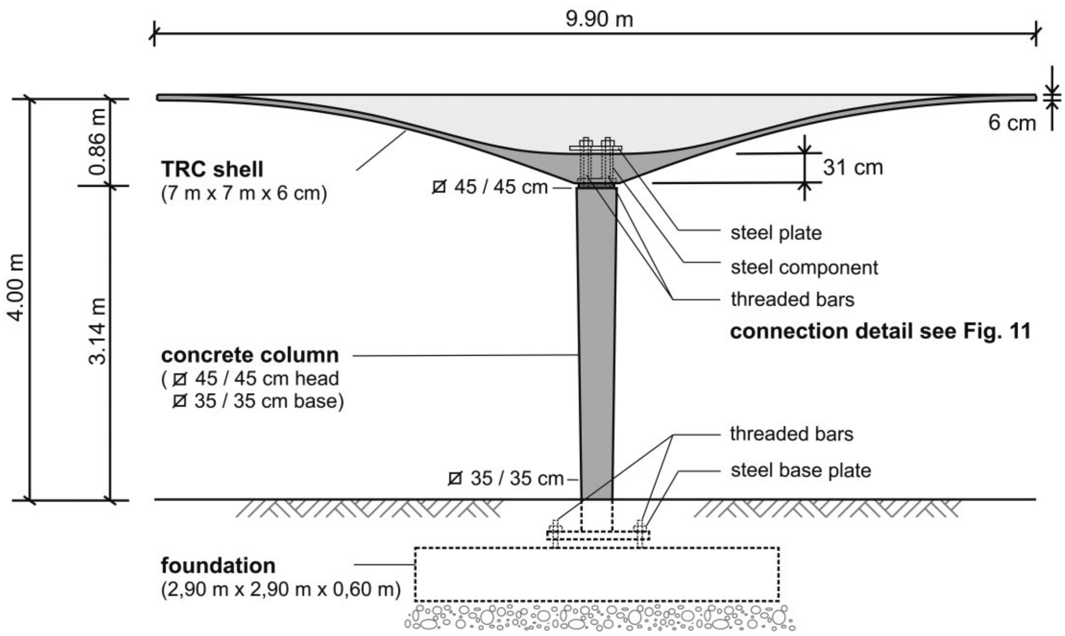

Fig. 3. Diagonal section through the structure consisting of TRC shell, RC column and foundation

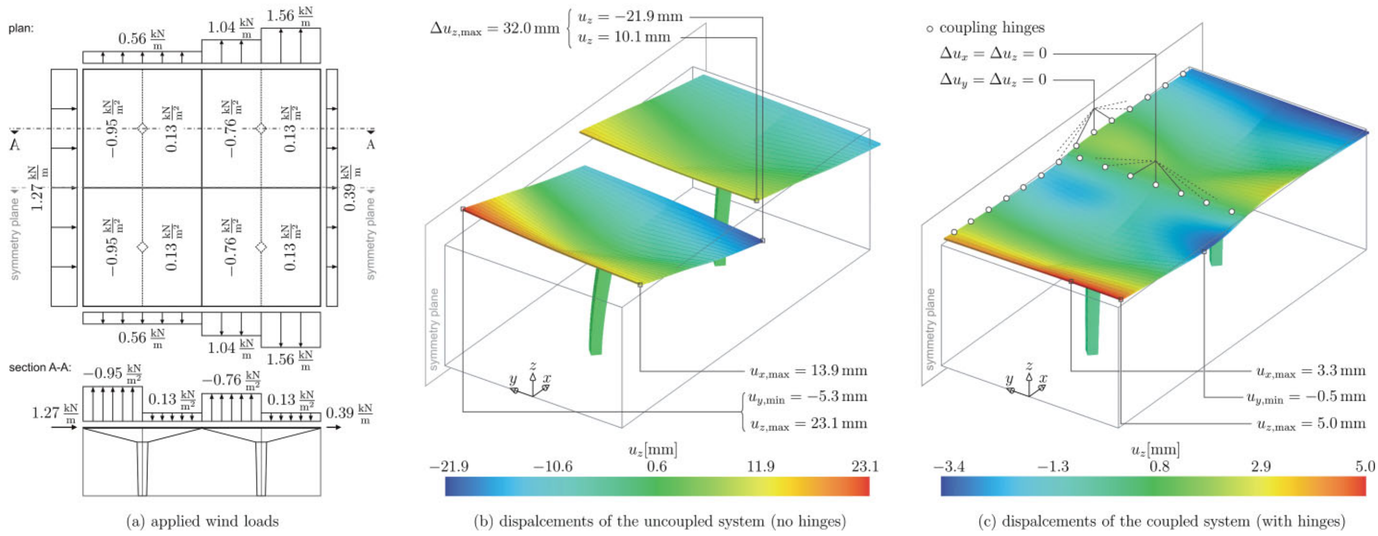

Fig. 4. Displacements of the structure under horizontal load with and without coupling of the shells

the column cross-section from top to bottom, thus emphasizing the lightness of the loadbearing structure from an architectural point of view.

The umbrellas are joined at seven points at 1 m spacing along the adjacent edges of each shell as depicted in Fig. 5a. Each steel hinge was subsequently fixed to the TRC shell on the upper shell surface with four bolts (Figs. 5b and 5c).

2.2 Analysis of loadbearing behaviour for preliminary design

The advantageous loadbearing characteristics of shell structures are based on their ability to carry the loads applied mainly through membrane stresses. During the preliminary design phase, the effect of the shell thickness and the rise of the hypar shell on the stress distribution due to vertical uniform loads was analysed in order to identify a shell geometry with a prevailing membrane stress state for vertical loads. Fig. 6 shows the distribution of the principal tensile stresses due to self-weight as obtained by linear-elastic FE simulation for the shell geometry chosen. Since this stress state is symmetric with respect to the common edges, only one umbrella is shown. Owing to the high compressive strength of the fine concrete used and the lightweight nature of the structure, it was assumed that the tensile stresses would be critical for the ultimate limit state design. Therefore, only the distribution of positive princi-

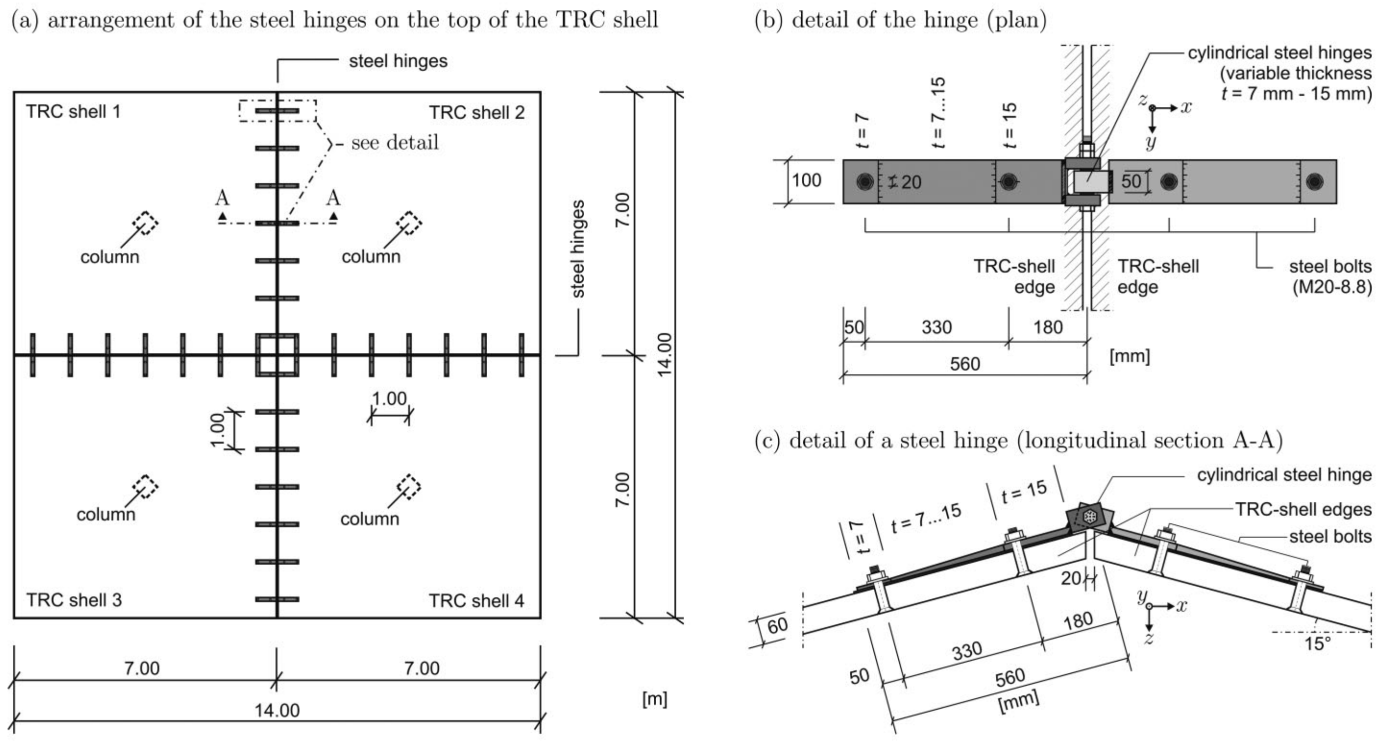

Fig. 5. Cylindrical steel hinges used for coupling the TRC shells: a) arrangement of steel hinges on top surface, b, c) details of a single hinge

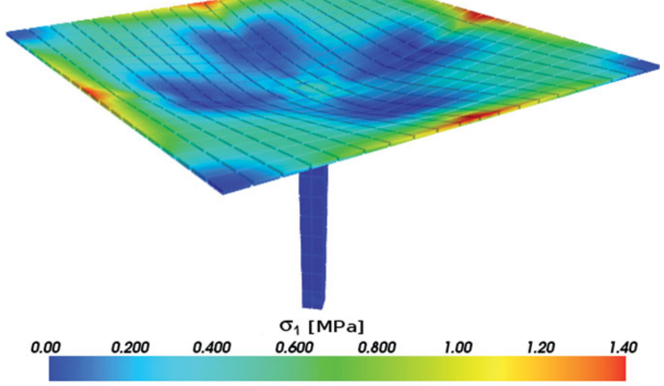

Fig. 6. Distribution of the principal tensile stresses in the shell structure due to self-weight

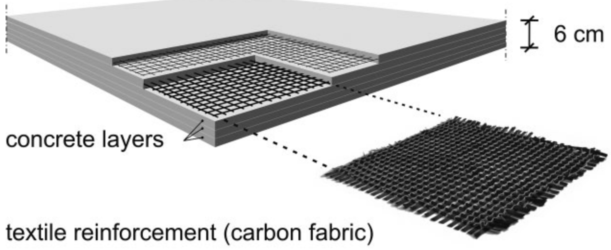

Fig. 7. Cross-sectional make-up of TRC shell

pal stresses ($\sigma_I > 0$) are shown in Fig. 6 in order to indicate the critical cross-sections within the shell. As the stress distribution indicates, tensile bands develop along the shell edges, whereas in the centre of the shell only compressive stresses occur. The highest value of tensile stress occurs in the middle of each shell edge in the direction parallel to the edge. In those areas the stress distribution over the depth of the cross-section is almost uniform.

Besides the shell geometry, several options for the coupling between the shells was also thoroughly analysed during the preliminary design phase. As a result, a cylindrical hinge was designed with the aim of enabling unrestrained rotation and relative in-plane displacement along the shell edges (y axis in Figs. 5b and 5c). The kinematics of the joint preserves the membrane state of the single shell and avoids additional stresses due to temperature and shrinkage.

With the given coupling kinematics, numerical analyses of the joint spacing were performed in order to identify an equidistant arrangement of joints with minimized hinge forces (Fig. 5a). Furthermore, the butt straps were designed to taper towards their ends (Fig. 5c) in order to avoid additional bending stresses in the connection between butt strap and shell.

2.3 Material components and their cross-sectional layout

In the preliminary design of the TRC shells, the highest tensile stress due to self-weight, snow and wind was evaluated for symmetrical boundary conditions at the TRC shell edges and compared with the tensile strength determined experimentally using TRC specimens with different types of reinforcement and different reinforcement ratios. Besides the requirements for a high loadbearing capacity of the textile reinforcement, a high shape flexibility of the fabrics was also required due to the double-curvature geometry of the shell. Therefore, only non-impregnated fabrics were considered which can be easily adapted to the shell geometry. Even though fabrics impregnated with epoxy or styrene butadiene exhibit a higher efficiency due to a larger number of activated filaments, they do not provide the sufficient form flexibility for the given curvature. Based on the preliminary tests, a non-impregnated carbon warp-knitted fabric, developed at the Institute for Textile Technology (ITA) of RWTH Aachen University, was selected as the reinforcement. The individual rovings have a linear density of 800 tex (= g/km) and their spacing in the longitudinal direction (0° direction) is 8.3 mm and in the transverse direction (90° direction) 7.7 mm. The warp-knitted fabrics used with their plain stitch bond [15] exhibit an especially flat and open yarn structure, thus resulting in a higher penetration of the cementitious matrix into the interstitial spaces between individual filaments of the yarns and leading to a significantly higher bond strength when compared with the more common pillar and tricot stitch types. The composite strength was investigated experimentally for various reinforcement ratios using dog bone-type tensile tests as described in the companion paper [13]. A maximum composite tensile stress of 24.1 MPa could be reached in tensile tests with specimens 4 cm thick and 12 layers of reinforcement, corresponding to a textile strength of 1625 MPa (see companion paper [13], Fig. 2). Based on the results of the tests performed and considering the production constraints, a 6 cm thick cross-section with 12 layers of textile fabric equally spaced at 4.6 mm was chosen, see Fig. 7.

The cross-sectional layout requires an appropriate production procedure allowing for simple insertion of the thin concrete layers one by one. An obvious choice is to use shotcrete technology. Hence, the fresh concrete properties of the fine concrete were optimized for shotcrete production of the shells. The concrete mix developed by the Institute for Building Research (ibac) of RWTH Aachen University (see details in Table 1) has a maximum grain diameter of 0.8 mm and contains short fibres of al-

Table 1. Composition of the cementitious matrix

material component	unit	value
Portland cement CEM I 52.5 N (c)	kg/m^3	490
fly ash (f)		175
silica fume (s)		35
aggregate 0.0–0.8 mm		1249
water (w)		280
admixture	% by wt. of c	3.8
short fibres (AR glass, 6 mm)	% by vol.	0.5
w/c ratio	–	0.57
w/c_{eq} ratio = $w/(c + 0.4f + s)$		0.47

kaline-resistant (AR) glass with a diameter of 14 µm, length of 6 mm and a volume fraction of 0.5 %. Regarding its compressive strength, with a mean value of $f_{\text{cm, cube, dry}}$ = 89.0 MPa the concrete is equivalent to high-performance concrete of strength class C55/67.

2.4 Reinforcement concept

The textile reinforcement is activated optimally only if the principal tensile direction coincides with the 0° direction of the fabric. As explained earlier, in the case of a symmetrical load at the point of maximum stress, the principal tensile stresses run parallel to the shell edges. Therefore, in the production of the TRC shells, the reinforcement layers were all inserted parallel to the shell edges, and discontinuities of the reinforcement in the middle of the shell edges were avoided (Fig. 8). Hence, all 12 layers are available for the load transfer. In general, in the reinforcement concept, butt jointing was used for all adjacent reinforcement fabrics on all sides (Fig. 8). In order to avoid multiple joints in a single cross-section, consecutive layers were laid on top of each other with an offset as shown in Fig. 9, a schematic section through the TRC cross-section at the shell edges. By using a total of six different widths for the edge fabrics, the reinforcement design could be optimized in such a way that at any point in the shell no more than two joints occur in a cross-section, meaning that at least 10 reinforcement layers are available for load transfer.

It should be noted that overlapping joints at the transitions of reinforcement fabrics were not used because of the small distance of only 4.6 mm in the thickness direction between the reinforcement layers. Overlapping joints would have led to an insufficient thickness of the concrete layers between the fabrics, inducing delamination at an early load level as observed in experiments.

In the shell centre where the cross-sectional thickness is locally increased, the textile reinforcement is divided into six layers that follow the shell geometry at the upper and also lower surface (Fig. 10). In this region there is a transition from a state of predominant membrane stress to a multi-axial stress state at the connection to the reinforced concrete column. This area of the structure was therefore locally reinforced with a prefabricated steel cage measuring 1.2 × 1.2 m (Fig. 11) in order to transfer the forces in a concentrated way into the reinforced concrete column. The bars of the lower reinforcement layer of the steel cage form a polygonal pattern and follow the hyperbolic shell geometry precisely. The bars of the upper steel reinforcement follow a straight line and at the same time define the level of the textile reinforcement on top of it. On account of the increased thickness of the TRC shell at its centre, the concrete cover necessary for the steel reinforcement was easily guaranteed. The reinforcement cage enclosed a steel component positioned at the centre of the shell (Fig. 11). The steel component served as an opening for rainwater drainage and was also used for transferring the TRC shell out of the formwork onto the column as will be described in section 3.2.

A detailed ultimate limit state assessment was performed for the cross-sectional layup designed for the TRC shell as described above. The underlying design approach based on the cross-sectional strength characteristics deter-

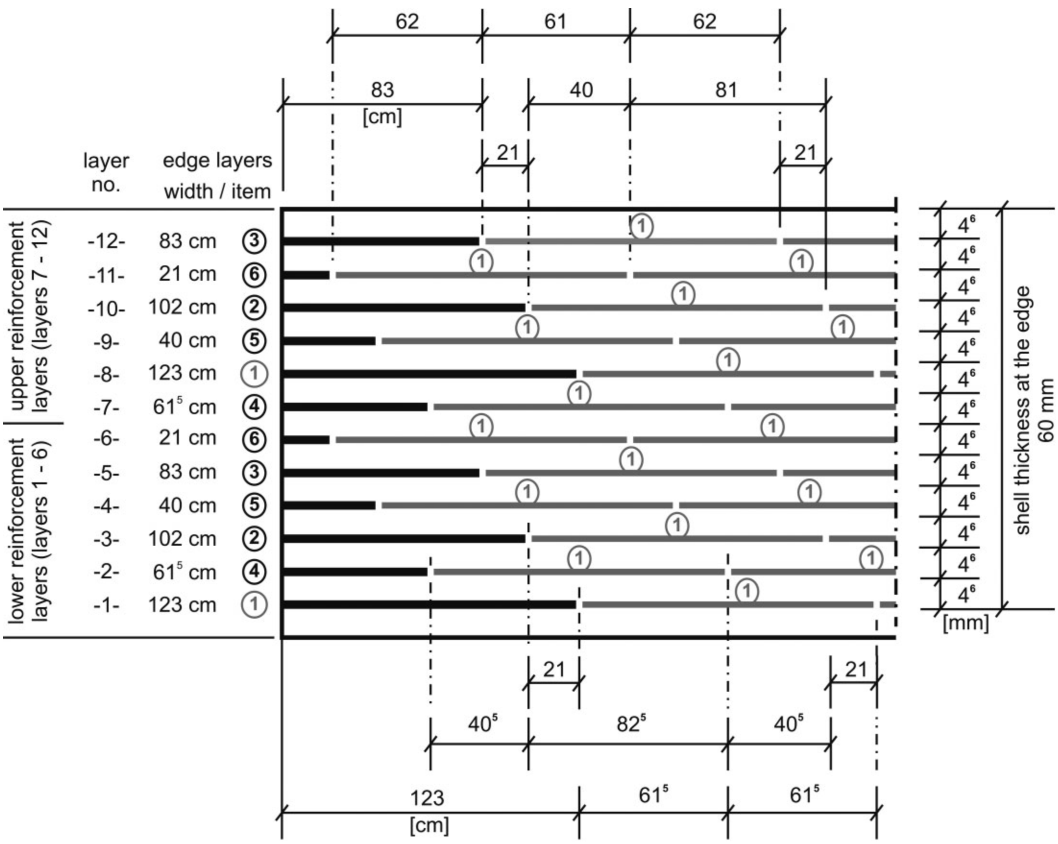

Fig. 8. Offsets of the butt joints between the fabric layers shown in a schematic section through the TRC shell cross-section at the edge

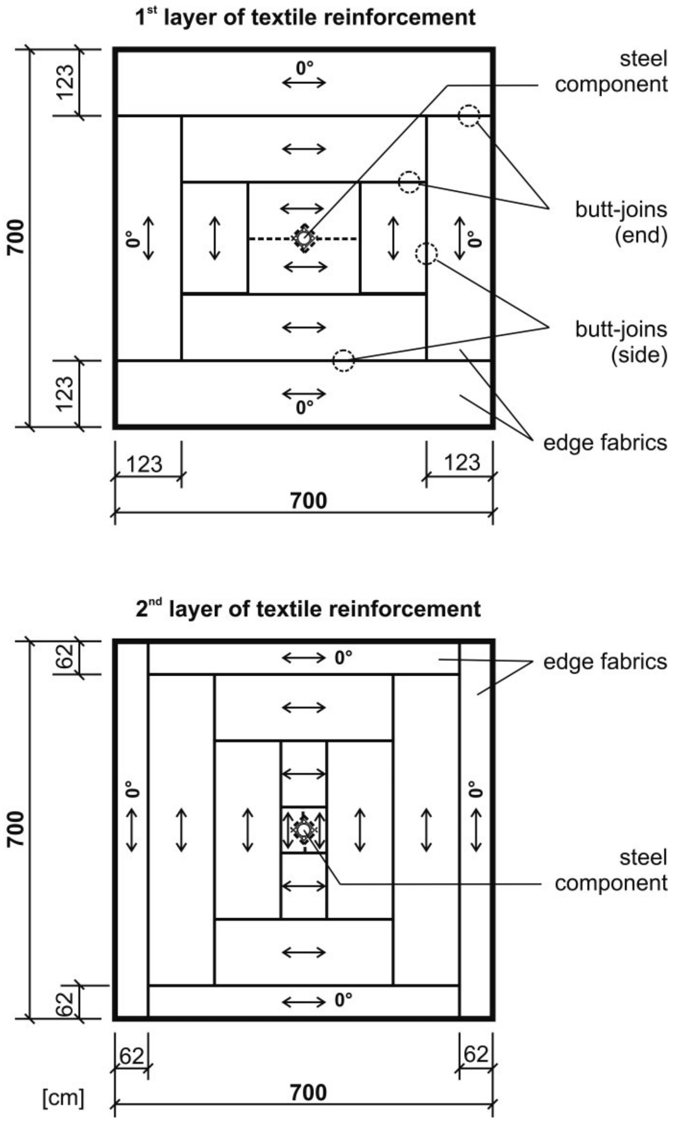

Fig. 9. Reinforcement concept of TRC shells shown for the first two layers of the textile reinforcement as an example

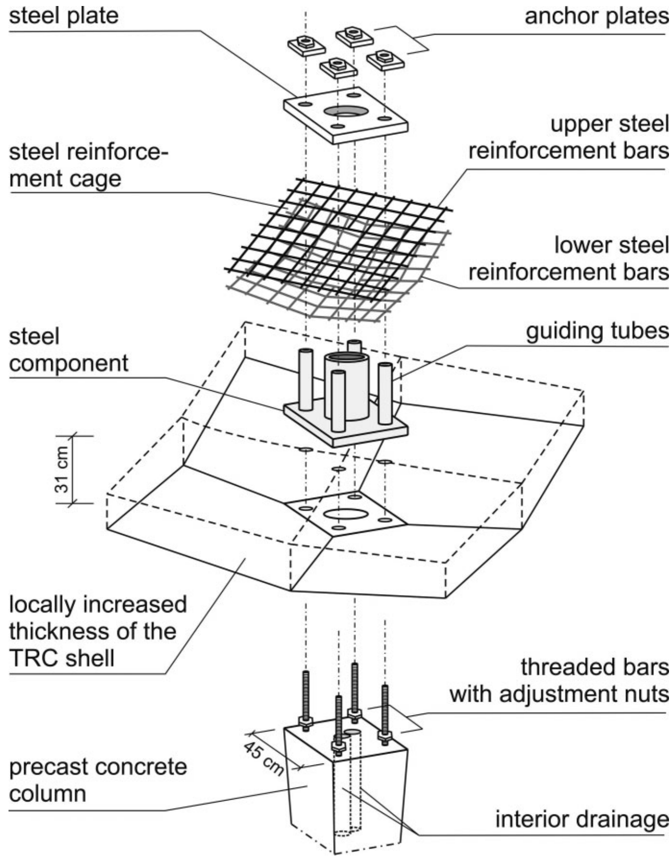

Fig. 11. Exploded view of the connection detail between TRC shell and RC column

mined experimentally as well as the numerical evaluation for all load case combinations are shown in detail in the companion paper [13].

3 Implementation in practice

3.1 Production of textile-reinforced concrete shells

The most challenging task concerning the production of the large (49 m^2) TRC shells was the stringent requirement for the positional accuracy of the textile reinforcement with tolerances as tight as 3 mm. In collaboration with the contractor (GQ Quadflieg GmbH, Aachen, Germany) a precast concept was developed which allowed for constantly high-quality production of all four shells under realistic building conditions. For this purpose, a temporary production tent was built with the formwork for the TRC

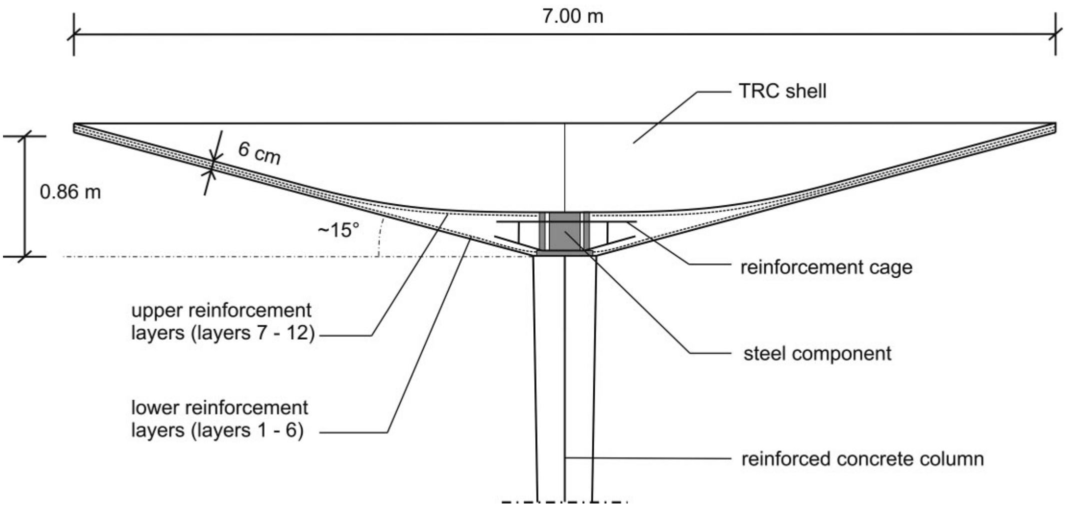

Fig. 10. Section through TRC shell showing the arrangement of the upper and lower textile reinforcement layers at the centre

shells at its centre. Since the shell could not be walked on during the production process, a movable working platform was installed from which every point of the shell could be reached (Fig. 12).

Layers of shotcrete approx. 5 mm thick were sprayed from the platform, and the textile reinforcement was laid in this afterwards. To do this, the rolls pf textile fabrics were attached to the scaffolding so that they could be easily unrolled into the shotcrete (Fig. 13).

Subsequently, the textile fabrics were laminated with rolls in the fresh concrete matrix in order to achieve a high penetration of the multifilament yarns by the cementitious matrix. Each new layer of reinforcement was started by inserting the peripheral edge fabric. Then the inner layers were aligned with their long sides flush with the edge fabric (Fig. 8). The varying width of the edge fabric resulted in the desired offset of the butt joints as explained in section 2.4. The edge fabrics were prefabricated in the widths required, which were chosen such that two edge fabrics with different widths could be produced simultaneously from a single textile roll 1.23 m wide (Fig. 9).

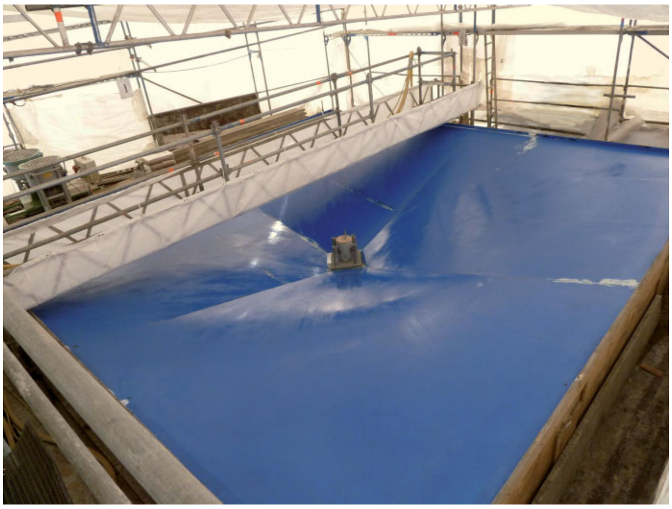

Fig. 12. Timber formwork for TRC shell in fabrication tent with movable working platform

At the front ends the textiles were initially rolled out with an overlap, and a flush butt joint was achieved with electric fabric scissors. The required positional accuracy of the reinforcement could be ensured through continuous measurement of the layer thickness.

After inserting the first six textile reinforcement layers, the pre-assembled steel reinforcement cage was installed in the centre of the shell (Fig. 11). The spacing of the reinforcing bars of the cage were adjusted in such a way that the reinforcement cage fitted precisely between the guiding tubes of the steel component. After installation, the reinforcement cage was completely encased in concrete and the production process of the TRC shell was continued by inserting the six further textile reinforcement layers (Fig. 10). Thus, each of the four TRC shells was completed within one working day in a continuous production process. The precast approach developed made it possible to produce all four shells with a single formwork. Production of the shells in situ would have required a continuous formwork for all four shells and elaborate falsework at the final height of 4 m. Furthermore, the heated production tent made it possible to produce the shells during the cold winter months.

Stripping could be carried out after only 10 days of curing because – owing to the use of high-strength concrete – the TRC shell then already had sufficient strength to accommodate the stresses induced by the stripping process.

3.2 Erection of the TRC shells

Prior to the erection of the TRC shells, the four reinforced concrete columns were levelled, aligned and brought to the desired height. The columns were then joined to the concrete foundation with threaded bars anchored in the concrete foundation. In particular, the steel base plate welded to the column reinforcement at the bottom of the columns was bolted to the pad foundation (Fig. 3).

In order to transfer the large-format TRC shell from the production tent to the reinforced concrete columns, the movable roof of the production tent was opened and the shell was lifted off its formwork with a mobile crane (Fig. 14).

Fig. 13. Production of the TRC shell using shotcrete

Fig. 14. Transferring a TRC shell from the production tent to the top of the RC column using a mobile crane

Fig. 15. Loadbearing structure after final adjustment and coupling of the TRC shells (photo: bauko 2, RWTH Aachen University)

The TRC shells were lifted with the crane at a single point only: the centre. From a structural point of view, the load during stripping corresponded to the final stress state with predominant membrane stresses. In this way no additional transportation anchors were needed for lifting. Instead, the connection of the TRC shell to the crane was realized using a thick-walled hollow steel profile, which was inserted into the embedded steel component and fixed by three steel bolts. The hollow steel profile about 1.20 m high automatically stabilized the shell during the stripping and erection process.

The embedded steel component was also used for the final positional adjustment of the shells and the structural connection between shell and column. For this purpose, the four threaded bars protruding from the column were fed through the four guide tubes of the steel component during erection (Fig. 11). In the final state it was then possible to align the shells accurately using nuts which were placed under the steel component, so that a planned gap of 2 cm between the shells was attained (Fig. 15).

After final adjustment of the umbrellas, the joints were sealed at each column head and base, and the TRC umbrellas were bolted together with steel joints as explained in section 2.1. Temporary scaffolding was necessary for erecting and coupling the TRC shells, which was dismantled after completion of the work.

4 Conclusions

This paper describes the structural design as well as the construction of a demonstration structure with a roof consisting of textile-reinforced concrete (TRC) shells. Based on the analysis of the loadbearing behaviour of the hypar shells, a reinforcement concept was developed reflecting the flow of the principal stresses within the shell structure. Furthermore, a fabrication technique for the TRC shells as precast elements was developed together with the contractor which met the high requirements regarding the positional accuracy of the textile reinforcement layers over the filigree shell thickness. Besides the issues concerning the structural design and production of the shells as precast elements, it was also necessary to address the appropriate design of the connections. A solution for erecting and aligning the shells has been proposed and realized as well. Issues concerning the material behaviour and ultimate limit state assessment are presented in the companion paper [13].

These large shells demonstrate the application potential of this innovative, high-performance composite material. The present example of the TRC pavilion is intended to inspire designers and architects to implement further new applications of textile-reinforced concrete in practice.

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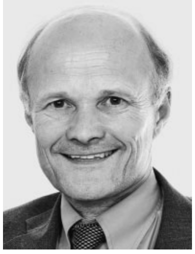

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