JOURNAL OF THE INTERNATIONAL ASSOCIATION FOR SHELL AND SPATIAL STRUCTURES: **J. IASS**

SHELLS MADE OF TEXTILE REINFORCED CONCRETE – APPLICATIONS IN GERMANY

Silke SCHEERER[1], Rostislav CHUDOBA[2], Maria Patricia GARIBALDI[1], Manfred CURBACH[3]

[1]Dr.-Ing., Institute of Concrete Structures of Technische Universität Dresden (Germany), D-01062 Dresden,
silke.scheerer@tu-dresden.de | patricia.garibaldi@tu-dresden.de
[2]Dr.-Ing., Institute of Concrete Structures of RWTH Aachen University (Germany), D-52056 Aachen,
rostislav.chudoba@rwth-aachen.de
[3]Prof. Dr.-Ing. Dr.-Ing. E.h., Institute of Concrete Structures of Technische Universität Dresden (Germany), D-01062 Dresden,
manfred.curbach@tu-dresden.de

Editor's Note: Manuscript submitted 20 September 2016; revision received 9 February 2017; accepted 8 March. This paper is open for written discussion, which should be submitted to the IASS Secretariat no later than September 2017.

DOI: https://doi.org/10.20898/j.iass.2017.191.846

ABSTRACT

Textile reinforced concrete (in short: TRC) is a relatively new building material. It is characterized by the possibility to produce very thin layers with a high tensile strength. Due to the use of flexible reinforcement, TRC is particularly suitable for shell building. In this paper we want to give a short overview about the development of TRC in Germany and the typical material properties. Further we want to describe realized projects in the fields of new shell buildings and of strengthening of reinforced concrete shell structures. The focus is here on manufacturing methods, and we want to demonstrate the potential of textile reinforced concrete for building constructions. We close with a short outlook.

Keywords: *Textile reinforced concrete, TRC, textile reinforcement, concrete shells, realized projects, strengthening of structures*

1. WHAT IS TRC? A SHORT INTRODUCTION

Textile reinforced concrete or 'TRC' is a relatively new high performance building material. TRC is based on the idea to combine concrete with textile grids made of non-corrosive endless filaments with a very high tensile strength instead of corrodible reinforcing steel that is usually used in reinforced concrete. At first, some thoughts on the history and on some other possibilities of alternative reinforcement as a differentiation to TRC which is the subject of this paper.

It is well known that the use of interwoven fibers within concrete like brittle materials is not a new thread in construction. Besides the addition of straw into clay bricks thousands of years ago [1], already Marcus Vitruvius Pollio, a Roman architect, best known through his famous 'Ten Books on Architecture' [2], explained a method of creating a vault that could be seen as an earliest description of a fiber reinforced fine grained mortar shell. An example for a shell made of "modern" short fiber reinforced concrete is Jörg Schlaich's exhibition pavilion for the "Bundesgartenschau"[1] in Stuttgart 1977 – along the lines of Candelas concrete shell in Xochimilco (Mexico) – which was made of prefabricated concrete elements that contained short glass fibers, e.g. [3]. Vitruvius described also instances where natural fibers were used as a falsework, an earliest predecessor of today's fabric formwork, which is being researched today internationally in different places. Well known examples are the research at C.A.S.T. (Manitoba, founded by Mark West, e.g. [4], [5]), the Block Research Group in Zurich [6] or researchers from Bath University [7], to name just a few.

The two possibilities mentioned above for the use of alternative reinforcement materials are not deepened further. Rather, we would like to discuss a third variant – the replacement of the steel reinforcement in the interior of concrete components by means of concentrated reinforcing elements in the form of yarns made of continuous fibers, which are further processed on textile machines to reinforcement grids of high stiffness.

[1] in English: national garden festival

A detailed description of the development history of textile reinforced concrete is given in Scheerer et al. [1]. In this paper, we want to give only short information about the history of the development of textile reinforced concrete. For more information we recommend e.g. [8] or [9]. Considerations about the use of textiles as reinforcement for concrete have already started in the early 1980s. An unpublished study of Fuchs [10] refers to activities of the Sächsisches Textilforschungsinstitut e.V.[2] STFI in Chemnitz, and the WTZTT[3] in Dresden as well as to the first existing patents. Initial research projects followed and first utility models too. Early on, researchers at the universities in Dresden and Aachen worked closely together, and they are still a leading group in the textile reinforced concrete research.

The knowledge developed in the first joint projects involving the different research institutes, was the basis of a state-of-the-art report about textiles in structural concrete, Curbach et al. [11], and two Collaborative Research Centres (CRC, in German: SFB) funded by the German research funding organization DFG between 1999 and 2011 at Technische Universität Dresden (SFB 528, [12]) and at RWTH Aachen University (SFB 532, [13]). By the mid-2000s, first application projects have been completed. Some of them are described in this paper.

For TRC we need alkali resistant textile reinforcement and a special concrete with finer aggregates than those used in standard concrete. Of particular interest are alkali-resistant fiber materials with a high stiffness and strength. Both requirements are met by alkali-resistant (AR) glass fibers (it was mainly used in the 1990s and early 2000s) and by carbon fibers (used since the mid-2000s), being both the currently preferred material options. During the manufacturing process, the fibers or yarns get impregnated with a coating to increase their mechanical strength and to ensure the bond between the edge fibers and the mineral matrix, as well as the bond between the edge fibers and the fibers lying in the inner core of a yarn. A yarn consists of hundreds or thousands continuous fibers up to 50,000 in carbon fiber heavy tows (CFHT). The yarns are further processed, with the help of textile machines, and set as textiles of different geometries depending on the intended use. A carbon fiber grid is shown in Figure 1.

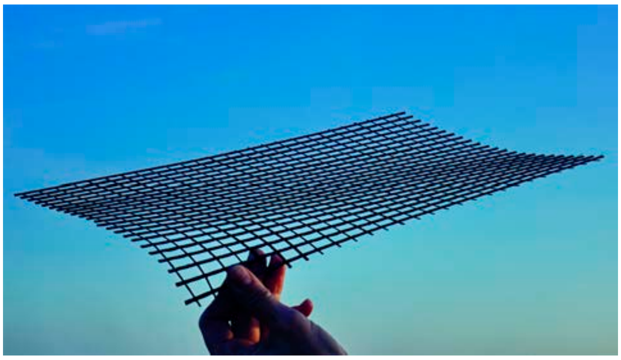

Figure 1: *A carbon textile is light and easy to deform [photo: Manfred Curbach, TU Dresden]*

The mechanical properties of textile yarns or grids made of them depend on several factors like fiber material and number of fibers in a yarn, coating (type and quantity), textile manufacturing method and grid geometry (this means e.g. direction of the yarns and yarn distance), see e.g. Rempel et al. [14], Schütze et al. [15], Chudoba & Scholzen [16]. As an example, (Lorenz et al. [17]): the upper limit of the carbon yarn tension strength in concrete is currently at about 3,000 N/mm², the modulus of elasticity is approximately 200,000 N/mm². If the yarns are processed into grids, the mechanical properties change. In Germany, there is a general building approval ([18], [19]) for a special carbon fiber grid with a yarn spacing of 12 mm in warp direction. The warp yarns have a fineness of 3,200 tex (1 tex = 1 g per 1,000 m, 3,200 tex correspond to 48 K = 48,000 single filaments per yarn), which means a reinforcement cross section of 1.40 cm²/m. In weft direction, the yarns with 800 tex (12 K) have a distance of 16 mm (0.28 mm²/m). The characteristic tensile strength of the processed impregnated yarn is 1,550 MPa and the modulus of elasticity 170,000 MPa (warp direction) resp. 152,000 N/mm² (weft). The weight of the grid is ca. 330 g/m². For comparison: a conventional steel mat with Ø 6 mm every 150 mm (longitudinal direction) and 250 mm (transverse) weighs 2.43 kg/m².

For embedding in concrete, lattice-like scrims are used with yarn distances between 5 and 20 mm. Hence, we need a special fine grained concrete with maximum aggregate sizes between 1 and 7 mm. Based on this, such matrix may be classified as a mortar; based on its mechanical properties, it can be regarded as high-strength concrete. Therefore, the

[2] STFI, Saxon Textile Research Institute
[3] WTZ Technology Textiles

term fine grain concrete has established itself in the technical world. Common mix compositions have been documented in the literature, for example Lieboldt [20] or Mechtcherine et al. [21]. In [18], a commercially available instant mix Pagel 'TF 10' is approved, suitable for construction, that can be used in-situ just by adding water. Typical mechanical properties of the fine-grained concrete are compressive strengths between 65 and 90 N/mm² and a modulus of elasticity between 25,000 to 30,000 N/mm².

Textile reinforced concrete can be produced either by laminating – applying layers of textile grids and fine concrete (by hand or as a shotcrete) alternately, see Figure 20 in paragraph 3 – or by using a formwork to cast the concrete, in which the textile reinforcement has been previously placed, Figure 2.

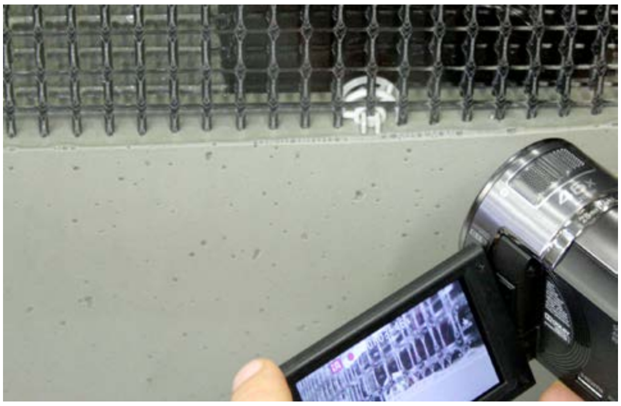

Figure 2: *Production of TRC in casting method, here during an experiment in the laboratory, where a plexiglass formwork was used [photo: Tobias Walther, TU Dresden]*

The thickness of a TRC layer depends on the requirements to ensure the force transmission between yarn and concrete, on the thickness of the grid itself and on the required tensile strength that determines the total number of textile layers. Accordingly, it is feasible to build new structures as thin textile reinforced concrete elements, or to apply strengthening layers to an existing structure. In reinforced concrete construction, we work in a decimeter range, where few centimeters are usually sufficient for TRC constructions. In combination with the flexibility and the low weight of the textile reinforcement, TRC is excellent suitable for the construction of concrete shells. Some examples are given in the following sections.

Parallel to the described development of TRC, there are other projects known, where researchers deal with textiles in concrete. For testing purposes, for example, fabrics made of E-glass fibers or nonwoven are used, which in principle are also suitable for building shells, see e.g. [22]. The authors are currently not aware of realized structures from these material combinations.

2. SHELLS MADE OF TEXTILE REINFORCED CONCRETE

As has been shown, concrete with alternative reinforcing materials is being explored worldwide. Let us emphasize that the paper does not describe the state-of-the-art worldwide but focuses on selected TRC shell structures constructed during the last decade in Germany, which have advanced TRC construction in each case – by improving the manufacturing methods or by opening up a new application area. Other examples are known, for example [23] or [24], but are not to be described here.

The chapter 2. is divided into two parts – new shell structures made of TRC and TRC as strengthening material for reinforced concrete structures. The projects are presented in chronological order.

2.1. TRC shell structure as pedestrian bridge

Based on several years of basic research on textile reinforced concrete, a first pilot project was carried out in Oschatz/Saxony in 2005, e.g. Curbach et al. [25], Jesse & Jesse [26]. Within the framework of a regional garden show, the city of Großenhain wanted to demonstrate non-standard bridge structures made of innovative materials or in a special construction type. This was the chance for the TRC researchers in Dresden to build a first real structure. With the bridge design both conditions were fulfilled: TRC was an innovative material and, in Germany, the segmental construction method is only used in exceptional cases.

The TRC bridge spans over the Döllnitz River, providing a path for pedestrians and cyclists. With a span of 8.66 m and a width of 2.50 m, it is just a small bridge, but in terms of TRC as a new building material it was a huge step towards transferring the research into building practice.

The basic idea for the bridge is to build as lightly and material effectively as possible. The organic shaped superstructure consists essentially of a 30 mm thick shell made of textile reinforced concrete (Figure 3, left). This shell forms at the same time the structure, the walkway and the railings. The cross section is shown in Figure 4. The integral railings, in the longitudinal direction, act as structural elements. At the outer corners and on the underside of the U are cross sectional widenings. They act as stiffeners (Figure 3, middle) for the whole cross section, so that the deformations during use remain within the permissible limits. Also, the prestressing tendons are located in the longitudinal stiffeners on the corners.

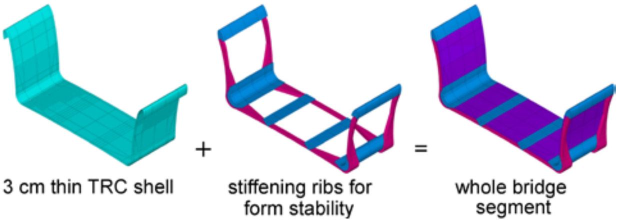

Figure 3: *Schematic structure of the segments [graphic: Harald Michler, TU Dresden], after [27]*

As a rule, there are four layers of AR-glass textile reinforcement arranged in the cross-section. We used biaxial grids with yarn spacings of 10.8 mm in warp and in weft direction. The yarns had a fineness of 2,400 tex, providing 79.3 mm²/m of reinforcement cross-section per each textile layer. The uniaxial tensile strength of one textile in concrete was 600 N/mm². Additional textile reinforcement is provided in the stiffeners region. In the transverse direction, the segment edges are stiffened to absorb the bending forces. Here, additional reinforcing bars made of non-corrosive steel were used (one bar with a diameter of 8 mm in vertical direction resp. one with 12 mm diameter horizontally at each element edge).

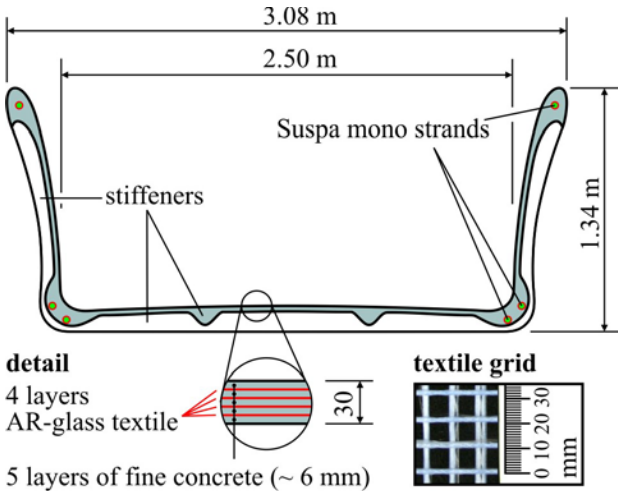

Figure 4: *Cross-section of the TRC bridge in Oschatz/Saxony [graphic: Silke Scheerer, TU Dresden]*

The main reason for the chosen construction type was the lack of suitable prefabrication methods for textile reinforced concrete structures. By dividing the superstructure into 10 equal segments, it was possible to reduce the costs for the formwork significantly. The segments were successively prefabricated at the Oschatz concrete yard, using the hand-laminating method, Figure 5. After hardening, the concrete elements were clamped together with six SUSPA monostrands 150. The whole superstructure could be transported by a truck to the installation site, where it was lifted and set into the already prepared abutments.

As a result of the clamping of the segments, in the longitudinal direction, a beam is obtained in a simplified manner. Due to the slim dimensions of the single elements, however, there is still a very soft superstructure. This U cross-section had to be

Figure 5: *Manufacturing of a bridge segment: modeling a fine grained concrete layer, placing of the textile; final smoothing of the surface [photos: Dirk Jesse & Harald Michler, TU Dresden], [28]*

considered and modeled as a shell in order to be able to estimate the load bearing capacity correctly. Whether the superstructure acts more as a bar or rather a shell depends on the concrete load case. As an example of the results of the modeling, the first eigenform of the superstructure can be seen in Figure 6.

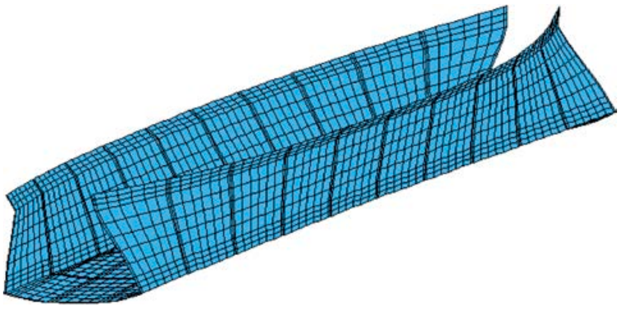

Figure 6: *First eigenform of the Oschatz TRC bridge [graphic: ISD, TU Dresden]*

Both the use of textile reinforced concrete and the proposed segmental construction required an individual approval. Here, a load test on a real scale prototype was included, in which a 3.5-fold safety against the working load level was achieved.

A few years later, a similar TRC bridge was erected in Kempten/Allgäu with a span of 16 m. The superstructure was also prefabricated in Oschatz. The bridge is available to carry pedestrians, cyclists and a small snow-clearer too, see e.g. Michler [27] and Figure 7. This bridge won an official competition – it was not more expensive than a usual RC one. Because of its low weight, it could be completely prefabricated in Oschatz concrete yard (Saxony) und transported by a low loader to the site in Kempten (Bavaria). The erecting time was only some hours.

Figure 7: *Textile reinforced bridge 'Rottachsteg' in Kempten [photo: Harald Michler, TU Dresden], [27]*

2.2. Pavilion made of precast shell elements

The aim of this project was the development of a building made of precast TRC elements which can be assembled and disassembled as often as you want, Kupke & Rupp [29]. By combining several shell-shaped prefabricated elements, it should be possible to create buildings with different layouts. The construction of a demonstrator was also part of the project, built with the collaboration of 4 partners from the construction industry and 3 institutes of TU Dresden.

The form finding for the precast elements was influenced by several boundary conditions such as:

- double curved surface (to test the possibilities and limitations of materials and manufacturing methods),
- high variability in terms of possible layouts,
- transportable by means of a normal truck,

which were coordinated in advance with the funding provider and the project partners.

The element that had been developed had a length of 5 m along two largest edges, and a dimension of 70 cm at the base of a single element. Some examples of possible arrangements of the elements are shown in Figure 8. The static analysis result a component thickness of 4 cm. This is sufficient to integrate the 2 necessary layers of carbon textiles as well as the overlap areas in good quality.

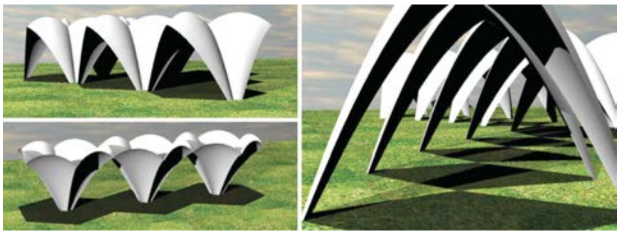

Figure 8: *Possibilities to combine the shell elements for the TRC pavilion [graphics: Elisabeth Schütze, TU Dresden], [30]*

Since the laminating method is very laborious (as can be seen in Figure 5) and time-consuming, casting method should be used to manufacture the elements for the demonstration structure. Up to this time, the casting process had only been tested on small-sized components on the one hand and, on the other hand, only in the laboratory. For this purpose, various problems had to be solved.

At first, it was necessary to develop a flowable, self-compacting fine grained concrete (with a maximum aggregate size of 1 mm). Furthermore, the concrete had to be easy to pump, and with low shrinkage properties. When strengthening a building with TRC, which was the main focus of research in Dresden at that time, a more soft consistency of the concrete and a good adhesion 1. between the fresh concrete layer and the old concrete and 2. between two fine concrete layers is crucial. In the casting process in a precast unit, the flow behavior as well as the and shrinkage behavior are important. Simultaneously, segregation must be prevented. The solution was a self-compacting concrete mixture with a maximum aggregate size of 1.5 mm. The precise concrete composition is a development of Kahla concrete yard and is subject to secrecy. Compared with a typical concrete mixture for TRC (M1 or M3 in [21]), the SVB for the pavilion had a comparable binder content of ca. 800 kg/m³ and nearly the same content of sand (~1,000 kg/m³). The amount of water was comparatively higher (~270 kg/m²), the content of plasticizer was nearly fivefold.

A second goal was to keep the quantity of textile needed to a minimum. To find an optimum, the shell surface has been projected in the plane, from which a cut pattern has been created. The resulting shear angles in the textile were limited to 3°. The chosen carbon reinforcement was cut CNC controlled by an ultrasonic cutter.

To guarantee a smooth surface, different materials for the formwork's skin and release agents were tested. The formwork itself was made in a classic style, with stiffening ribs under the formwork's skin (Figure 9). First, the wooden rib system was made, then a smooth layer of glass fiber reinforced plastic – this was the best variant after the preliminary tests – was added. In the end, the two parts of the formwork were placed on erectable steel constructions.

As reinforcement, a biaxial CFHT grid with a fineness of 3,000 tex per direction was chosen. The yarns had a distance of 10.8 mm in both directions. Near the longitudinal edges of the 1.2 m wide textile panel, the distances between the yarns parallel to the edge was only 7.2 mm. Before

Figure 9: *Wooden rib system for the formwork [photo: Daniel Ehlig, TU Dresden], [29]*

casting the concrete, the pre-cut carbon textiles were placed horizontally and fixed with plastic spacers on the upper face of the formwork. The development of these spacers was a part of the project because at this time there was no system available on the market. Then, the formwork was enclosed, turned into a vertical position (with the element's foot point up) and filled with flowable concrete by pumping it from the bottom side up. After some days, the hardened elements were demolded (Figure 10) and then stored standing sideways.

Figure 10: *Demolding of a hardened shell element in the concrete yard in Kahla/Saxony [photo: Daniel Ehlig, TU Dresden]*

In August 2012, the six prefabricated shell elements were combined to the pavilion shown in Figure 11. To connect the elements, different variants were examined in advance. The connections should allow for multiple assembly and disassembly. The assembly process on site had to be as simple as possible. The most suitable ones for this application were steel L- or T-profiles, which were concreted at the element edges during casting. Opposing flanges were screwed. The contact areas of the steel components were carried out in different ways. Some were additionally glued with a cement mortar, others were simply put together without any adhesive. The performance of both methods will be investigated in this demonstrator, by means of a subsequent long-term monitoring.

Figure 11: *TRC structure made of six cast elements [photo: Ulrich van Stipriaan, TU Dresden]*

Remark: the spacers used in this pilot project were the starting point for a spacer system which has now been developed specifically for TRC, see Figure 12, Walther et al. [31] and [32]. In the future, the system distTEX will help to facilitate the casting process especially at the production of precast TRC elements, where the benefit of reduced time and space requirements, coupled with the feasibility of producing two smooth surfaces, are evident.

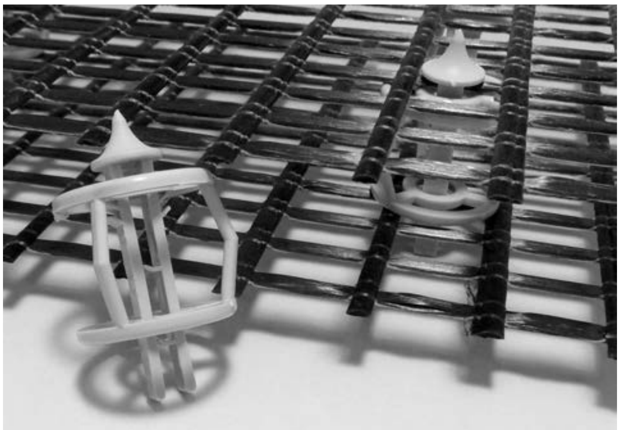

Figure 12: *distTEX: special spacers for textile grids [photo: Frank Schladitz, TU Dresden]*

2.3. Hypar-shell at RWTH Aachen

Another impressive completed project is a pavillon at RWTH Aachen, e.g. Scholzen et al. [33], [34], Hegger & Will [35]. For the building, four 7 × 7 m large, thin-walled double-curved hypar-shell elements were constructed with TRC. At the middle of each shell element, a thickness of 31 cm was necessary, because at this point the ready shell element was supported in the end. The thickness decreases towards the edge areas, where only a thickness of 6 cm was needed.

As reinforcement, a biaxial carbon grid made of 800 tex yarns was used. To determine the amount of reinforcement required, it was important to notice that the orientation of the yarn does not always match the direction of the main tensile strains. This oblique loading results in a reduction of the load bearing capacity, which was considered by a corresponding reduction factor (for more information see Scholzen et al. [34], Hegger & Voss [36] or Jesse [37]). All together 12 carbon textile layers were needed. At the middle of the shells, additional steel reinforcement was added because of the high multiaxial stresses occurring there. Moreover, for each element, a steel fitting had been cast in the concrete, which was used at first to lift the element from the formwork, and later to connect it with a supporting reinforced concrete column.

The manufacturing of the nearly 50 m² large shell elements was by itself a challenge, Scholzen et al. [33], [38], (Figure 13). For this purpose, right next to the building site, a temporary heatable tent with a movable roof was installed, where the wooden

Figure 13: *Manufacturing of the TRC hypar-shell layer by layer by shotcrete [photo: © RWTH Aachen], [38]*

formwork was assembled. The fine concrete was applied, in 5 mm thin layers, from a moveable working platform. The maximum aggregate size was 0.8 mm. To increase the tensile strength of cementitious matrix, AR-glass short fibers were added. After finish one layer, the textile reinforcement was placed on the concrete's surface by hand as can be seen in Figure 13.

After 10 days, the elements had hardened and they were demolded. With the help of a mobile crane, the elements were lifted and centered on the supports. The occurring stresses in the shell element during the lifting corresponded to that due to the dead load in the final state. To connect the shell elements and the columns, prestressed screws were used to create a nearly rigid restraint.

At the end, the inner edges of the 4 shell elements were connected with steel hinges (7 per edge). With these connections, the horizontal stiffness of the building had been clearly increased, especially against wind loads. Figure 14 shows the connected shells before the façade was mounted. Today, the pavilion is used by students or for events.

Figure 14: *TRC hypar-shells at RWTH Aachen [photo: Robert Mehl; RWTH Aachen]*

2.4. Light weight barrel vault shells

The motivation for the construction of the bicycle roof stand at Campus Melaten of the RWTH Aachen University was to develop and demonstrate an efficient manufacturing technology for prefabricated elements using the lamination procedure. As shown in Figure 15 (left side), the structure consists of four cylindrical vault shells with the thickness of 20 mm, length of 4.40 m and width of 2.14 m (as can be seen on the right in Figure 15). The laminated cross-section contains six layers of non-penetrated carbon fabrics with rovings of fineness 800 tex spaced at 8.3 mm. Prior to the construction of the bicycle stand, three shell prototypes were fabricated in collaboration with Durapact GmbH Düsseldorf to develop an efficient prefabrication procedure by alternating lamination sprayed fine-grained concrete and textile fabric layers with high precision of material layout in the final products.

The time needed for the manufacturing process of a single shell was four hours with a crew of five workers. The high precision of production has been examined and statistically processed using cuts through the tested shells showing the maximum deviation of the fabric position from the ideal layout less than 1.3 mm [39].

The three shell prototypes were used for experimental study of the structural behavior and for the validation of the developed approach to ultimate limit state assessment [33]. The test set-up is shown in Figure 16. The experimentally obtained ultimate load of a shell element with the weight of 4 kN was 98 kN revealing the structural redundancy of 57 % with respect to the linear ultimate limit state assessment. The performed tests provide valuable data for the validation of the numerical models suitable for carbon concrete composites

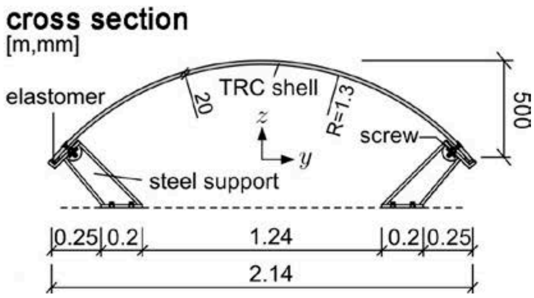

Figure 15: *Roof of the bicycle stand made of laminated TRC barrel vault shells; on the left: view, on the right: cross section [photo and graphic: RWTH Aachen], [41]*

with finely distributed textile fabric reinforcement [40]. An example of structural analysis performed using an anisotropic strain-hardening damage model developed for this type of TRC shells is exemplified in Figure 17.

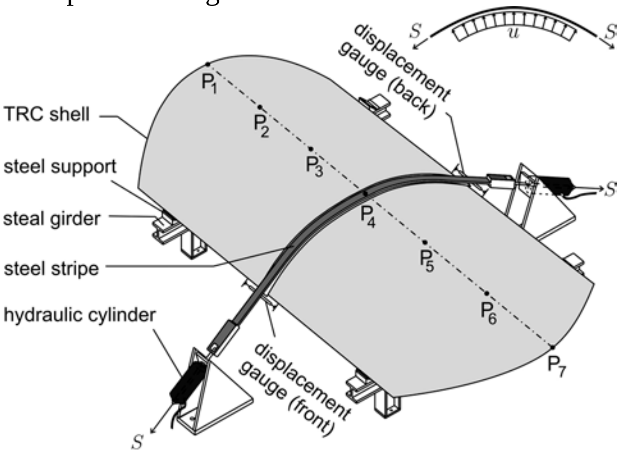

Figure 16: *Full scale test setup [graphic: RWTH Aachen], [41]*

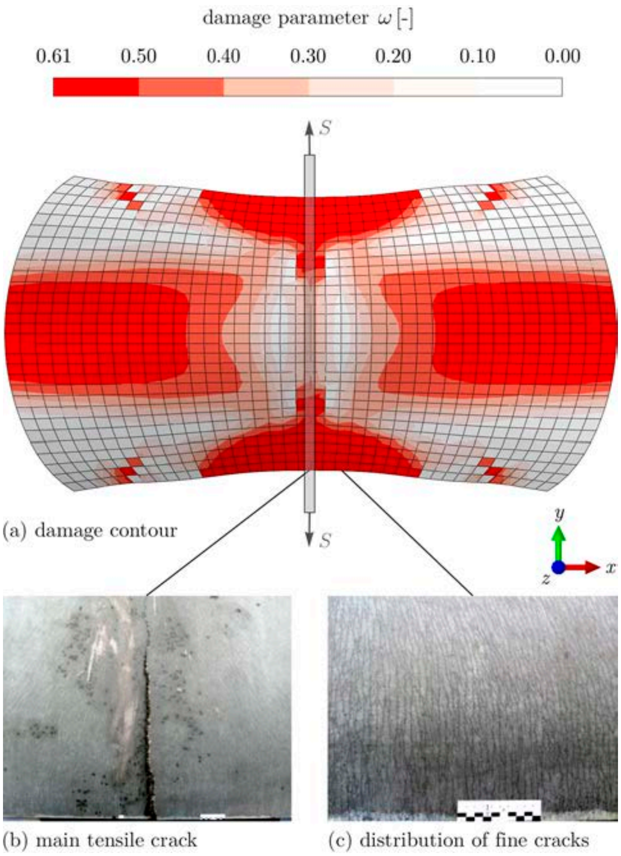

Figure 17: *a) Distribution of maximum damage component in the shell at ultimate failure load; b) Failure crack; c) Distributed fine crack pattern [graphic & photos: RWTH Aachen], [41]*

The detailed study of the structural behavior that exhibits nonlinear, ductile response owing to the fine crack pattern propagation, and the evaluation of structural redundancy is provided in [41].

2.5. Folding TRC – Oricrete

As long as costly and time consuming falseworks are required to create curved shapes, modern concrete shells will be scarcely built in the future. To change this situation, within the Priority Programme SPP 1542, [42], funded by the DFG, alternative manufacturing methods are investigated. An idea, that is particularly suitable for textile reinforced concrete, is folding. Following the well-known origami, the method is called 'oricrete' and was developed by researchers of RWTH Aachen, van der Woerd et al. [43], [44].

The idea of 'oricrete' is really easy: At first, a flat TRC plate is manufactured, e.g. by laminating. Where later the plate should be folded, wooden strips were previously attached on the formwork to create a joint. After hardening of the textile reinforced concrete, the plate can be lifted from the formwork and folded. Temporary supports are used during construction, in such a manner that open joints can be filled with a cementitious matrix. The spatial folded shell construction is finished when the casting compound is hardened. The procedure is shown in Figure 18, [45]. A bike shelter made of an Oricrete shell, built by researchers of RWTH Aachen, is shown in Figure 19. More specific information about this project gives [44].

Figure 18: *Manufacturing of a TRC oricrete structure [photos: Jan Dirk van der Woerd, RWTH Aachen], [45]*

Figure 19: *Oricrete bike shelter ('shell-ter' in [44]), designed and realized by researchers from RWTH Aachen [photo: Jan Dirk van der Woerd, RWTH Aachen], [44]*

3. STRENGTHENING OF REINFORCED CONCRETE SHELL STRUCTURES

3.1. TRC to strengthen a saddle roof

Besides the building of new constructions, TRC has enormous potential for application in the strengthening of structures. Within this method, advantages such as high productivity and optimum concrete consolidation due to spraying are combined with a low increase of dead load and a high material strength. Because the reinforcement is very light and flexible, the material is suitable to be used inside buildings. In comparison to CFRP sheets, textile grids are ideal for a 2-dimensional load transfer.

The first realized project in Germany was the strengthening of a large roof that had the form of a hyperbolic paraboloid at the University of Applied Sciences in Schweinfurt in 2006, see e.g. Curbach et al. [46] or Raupach & Morales Cruz [47].

The roof has edge lengths of nearly 28 × 28 m. Near the edges of the shell, unacceptable deformations had occurred. The result of the recalculation indicated that there was a lack of reinforcement in the 8 cm thin reinforced concrete structure. Since the structure is a protected building, a demolition of the existing structure, and replacement by a new construction wasn't an option. The spatially curved shaped roof was not suitable for a dramatic increase in dead load, and thus a requirement to maintain the additional weight as low as possible was successfully achieved by strengthening the structure with TRC.

Such a building measure is generally carried out according to the following scheme: First the surface shall be cleaned and loose parts of the old concrete shall be removed, cracks shall be sealed, and – if necessary – corroded reinforcement shall be replaced. Before applying the first concrete layer, the surface has to be cleaned from dust etc., roughened (e.g. through sand blasting) and evenly moistened to ensure a good bond between old and new concrete. Then, layer by layer, fine concrete and textile reinforcement can be applied. The upper concrete layer can be smoothened or formed into a

Figure 20: *Strengthening of the hypar-shell in Schweinfurt (from top left to bottom right): before the measure, spraying of a first concrete layer, cutting, applying and slight impressing of a sheet of carbon reinforcement, smoothening the last concrete layer and checking of the layer thickness, ready strengthened structure [photos: Silvio Weiland and Ulrich van Stipriaan, TU Dresden], [48]*

desired surface profile. As for reinforced concrete structures also, a proper aftertreatment is important.

In Schweinfurt, a 1.5 cm thin TRC layer, containing three layers of carbon fiber textiles, was sufficient to strengthen the shell. A grid with carbon yarns of 800 tex in both directions was used. This was enough to ensure the load bearing capacity and to prevent further deformation. It took only few days to strengthen the whole structure. Figure 20 depicts the strengthening process described above.

3.2. TRC for repair

TRC can also be used for rehabilitation, such as damaged concrete surfaces. For example, the inner surface of a cylinder-shaped sugar silo was renovated in 2015 [49], Figure 21. There, fire had caused extensive damage of the roof structure. Within a few weeks, 14,000 m² carbon fabrics were applied in three layers with a thickness of 1.5 cm all together. The concrete matrix made of standard Pagel TF10 had to be pumped up to a height of approx. 60 m. At the end, the surface was merely polished and covered with a food-safe coating after dismantling of the scaffold. At the end, the usable volume of the silo was only slightly reduced.

Figure 21: *Scaffold inside of silo 9, Nordzucker AG Uelzen, during repair works with carbon reinforced concrete [photo: Harald Michler, TU Dresden], [49]*

4. TRC BEYOND CONSTRUCTION

Textile reinforced concrete has not only a great potential in construction, but it is also an interesting material for designers and artists, e.g. Scheerer & Michler [28], due to its typical flexibility properties, that enables it to be formed in thin and light structures.

The researchers of the CRC 528 in Dresden took advantage of this 10 years ago, because art is an excellent way to raise public awareness on a new development. As part of the CRC 528, two art projects have been realized by two Dresden artists. Einhart Groteguth experimented with concrete paintings and Volker Mixsa created filigree sculptures with carbon reinforced concrete (one of them is shown in Figure 22). The majority of the sculptures was manually laminated on steel formworks – designed by Mixsa and his son – in the laboratory of our institute. An exhibition catalog [50] and a vernissage with public presentation of the objects to a wider audience showed the possibilities offered by modern concretes and reinforcement materials.

Figure 22: *Concrete wind chime of Volker Mixsa [photo: Ulrich van Stipriaan, TU Dresden], [50]*

5. SUMMARY AND OUTLOOK

In this paper, we presented a survey of TRC shell structures constructed in Germany during the recent decade in order to illuminate the potential available in this type of novel material and construction technology. All strengthened or new fabricated buildings are still in use with the exception of the pavilion presented in section 2.2. This pavilion was built for R & D purposes and is not open to public. It was erected on the property of the Kahla concrete plant. Actually it is used to monitor the durability of the TRC surfaces, the functionality of the joints and the long-term deformations of the structure.

Today, the focus of the research in Germany is primarily on carbon reinforcement for concrete as two or three dimensional grids or bars with different diameters, for example, in the large-scale research project C^3 – Carbon Concrete Composite [51], which is funded by the German Federal Ministry of Education and Research (in German: BMBF) within the support program 'Zwanzig20 – Partnerschaft für Innovation'[4]. The project started in 2014. Currently, more than 150 partners from science, industry and associations from all over Germany work together with the goal to further develop the material carbon reinforced concrete and to establish it into the building practice. In addition, there are numerous international research projects worldwide.

But not only the materials themselves are to be further investigated and improved, but also the construction methods. Some possibilities were presented in the paper, but there are more different interesting approaches like 3D printing of concrete or reinforcement meshs or the use of robots and digitalization for manufacturing of concrete structures, e.g. [52] as only one example out of a worldwide research community.

ACKNOWLEDGMENT

The authors thank the different funding organizations, e.g. the DFG for the establishment of the CRC in Dresden and Aachen and the German Federation of Industrial Research Associations – in short AiF – for the support of many R&D projects as cooperation between science and practice.

[4] Twenty20 - Partnership for Innovation

REFERENCES

[1] ***Rienecker, F. and Maier***, *G., Lexikon zur Bibel*, 6th Edn (Brockhaus, Wuppertal, 2006).

[2] ***Vitruvius; Morgan, M. H.*** (tran.), *The Ten Books on Architecture*. Harvard University Press, 1914.

[3] ***Holgate, A.***, *The Art of Structural Engineering*. Edition Axel Menges, 1997.

[4] ***Abdelgader, H., West, M., and Górski, J.***, State-of-the-Art Report on Fabric Formwork, *Proc. of ICCBT 2008*, B – (08) – pp. 93-106.

[5] ***West, M.***, *The Fabric Formwork Book: Methods for Building New Architectural and Structural Forms in Concrete*, London · New York: Routledge, 2017.

[6] ***Veenendaal, D., West, M, and Block, P.***, History and overview of fabric formwork: using fabrics for concrete casting, *Structural Concrete*, Vol. 12, No. 3, 2011, pp. 164-177. [DOI: 10.1002/suco.201100014]

[7] ***Orr, J. J., Darby, A. P., Ibell, T. J., Evernden, M. C., and Otlet, M.***, Concrete structures using fabric formwork, *The Structural Engineer*, Vol. 89, No. 8, 2011, pp. 20-26.

[8] ***Taerwe, L.***, Non-Metallic (FRP) Reinforcement for Concrete Structures: *Proceedings of the Second International Rilem Symposium*, Taylor & Francis, 1995.

[9] ***Scheerer, S., Schladitz, F., and Curbach, M.***, Textile reinforced Concrete – from the idea to a high performance material, *Proceedings of the FERRO-11 and 3rd ICTRC (PRO 98)*, Ed. Brameshuber, W., Bagneux: S.A.R.L.Rilem Publications, 2015, pp. 15-33.

[10] ***Fuchs, H.***, *Ausarbeitung zu Vorarbeiten des WIZTT / STFI vor 1991 für das FK Textil*, unpublished document, 2001.

[11] ***Curbach, M., Fuchs, H., Hegger, J., Noisterning, J. F., Offermann, P., Reinhardt, H.-W., Sasse, H.-R., Schorn, H., Wörner, J.-D., Wulfhorst, B., Franzke, G., Will, N., Arnold, R., Bartl, A.-M., Bischoff, Th., Deußer, S., Döinghaus, P., Jesse, F., Kleist, A., Rößler, G., and Schneider, M.***, *Sachstandbericht zum Einsatz von Textilien im Massivbau*, Ed. Deutscher Ausschuss für Stahlbeton DAfStb, DAfStb publication series No. 488, Beuth, 1998.

[12] Homepage of SFB 528 in Dresden: http://tu-dresden.de/sfb528 or research report: Ed. ***Ortlepp, R., and Curbach, M.***, Schlussbericht des SFB 528, http://www.qucosa.de/fileadmin/data/qucosa/documents/8642/SFB528-Abschlussbericht_gekürzt.pdf, TU Dresden, 2012.

[13] Homepage of SFB 532 in Aachen: http://www.textilbeton-aachen.de/

[14] ***Rempel, S., Kulas, Ch., and Hegger, J.***, Bearing behavior of impregnated textile reinforcement, *Proceedings of the FERRO-11 and 3rd ICTRC (PRO 98)*, Ed. Brameshuber, W., Bagneux: S.A.R.L.Rilem Publications, 2015, pp. 71-77.

[15] ***Schütze, E., Lorenz, E., and Curbach, M.***, Static and Dynamic Fatigue Strength of Textile Reinforced Concrete, *Elegance in Structures, Proceedings of IABSE Conference 13.-15.5.2015 in Nara (Japan)*, printed in Japan, 2015, pp. 332-333 (abstract; full paper on CD: 8 pages).

[16] ***Chudoba, R., and Scholzen, A.***, Textile-reinforced concrete – structural behavior, *Textile Fibre Composites in Civil Engineering*, Ed. Triantafillou, T. C., Woodhead Publishing, 2016, Chapter 9, pp. 209-226. [DOI: 10.1016/B978-1-78242-446-8.00010-0]

[17] ***Lorenz, E., Ortlepp, R., Hausding, J., and Cherif, Ch.***, Effizienzsteigerung von Textilbeton durch Einsatz textiler Bewehrungen nach dem erweiterten Nähwirkverfahren, *Beton- und Stahlbetonbau*, Vol. 106, No. 1, 2011, pp. 21−30. [DOI: 10.1002/best.201000072]

[18] ***Z-31.10-182***, Verfahren zur Verstärkung von Stahlbeton mit TUDALIT (Textilbewehrter Beton), DIBt, Berlin, 2016/12/12 (General building approval).

[19] Verstärken mit Textilbeton, *Beton- und Stahlbetonbau*, Volume 110, Issue Supplement 1, 2015, 112 pages.

[20] ***Lieboldt, M.***, Feinbetonmatrix für Textilbeton, *Beton- und Stahlbetonbau*, Volume 110, Issue Supplement 1, 2015, pp. 22-28. [DOI: 10.1002/best.201400100]

[21] ***Mechtcherine, V., Schneider, K., and Brameshuber, W.***, Mineral-based matrices for textile-reinforced concrete, *Textile Fibre Composites in Civil Engineering*, Ed. Triantafillou, T. C., Woodhead Publishing, 2016, Chapter 2, pp. 25-43. [DOI: 10.1016/B978-1-78242-446-8.00003-3]

[22] ***Verwimp, E., Tysmans, T., Verbruggen, S., and Mollaert, M.***, Experimental and numerical analysis of textile reinforced cmenet composites as tensile reinforcement in concrete shells, *Proceedings of the FERRO-11 and 3rd ICTRC (PRO 98)*, Ed. Brameshuber, W., Bagneux: S.A.R.L.Rilem Publications, 2015, pp. 53-6

[23] Textile reinforced concrete egg in Switzerland: http://www.oberhauser-schedler.at/?cat=14&page=16&articles=list&articles_id=207

[24] TRC hypar shell at university Anhalt (Dessau-Roßlau): https://www.stylepark.com/en/news/the-construction-material-of-the-future

[25] ***Curbach, M., Graf, W., Jesse, D., Sickert, J. U., Weiland, S.***, Segmentbrücke aus textilebewehrtem Beton – Konstruktion, Fertigung, numerische Berechnung, *Beton- und Stahlbetonbau*, Vol. 102, No. 6, 2007, pp. 342-352.
[DOI: 10.1002/best.200700550]

[26] ***Jesse, D., and Jesse, F.***, Textile Reinforced Concrete for Lightweight Segmental Bridges with Post-Tensioning, *Proceedings of 3rd International fib Congress incorporating the PCI Annual Convention and Bridge Conference 2010*, 29.5-2.6.2010 in Washington, D.C., 2010, paper no. 154, published on CD.

[27] ***Michler, H.***, Segmentbrücke aus textilbewehrtem Beton – Rottachsteg Kempten im Allgäu, *Beton- und Stahlbetonbau*, Vol. 108, No. 5, 2013, pp. 325-334.
[DOI: 10.1002/best.201300023]

[28] ***Scheerer, S., and Michler, H.***, Freie Formen mit Textilbeton, *Beton- und Stahlbetonbau*, Volume 110, Issue Supplement 1, 2015, pp. 94-100.
[DOI: 10.1002/best.201400113]

[29] ***Kupke, M., and Rupp, M.***, Schalenförmiges Fertigteil als Hüllfläche und Tragkonstruktion eines Gebäudes, *Tudalit-Magazin*, No. 5, 2011, pp. 13 – online: http://tudalit.de/uploads/TUDALIT5screen.pdf – and presentation at the 3rd Anwendertagung Textilbeton, 2011/09/19-20 in Berlin.

[30] ***Schütze, E.***, Entwurf eines Gebäudes aus Textilbeton, project work, Institut für Massivbau, TU Dresden, 2011, 98 pages.

[31] ***Walther, T., Schladitz, F., and Curbach, M.***, Textilbetonherstellung im Gießverfahren mit Hilfe von Abstandhaltern, *Beton- und Stahlbetonbau*, Vol. 109, No. 3, 2014, pp. 216-222.
[DOI: 10.1002/best.201300080]

[32] Homepage of DistTEX with information about the spacer system: https://www.disttex.com/bilder-pictures/

[33] ***Scholzen, A., Chudoba, R., and Hegger, J.***, Thin-walled shell structures made of textile-reinforced concrete – Part I: Structural design and construction, *Structural Concrete*, Vol. 16, Issue 1, 2015, pp. 106-114.
[DOI: 10.1002/suco.201300071]

[34] ***Scholzen, A., Chudoba, R., and Hegger, J.***, Thin-walled shell structures made of textile-reinforced concrete – Part II: experimental characterization, ultimate limit state assessment and numerical simulation, *Structural Concrete*, Vol. 16, Issue 1, 2015, pp. 115-124.
[DOI: 10.1002/suco.201300071]

[35] ***Hegger, J., and Will, N.***, Textile-reinforced concrete: Design models, *Textile Fibre Composites in Civil Engineering*, Ed. Triantafillou, T. C., Woodhead Publishing, 2016, Chapter 8, pp. 189-207.
[DOI: 10.1016/B978-1-78242-446-8.00009-4]

[36] ***Hegger, J., and Voss, S.***, Investigation of the bearing behaviour and application potential of textile reinforced concrete, *Engineering Structures*, Vol. 30, No. 7, 2008, pp. 2050-2056.
[DOI: 10.1016/j.engstruct.2008.01.006]

[37] ***Jesse, D.***, Tragverhalten von textilbewehrtem Beton unter zweiaxialer Zugbeanspruchung, dissertation, TU Dresden, 2011, pp. 1-503. URL: http://nbn-resolving.de/urn:nbn:de:bsz:14-qucosa-69387

[38] ***Scholzen, A., Chudoba, R., and Hegger, J.***, Thin-walled shell structure made of textile reinforced concrete: design, dimensioning and realization, *Beton- und Stahlbetonbau*, Vol. 107, No. 2, 2012, pp. 767-776.
[DOI: 10.1002/best.201200044]

[39] ***Scholzen, A., Chudoba, R., Hegger, J., and Will, N.***, Leichte Dachschalen aus Carbonbeton, *Beton- und Stahlbetonbau*, Vol. 111, No. 10, 2016, pp. 663-675.
[DOI: 10.1002/best.201600030]

[40] ***Chudoba, R., Sharei, E., and Scholzen, A.***, Strain-hardening microplane damage model for thin-walled textile reinforced concrete shells, calibration procedure and experimental validation, *Composite Structures*, Vol. 152, 2016, pp. 913-928.
[DOI: 10.1016/j.compstruct.2016.06.030]

[41] ***Sharei, E., Scholzen, A., Hegger, J., and Chudoba, R***., Structural behavior of a lightweight, textile-reinforced concrete barrel vault shell, *Composite Structures*, Vol. 171, No. 7, pp. 505-514, available online: 21.3.2017.

[42] Homepage of DFG Priority Programme SPP 1542 – Concrete light: http://spp1542.tu-dresden.de/

[43] ***van der Woerd, J. D., Chudoba, R., Bongardt, Ch., Hegger, J***., Oridome: Construction of a dome by folding, *Shells, Membranes and Spatial Structures: Footprints – Proceedings of the IASS-SLTE 2014 Symposium*, 2014/09/15-19 in Brasilia, Ed. Brasil, R., Pauletti, R., published on USB stick.

[44] ***van der Woerd, J. D., Chudoba, R., and Hegger, J***., Folded bike shellter: Application of oricrete design and manufacturing method, *Spatial Structures in the 21st Century – Proceedings of the IASS Annual Symposium 2016*, 2016/09/26-30 in Tokyo (in print).

[45] Project page – Oricrete: http://spp1542.tu-dresden.de/programm/arbeitsgruppen/bauteile-2d-3d/chudoba-hegger

[46] ***Curbach, M., Hauptenbuchner, B., Ortlepp, R., and Weiland, S***., Textilbewehrter Beton zur Verstärkung eines Hyparschalen-tragwerks in Schweinfurt, *Beton- und Stahlbetonbau*, Vol. 102, No. 6, 2007, pp. 353-361.
[DOI: 10.1002/best.200700551]

[47] ***Raupach, M., and Morales Cruz, M***., Textile-reinforced concrete: Selected case studies, *Textile Fibre Composites in Civil Engineering*, Ed. Triantafillou, T. C., Woodhead Publishing, 2016, Chapter 12, pp. 275-299.
[DOI: 10.1016/B978-1-78242-446-8.00013-6]

[48] ***Curbach, M., and Scheerer, S***., Concrete light - Possibilities and Visions. *Concrete Engineering for Excellence and Efficiency – Prof. of Int. fib Symposium 2011*, Ed. Sruma, V., Vol. 1, Prague, 2011/06/08-10, pp. 29-44.

[49] ***Michler, H***., Carbon concrete for caramel, https://tu-dresden.de/bu/bauingenieurwesen/imb/forschung/Forschungsfelder/TRC-C3/Praxisprojekte/copy6_of_MUSTER?set_language=en

[50] ***Ed. Curbach, M***., *Hans-Volker Mixsa – Skulpturen in Beton*, 2. erw. Auflage, Institut für Massivbau der TU Dresden, 2012, 1-48.
Online: https://tu-dresden.de/bu/bauingenieurwesen/imb/ressourcen/dateien/forschung/publikationen/monographien/Katalog-Mixsa-NEU-screen.pdf?lang=de

[51] Homepage of C^3 project: http://www.bauen-neu-denken.de/

[52] Homepage of the research group around Prof. Gramazio & Prof. Kohler (ETH Zurich): http://gramaziokohler.arch.ethz.ch/web/e/forschung/index.html

Remark: All internet sources were checked on 2017/02/08.