TEXTILE REINFORCED CONCRETE – FROM THE IDEA TO A HIGH PERFORMANCE MATERIAL

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Abstract: Textile reinforced concrete (TRC) is on everyone's lips. But who had the idea for this new building material? This question was the intention of this article, however, the question cannot be answered clearly and the authors do not even claim to be able to give a complete overview. The article presents early approaches for the reinforcing of building materials and structures. It presents selected alternatives to conventional reinforcing steel that has been constantly developed, especially since the 1980s. Then this article takes a much closer look on research and developments in the run-up to the two major Collaborative Research Centres (CRCs, in German: SFB) for textile reinforced concrete in Dresden and Aachen. In these two collaborative projects, the research on the composite material was mainly pushed. The CRCs will be presented in their basic features and it will be demonstrated how the transition from theory to practice took place. Other aspects of this last part of the article are the focal points of recent research initiatives and perspectives for the use and the application of carbon in the building industry.

INTRODUCTION

The use of relatively brittle materials with a low tensile strength such as clay or concrete has been known for thousands of years. It is almost a philosophical question of when the first material was produced that is comparable to "concrete" in the modern sense [1]. The idea of embedding fibres in brittle materials, so that cracking does not lead to failure, is also not new. Even thousands of years ago straw was incorporated to clay brick (e.g. left in Figure 1) in order to make it more resistant to cracking e.g. due to strong temperature fluctuations during the day [2]. Later, other methods were devised to strengthen solid concrete structures. References [3] and [4] for example, report on iron brackets on head joints already in antiquity, e.g. at Rome’s Colosseum or at Porta Nigra in Trier, and in [4] on first tensile rings used at brick domes. Best-known early examples are the wooden tensile ring made of chestnut logs at the dome of Florence Cathedral and the iron tensile ring around the dome of St. Peter's Basilica in Rome [5]. At the end of the 16th century iron ring anchors were already installed in this amazing dome that should take the bow thrust.

“Was the use of iron pieces to reinforce concrete in the middle of the 19th century really the most obvious? One might suspect it, ... ”, Wieland Ramm writes in [4]. The first patents date back to the year 1854 (Coignet and Wilkinson) and 1865 (Lambot) and were issued in England, France and Belgium. The beginning and the subsequent history of the "Building Material of the Century" reinforced concrete as the leading building material of modern times is well known, see [4]. Progress in design and construction, materials and construction methods have established reinforced concrete as the leading building material in almost all construction projects. However, there is one major disadvantage: reinforcing steel can corrode. Following Wieland Ramm one has to ask oneself the question, whether the search for alternative reinforcement materials was not a logical consequence of previous developments.
ALTERNATIVE REINFORCING MATERIALS

In recent decades, various ways have been developed to replace the conventional reinforcing steel. Some will be described briefly. There is no exact date when the development of short fibre concrete or fibre concrete (Figure 1, centre) was intensified as an alternative to steel reinforced normal concrete. It is, however, certain that the beginning of this composite material dates back as early as the starting time of reinforced concrete construction. In reference [6] asbestos cement is described as "the first diverse, popular, and industrial level cement composite material". Today, it is mainly alkali-resistant glass fibres (AR glass fibres), steel or plastic short fibres that are added to the matrix of short fibre concrete. In addition to an increase in the compressive and tensile strength, the fibres mainly have a positive effect on the flexural strength, which is why the material is often used for highly loaded industrial floors. Other applications are concrete products or thin-walled precast elements ([7], paragraph 6). A more recent development is the ultra-ductile concrete, e.g. [8], right in Figure 1. A disadvantage is that the fibres usually are randomly oriented. Therefore, short fibres cannot be used for a load transfer in a defined direction.

Another alternative development is the use of fibre reinforced plastics (FRP) in concrete structures, see references [7], [9], [10], and [11]. In general, fibre reinforced plastics include materials that are made of plastic-embedded fibres, for example carbon, glass, and aramid, which have hitherto been mainly used in lightweight construction. Such a matrix achieves the full utilisation of the high efficiency of the individual fibre material within the construction. FRPs usually have clearly directional strength and stiffness properties. A variety of publications in journals and proceedings verifies early research on fibre materials in Japan like the CSCE, the Japan Society of Civil Engineers (JSCE) which established a “committee on continuous fibre reinforced materials” in 1987 [11]. A State-of-the-Art report of this topic was already published in 1992 by JSCE. For solid construction, carbon fibre reinforced plastics CFRP are especially interesting. Currently CFRP can mainly be found in the form of sheets as well as bars and ties, see references [7], [11], [12], [13] and Figure 2 in the middle and on the right. The joint research project “C3 – Carbon Concrete Composite” has the aim to significantly expand the field of application of carbon in construction (see paragraph 6). It should be mentioned that reinforcing bars made of glass fibre reinforced plastics (GFRP rebars left in Figure 2) have been developed and applied, see reference [14]. Currently there is only one product approved by the building authority in Germany [15]. Considerations to replace steel reinforcement by the use of continuous fibres or grids that were made from continuous fibres already began in the 1980s, see refer-
ence [7]. Among experts this new, innovative composite building material is known today as textile reinforced concrete or TRC. The development shall be represented in more detail below, but there is no claim to completeness.

Figure 2: on the left side: ComBar – GFRP reinforcement bars from Schöck (http://www.schoeck.de/de/produktloesungen/typen-zubehoer-101), middle: carbon tendon [13], on the right side: strengthening with CFRP strips (http://www.bautas.ch)

THE BEGINNING OF RESEARCH ON AND DEVELOPMENT OF TRC

First activities and patents

Considerations about the use of textiles as reinforcement for concrete have already started in the early 1980s. Reference [16] refers to activities of the Sächsisches Textilforschungsinstitut e.V. STFI¹, Chemnitz, and the WTZTT² Dresden as well as to the first patents. Patent DD 210102 (December, 1982) offers and patents a possibility for the substitution of steel reinforcement for transport safety (Figure 3). This applies, for example, for minor building products such as plates for slops or for tracks for agricultural infrastructure constructions. Shortly later, concrete barriers were developed with rope-like reinforcing elements made of production waste, and combined with pieces of textile or fibre concrete [17], patent no. DD 253,442 (20/01/1988). Patent no. DD 275 008 "Procedures for fixing the position of line-shaped flexible reinforcement elements in the vertical machining of plate-like elements" (also spacers), describes examples of textile reinforcements: "reinforcing strands" with a diameter of 8 mm and a mesh size of 25 mm. It gives a first impression on textile reinforced concrete.

Figure 3: Early textile reinforcement element, taken from DD 210102

1: single component  
2: reinforcement with  
3: heavily perforated, outer sheath  
4: slidable sleeve  
5: fibrous sheath  
6: tension carrying core (here: slidable)

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¹ Saxon Textile Research Institute  
² WTZ Technology Textiles
The following discussion will mainly focus on the research and development of the composite building material textile reinforced concrete TRC. This would not have been possible, of course, without trend-setting developments in other relevant disciplines. To mention all technological progresses in textile technology, fibre production and fibre processing, concrete design and modelling – to name just a few – would, at this point, exceed the scope of this article by far.

Research in the 1990s in Germany
Initial research projects followed first utility models and patents soon. In Saxony, for example, there was a project funded by the BMFT at the beginning of the 1990s at STFI Chemnitz and the ITT Dresden. In this project, the suitability of flax fibres that had been converted into grid-like knits, was investigated for use in reinforced lightweight concrete or plaster elements [18]. At that time topics that influence the effectiveness of textile grids / fabrics embedded in fine concrete, were already the main subjects of research, e.g. the interaction between surface and core fibres, the bond or the alkali resistance.

Other projects followed. In order to achieve rapid progress in exploring the performance of the new building material, it was essential to cluster expertise. Early on researchers of the universities in Dresden and Aachen worked closely together and are still leading in the textile reinforced concrete research. The initial cooperation can be demonstrated by two joint research projects, while the second project in particular was decisive for further research. In 1996 the AiF-Project No 9272 "Knitted reinforcement fabrics for textile construction" was completed [19], which was handled by the Institute of Textile Technology at RWTH Aachen and the Institute of Textile and Clothing Technology at the Technische Universität Dresden (now: ITM, Institute of Textile Machinery and High Performance Material Technology). Involved in another joint AiF-research project (No. 10378 B) on "Fundamental studies on the development of knitted reinforcement scrims for the use in thin-walled parts made of mineral building materials" were also the Institute of Structures and Materials (now: Institute of Construction Materials, TU Dresden), the Sächsisches Textilforschungsinstitut e.V. (STFI, Chemnitz) and the Institute of Textile and Clothing Technology Aachen [20]. In 1996 — after an early recognition on a TechTextil Conference in the 1990s — a construction made of textile reinforced concrete won a price for the first time and set an example at least among the professional public: the design prize of the Deutscher Betonverein e.V. for a textile reinforced concrete boat that students had been built for the Concrete Canoe Regatta of 1996 in Dresden. The students of the concrete boat team were supported by several research institutes of the TU Dresden with technical advice and working space. These include the Institute of Construction Materials and the Institute of Concrete Structures with their experience and the latest research results regarding the building with concrete. Furthermore it was also the textile researchers, who, according to [21], had recently succeeded to process the world’s first continuous yarns from alkali-resistant glass to knits or fabrics by using the Malimo-technique, which were then used as reinforcement in the boats. Thus, two boats emerged for the design competition: "August the Strong" with a reinforcement of AR glass and the "Tender Gustel" with a reinforcement of carbon fibres (left in Figure 4). Subsequent to the competition the "Tender Gustel" was a popular exhibit and travelled to Amsterdam, Atlanta and Ulm [22].

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3 Saxon Textile Research Institute
4 German Concrete Association
At this point it was clear: building with textile fabrics has a large potential. Based on earlier research, further and sometimes smaller projects were initiated at various institutions of both universities. First doctoral dissertations were written, for example [23], [24]. The collective knowledge was then collected in the "Gemeinschaftsforschungskreis Textilbewehrter Beton" of the Deutscher Betonverein e.V. and summarized in 1998 into the "Sachstandbericht zum Einsatz von Textilien im Massivbau" [7]. Contributors were not only researchers from Dresden and Aachen but also colleagues from the University of Stuttgart, TU Darmstadt, Dywidag and from STFI Chemnitz. The report includes a summary of preliminary research results on the structural composite textile reinforced concrete. In the following the topics are mentioned briefly (paragraph 7 in [7]):

**RWTH Aachen:** As preliminary work for a planned Collaborative Research Centre (CRC), flexural and tensile properties of textile reinforced, flat and U-shaped specimens were carried out with different reinforcement. A typical early textile can be seen right in Figure 4, first test specimen in Figure 5. In addition to the ultimate bearing capacity and basic information on the state of use it was essential to learn more about the bonding behaviour, the ductility or the use of theoretically possible tensions.

![Textile-reinforced concrete specimens](image)

0: reference without reinforcement
1: short fibres (1.5 mass-%)
2: short fibres (1.5 mass-%) and 2 textile layers
4: 2 textile layers all around

Figure 5: First experiments on textile reinforced concrete specimen on RWTH Aachen: specimen for tensile and bending tests with different reinforcement ratios, [7]
TU Dresden: First experimental tests were carried out on hollow blocks, thin TRC-plates, and on reinforced concrete slabs that had been reinforced with textile reinforced concrete. The hollow blocks were reinforced with textiles made of AR glass fibres and carbon fibres, the reinforcing layers in the bending tests were only reinforced with AR glass fibres (Figure 6). Impressive is the significantly increased load capacity of reinforced components. Since the existing textiles were not as load-bearing as those today, many layers were applied, but the cross-sectional thickness itself was increased by only 10 ... 15 %. This is contrasted with an increase of the load bearing capacity by 75 %. In addition, with the same applied load there were significantly smaller deflections up to the time of failure of the textile reinforced concrete layer compared to the reference that has not been reinforced.

Figure 6: First specimens and test results; on the left side: window lintels with polystyrene core; on the right: results of 3-point bending tests on RC-plates without and with TRC-strengthening layer on the bottom side, according to [25]

Since the mid-1990s there were also research activities in Stuttgart and Darmstadt. Prof. Reinhardt and colleagues (University of Stuttgart) dealt with aramid textile reinforcements and later on with the prestressing of TRC, e.g. [26], [27]. The researchers led by Prof. Wörner (TU Darmstadt) dealt with the use of surface near textile grids to restrict the crack width, e.g. [28].

International research on textile reinforced concrete
A complete overview of international research activities in the field of textile reinforcement of concrete cannot be given. Though, there are three examples of research groups / regions that should be noted.

University of Surrey (UK), Prof. D.J Hannant and colleagues: known are various publications, for example on reinforcement webs made of polypropylene fibres from the 1980s. The Ohno-Hannant effect is often mentioned with regard to explanations of the behaviour of fibre bundles in a mineral matrix. The effect describes the interaction of the outer fibres with direct bond to the matrix and the inner core fibres that can only partially absorb strains [29].

Ben Gurion University of the Negev and the Technion (Israel), e.g. [30]: At the beginning of the 1990s Prof. Alva Peled, Prof. Arnon Bentur and colleagues have studied the influence of the structure of fabrics on the mechanical properties of composite materials made of textiles in a cement matrix. Until today, there is a close research exchange between re-
search institutes in Israel and Germany. Prof. Peled is one of the world's leading scientists in the field of textile reinforcements for concrete and is so far the only one with first experiences on the use of mineral fillers for textile structures [31]. She already stayed several times as a guest scientist in Dresden, recently in 2014 at the Institute of Construction Materials.

Japan also began quite early with very extensive research on the application of alternative fibre materials in concrete, see paragraph 2. To name just two examples: one patent (1987) and a research paper (1990). Reference [32] describes the use of fibres embedded in resin, which could then be used as a grid-like reinforcing element which could be made of various fibre materials such as glass, carbon or aramid. In [33] results are presented for the use with carbon fibre networks in a mineral matrix.

One can only guess the existing research worldwide. For further information please see [7] or [10] and proceedings of relevant symposia and the according literature. However, international activities do not exceed the comprehensive and profound research carried out by the two Collaborative Research Centres7 (CRCs) funded by the Deutsche Forschungsgemeinschaft8 DFG in 1999. There is not only the combination textile fabrics and concrete but also the strengthening of masonry (e.g. [34], chapter 22) and of wooden structures [35]. In the 1990s there have been first textile reinforced prototypes and first applications of textile fabrics used for structures. For further information please see the references, e.g. [7], [36].

**FUNDAMENTAL RESEARCH IN THE DFG-CRC 528 AND 532**

Based on the wide preparatory work two Collaborative Research Centres (CRCs, in German: SFB) were prepared in the late 1990s in Dresden and in Aachen and were presented to the German Research Foundation DFG. Despite their formal similarity both projects were recommended by the experts for funding. This was a unique opportunity to explore a wide research field in different locations simultaneously with combined efforts. To exclude a double funding, the individual research fields were strictly defined during the application stage. This is also reflected in the titles of the respective CRC:

- CRC 528 (Technische Universität Dresden; speaker: Manfred Curbach, Institute of Concrete Structures): „Textile reinforcements for structural strengthening and repair“ [37],
- CRC 532 (RWTH Aachen University, speaker: Josef Hegger, Institute of Concrete Structures): „Textile reinforced concrete – basics for the development of a new technology“ [38].

Both CRCs were funded by the German Research Foundation (DFG) between 1999 and 2011. The main research topics will be presented shortly on the following pages.

**CRC 528 in Dresden**

The researchers in CRC 528 had set themselves the goal to provide a verified basis for the use of textile reinforcements for strengthening and repair in construction. The scientists conducted research regarding materials and their mechanical description, regarding design and constructive details. Of interest were further the technological application, the tech-

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7 In German: Sonderforschungsbereich SFB
8 German Research Foundation
nical construction work, and the long-term properties of TRC and thus the safety and durability [39].

Figure 7: Project structure of CRC 528, according to [39]

There were four planned funding periods with twelve years runtime. In the beginning theoretical and experimental studies were conducted to develop basic knowledge of the source materials themselves, the bond between them and the bond between the old concrete and a new textile reinforced concrete layer under static loading. In addition, the potential of textiles to compensate anisotropies in wood and the resulting differences in strength and stiffness were examined. The research fields were later expanded and partially modified. The transfer of the new material TRC into the construction practice became more and more prominent since the third funding period.

The project structure in its main features is shown in Figure 6, see also [39], [40]. The experimentally oriented sub-projects are marked in blue, orange stands for the more theoretical projects. The capital letters in turn, represent one of the five big research areas:

- Research field A: material-oriented investigations of textile structures and fine concrete matrices (mesoscopic level). Over the entire period of the CRC various fine grained concretes were developed, varied and refined. Regarding the reinforcement, AR glass, carbon, aramid and polypropylene were used as fibre materials. Both, the fibres as well as the production of textiles including machine design and development of coatings were partial aspects. The experiments started with mostly static loading in period I. Later the project focused on dynamic and long-time effects.
- Research field B: Composite textile reinforced concrete (macroscopic level). In the beginning the uniaxial stress-strain behaviour was at the centre. Later biaxial stress conditions and dynamic loads were considered in addition. In Phase III and IV of the CRC statistical analyses were performed (in view of a safety fac-
tor) and intensive research was done on anchoring and overlapping lengths, since without this building with TRC would be impossible.

- Research field C: Bond between new and old. In the C projects the theoretical and experimental groundwork was laid in terms of the interaction between an already existing old concrete layer and a new TRC layer. Topics examined include the bond zone, the production technology and the problem of stress transmission. The combination of reinforcing textiles and wood has also been studied during the first two periods of the CRC.

- Research field D: Strengthening of structural components. Starting with the simplest example of application – the flexural strengthening of reinforced concrete slabs – the basis was set for the strengthening of structural components for the load cases bending, longitudinal forces, shear, torsion and combinations of these loads. Later, the fire loads and initial tests with respect to cyclic loading were added. Based on numerous experiments and theoretical considerations, engineering models were created to calculate the strengthening effect with the help of which the first applications have been realised, see e.g. [41], [42]. In the project area D photogrammetric methods have also been developed that were almost uncharted territory at the beginning of the CRC 528 and are now well known.

- Research field E: Safety and durability. Research field E addressed questions about the remaining service life of components, which were strengthened with TRC, as well as about the durability of the materials used. In parallel, the basic principles of a security concept for the strengthening with textiles as reinforcing structures were also covered.

In addition, accompanying research projects have been carried out, a part of which is also shown in Figure 7. First prototypes and practical applications followed (see chapter 5). Besides that, transfer projects were initiated to connect the basic research with the building practice more and more. A total of four faculties with 11 institutes and one non-university institution were involved in the research within the CRC 528. Within the duration of the CRC 528, 48 doctoral dissertations and several hundred publications has been written [37].

**CRC 532 in Aachen**

In the Collaborative Research Centre CRC 532 (Aachen) "Textile Reinforced Concrete – basics for the development of a new technology" the researchers focused their attention – in addition to basic research similar to the Dresden’s CRC – especially on textile reinforced concrete in terms of new components. The number of sub-projects and participating institutions was comparable. One can also find parallels in the general project structure, [43] and Figure 8:

- Research field A: Filaments / yarn,
- Research field B: Textile,
- Research field C: Concrete,
- Research field D: Composite,
- Research field E: Structural members and production,
- Research field Y: Technical information system.
Some points, where the research in Aachen is different from that in Dresden, are:

- At the beginning of both CRCs one dealt on both sides essentially with reinforcements made of AR glass. Later Dresden’s researchers focused on the material carbon. This was partly due to the fallen price of the fibres in the meantime and on the other hand to the higher performance and durability of carbon for the planned applications. In Aachen, however, the research on AR glass fabrics was deepened. A special feature are the by impregnation with resins stabilized, prefabricated reinforcement cages which are optimal as formwork for prefabrication and precast constructions (Figure 9).

- At RWTH Aachen there was a major focus of research on the production, which was discussed in Dresden just on the outskirts or in accompanying, smaller projects.

- Furthermore, in Aachen a technical information system for long-term research and application of TRC was established. It is based on a cross-institutional and interdisciplinary database. Based on this a freely accessible internet platform was created in period IV of the CRC 532 [38], that is currently being completed. Here one can get information about, for example, textiles, building products or calculation methods.

**Common activities**

During the preparation of the two CRCs there was already a very close collaboration between the Universities of Aachen and Dresden. Since then the exchange of experiences was encouraged. Noteworthy are the former six joint technical conferences „Colloquium...“
on Textile reinforced Structures (CTRS)“, which were carried out alternately in Aachen and Dresden with national and international participation since 2001. 2009, the first “user conference” on TRC took place directly after the CTRS4. This event will take place in 2016 for the seventh time [45]. Furthermore, joint publications were published (Figure 10), e.g. the RILEM State-of-the-Art Report about textile reinforced concrete [46], the 2004’s June issue of the peer-reviewed German journal Beton- und Stahlbetonbau that was completely dedicated to the topic TRC [47], and a special issue of the same journal to a first general building approval [48]. Another RILEM report – RILEM 232-TDT „Test methods and design of textile reinforced concrete“ – is being created currently headed by Prof. Brameshuber (RWTH Aachen) [49].

Figure 10: Important common publications, [7], [46]–[48]

THE STEP TO PRACTICE

Networking

The transfer of research results into practice has become increasingly important since the mid-term of the two CRCs. On the one hand there were transfer projects within the Collaborative Research Centres (see e.g. T-projects in Figure 7). On the other hand there were several projects with industrial partners, funded for instance within the funding “Zentrales Innovationsprogramm Mittelstand ZIM”9. Thus, the way into building practice was opened for TRC. Another important point was the establishment of the Deutsches Zentrum Textilbeton DZT10 in 2007. It was part of the model project "Exchange Platform for CRCs and Clusters of Excellence", initiated by the Stifterverband für die Deutsche Wissenschaft11. For the first time the transfer of new technology from science to industry was specifically promoted parallel to its basic research. As part of the TU Dresden AG (TUDAG), the DZT is a competence centre and a focal point for all companies who are interested in TRC. Expertise and networking of all actors along the value added chain play an important role for a successful market launch of the textile reinforced concrete. For this purpose, the TUDALIT e.V. was founded in 2009 [45]. This registered association has currently 28 members from industry and science. Association goals are networking and especially the jointly working on general construction approvals (abZ) in the field of textile concrete to establish the name TUDALIT® as a quality brand. Among others, the texton e.V. and working groups of the Alliance fibre-based materials Baden-Württemberg e.V. and the Carbon Composites e.V. deal with the topic TRC today.

9 Central Innovation Programme SME; SME: small and medium-sized enterprise  
10 German Centre Textile Reinforced Concrete  
11 Donors’ Association for German Science
Brief presentation of selected projects
A complete overview of the practical activities during both CRCs until today would fill a book. Therefore, this paragraph will mention briefly some exemplary projects in which the TU Dresden and the RWTH Aachen were significantly involved. This overview is intended to give an idea of the various application possibilities. For more information, reference is made to the numerous existing publications, e.g. the homepages of the CRCs or [41], [42], [48], [52].

Façade panels. Curtain walls of reinforced concrete are at least between 7 and 10 cm thick because of the necessary concrete cover. With TRC a thickness of 2 to 3 cm is often sufficient. The much lighter façades find a very wide application spectrum, because, among other things, the substructure can be executed filigree and transport and assembly are less expensive. In 2002, 240 m² façade surface of a new building for the Institute of Concrete Structures of the RWTH Aachen University were covered with small-scale textile concrete slabs developed in CRC 532. The company HeringBau received the first general construction approval for such components in 2004 [53]. The pilot application of large-format façade elements was carried out in 2008 at the construction of a new test facility at RWTH Aachen [54]. Many other applications followed, e.g. Figure 11, where large façade panels were used at the cafeteria of St. Leonhard Gymnasium in Aachen.

Balkony slabs. Often balconies are placed in front of existing residential buildings, consisting of a metal frame construction and accessible reinforced concrete plates. The weight of the 20–25 cm thick reinforced concrete slabs is often decisive for the design of the supporting steel structure, the costs of transport and the choice of a suitable crane. In a ZIM project, TRC balcony slabs were developed, which had an average thickness of approximately 7 cm [55], Figure 11. As a result, the steel structure can be designed filigree, material can be saved and the transportation costs and the necessary bearing capacity of the crane can be significantly reduced.

Shell structures. A material that is both lightweight and very load bearing is ideal for shell structures. Several buildings were realized with Dresden’s and Aachen’s participation, ranging from small roofing to complete pavilions (Figure 11).

Spacers. Today, TRC is often produced in lamination process, in which layers of fine grained concrete and textile fabric are built in a horizontal formwork step-by-step until the required component geometry and number of layers is reached. Much more efficient is the casting method that is usual for reinforced concrete. Within a ZIM project, unique spacers have been developed, which are specially adapted to thin and filigree textile fabrics, [56] und Figure 11.

Pontoon. Pontoons for working platforms, floating homes or boat launches are usually made of steel, in some cases made of reinforced concrete. The Institute of Concrete Structures of TU Dresden and the company Dyckerhoff developed textile reinforced concrete pontoons (Figure 11) and evaluated their abilities in a practical test. The Pontoons are thin walled, not susceptible to corrosion and still very viable. They consist of plane plates which have been glued together. The pontoons are a good alternative to existing solutions in terms of price.
**Heating with carbon reinforcement.** Carbon fibres are electrically conductive. In a ZIM project, a reinforcement-heating has been developed which takes over supporting and heating functions simultaneously [57]. This system can possibly save a separate heating at TRC houses in the future. After extensive testing, a first element with a wall heating was installed in a laboratory building at HTWK Leipzig. Figure 11 shows the installation of this element.

![Figure 11: New components made of textile reinforced concrete (from top left to bottom right): TRC façade panels at a high school building in Aachen [48] (photo: Robert Mehl); balcony slab on the site of Metallbau Guke GmbH in Seerhausen, Saxony (photo: Michael Frenzel); 14 × 14 large roofing made of TRC prefabricated elements, RWTH Aachen [52]; special spacers for textile reinforced concrete DistTEX (photo: filmaton); pontoon at the first practical test (photo: Frank Schladitz); textile reinforced concrete wall element with integrated heating (photo: Elisabeth Schütze).](image)

**Strengthening of structures.** In addition to the previously presented new components made of TRC, textile-reinforced concrete is mainly used for the strengthening and rehabilitation of existing reinforced concrete structures. On this topic, the researchers have specialized at the Technische Universität Dresden, see e.g. [41], [42], [59]. Columns, roofs, floor slabs, but also a monument, a sugar silo (Figure 12) and balcony structures were already strengthened. Other applications are currently in planning and execution, e.g. the rehabilitation of first sewage structures with textile reinforced concrete [58]. Meanwhile, TRC is an option even in the more unusual projects in conservation. An impressive example is the restoration of glass block windows from the 1960s. These have been installed after the Second World War in the Gothic St. Mary's tower of Aachen City Hall [52]. Later, the steel reinforcement used at that time was corroded locally. Spalling was the result. The solution was the use of carbon textiles impregnated with epoxy resin embedded in fine concrete (on the right in Figure 12).
Approvals

TRC is not yet a generally approved building product and its workmanship is still no generally approved construction method. Approvals for individual cases (ZiE) were thus required in previous applications in building practice. To avoid that one need separate approvals for each single building project, general technical approval (abZ) are necessary. First general approvals were given for small façades panels (see chapter 5.2). In June 2014, there was a first abZ for the flexural strengthening of reinforced concrete structures [60], [48]. This approval is the result of extensive evidence about the characteristics of fine grained concrete matrix, the special carbon reinforcement and the bond between these two. The approval is currently limited to flexural strengthening of indoor components under predominantly static loading. Nevertheless, the document is an important milestone. Extensions to the existing approval should now be possible with much less effort. In addition, one can refer to this existing document for future approvals. This approval is linked to the quality brand TUDALIT® and was financed by the members of TUDALIT e.V. The approval holder is the TUDAG. The TUDAG is also responsible for the granting of licenses that are needed to use the approval. A further requirement is that the user can show a certificate, which can be purchased in a two-day TRC-approval training organized by the TUDAG. More information gives the Deutsches Zentrum Textilbeton as part of TUDAG [50]. Figure 13 shows the strengthening of a slab as part of one of the TUDALIT training.
PROSPECT

The introduction of textile reinforced concrete onto the market has been accompanied with an extensive expansion of research on TRC and its components. For example, almost every institute of concrete structures in Germany deals with the topic TRC today. Even adjacent areas of research begin to consider textile reinforced concrete e.g. the lightweight construction. The DFG-Priority Programme SPP 1542 "Concrete Light" is just one example. The program is coordinated by the Institute of Concrete Structures at the TU Dresden. In several sub-projects, alternative reinforcements are used [61]. In addition, a wide variety of publications demonstrate the worldwide interest in this innovative building material.

Due to its comprehensive and profound research Germany has emerged as today's worldwide leader in the research on textile reinforced concrete and is able to set up quality standards. However, it has to be said: despite very successful research results and despite the excellent intrinsic material properties of textile reinforced concrete, the construction method is so far applied only to a small extent. Thus, it is vital to keep and expand the advanced knowledge, to pass this knowledge on to all professionals and establish it on the market, so that TRC can be applied on a large scale in the future. Nonetheless, is it sufficient to obtain more approvals and patents for the material and the construction method, to increase the bearing capacity of the reinforcement, to improve the utilisation of the materials and to reduce the retail price? Experts – whether planners, contractors, engineers and research institutions – agree that this is not enough. The design and construction method has to be reconsidered and a new construction design has to be introduced. Above all: future constructions have to be environmentally conscious, resource-efficient, durable, aesthetic and flexible. There are still open aspects like the need for a worldwide standardization of material testing and construction as well as questions about demolition, recycling, industrial health and safety as well as gaps in the value chain that have to be closed. Consequently, comprehensive studies are required now!

The large-scale project “C3 – Carbon Concrete Composite” funded by the German Federal Ministry for Education and Research (BMBF) tackles exactly that problem since 2014 [62]. This project is part of the funding program "Twenty20 – Partnership for Innovation" [63] and was initiated by the Technische Universität Dresden and is funded until the year 2020 with approximately 45 million euros. The project is carried out by a consortium with currently 130 partners from industry and science who have merged into a joint organization: the C3 e.V. As the partners contribute own financial resources the project has a total sum of nearly 70 million euros at its disposal. This is a great opportunity for TRC, but also a huge commitment for those involved. The vision of the project is nothing less than to find a new design to construct with carbon reinforced concrete and to put it on the market.

The project will focus on strategic considerations until the middle of 2015. The TU Dresden developed a concept for the general orientation of the whole project C3 until 2020 in accordance with superordinate boards. The result was a roadmap as shown in Figure 14. Almost all basic projects have already started; first individual projects are currently in motion. The basic projects mainly develop materials, establish standardizations and consider newest ideas on their feasibility. In 2016, the project will address the elimination of so-called market entry barriers and will consider issues such as production optimization, recycling and industrial health and safety aspects of textile reinforced concrete or its components. The following years will be characterized by technology implementation and the further development of applications.
In addition to this major research project funded by the BMBF, there are and will be more projects that will deal with textile reinforced concrete and its practical application for the construction industry. It is also certain that the number of construction projects with textile reinforced concrete as well as its users will continue to rise constantly as more and more professionals will be convinced of the benefits of the new design.

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Figure 15: Aesthetic and efficient concrete structures should shape our future! (graphic ai:L, HTWK Leipzig)

LITERATURE


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