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Textile Reinforcement Structures for Concrete Construction Applications – A Review

Authors:

Danny Friese[1], Martin Scheurer[2], Lars Hahn[1], Thomas Gries[2], Chokri Cherif[1]

[1]Institute of Textile Machinery and High Performance Material Technology, Technische Universität Dresden, Germany
[2]Institut für Textiltechnik, RWTH Aachen University, Germany

Keywords:

A. Textile-Reinforced Concrete (TRC)

B. Textile Reinforcement Structure

C. Robot-Supported Manufacturing

D. Non-Crimp Fabric

Abstract:

The use of non-metallic, textile reinforcement structures in place of steel reinforcement is a key component in making concrete constructions more sustainable and durable than they currently are. The reason for this is the corrosion resistance of textile reinforcements, which makes it possible to reduce the thickness of the concrete cover and at the same time extend the service life of concrete structures. This reduces the amount of cement required and thus also the emission of the greenhouse gas carbon dioxide (CO_2). By means of textile manufacturing technologies, customized, load-adapted reinforcement topologies can be adjusted to the requirements of highly stressed and well-designed concrete components. The objective of this paper is to give an overview of recent research literature dedicated to textile reinforcement structures that are already used for concrete applications in the construction industry as well as those currently under development. Therefore, textile reinforcement structures, which are divided into one-, two- and three-dimensional topologies, as well as common materials used for textile-reinforced concrete (TRC) are reviewed. Most research has so far been devoted to two-dimensional textile reinforcement structures. Furthermore, novel approaches to the fabrication of textile reinforcement structures for concrete applications based on robotic yarn deposition technologies are addressed.

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1. Introduction

The construction and operation of buildings in the European Union (EU) is responsible for roughly half of the use of extracted materials and energy as well as a third of the water consumption in the EU.[1] In addition, the sector causes approximately a third of the greenhouse gas emissions in the European Union.[2,3] The main driver for the emission of greenhouse gases in the construction sector is the production of cement, which alone accounts for about 8 % of global greenhouse gas emissions.[4].Reducing resource usage and emissions of greenhouse gases in the construction sector are therefore central challenges facing academia, governments and the industry alike.

One possible solution to reduce the use of concrete, and therefore of cement, involves the substitution of conventional steel reinforcement with a reinforcement made of non-metallic technical textiles.[5] While reinforcing steel requires a comparatively thick concrete cover to prevent/delay corrosion, technical textiles do not corrode in contact with air and thus do not deteriorate in mechanical strength and stiffness, allowing the concrete cover to be reduced to a minimum.[6] This leads to considerable savings of concrete and therefore reductions in resource usage and greenhouse gas emissions[7–10]. For example, a pedestrian and cyclist bridge built in Albstadt-Ebingen (Germany) in 2015 using carbon-fiber-based reinforcement decreased the required amount of concrete by 60 % and resulting carbon dioxide (CO_2) emissions by 26 % compared to a steel-reinforced alternative.[9] Although on a mass base, carbon fiber reinforcements as the main representatives of technical textiles in the construction industry are more energy-intensive in its production than steel reinforcements and hence also more carbon emissions intensive, the fact that far less of it is needed to reinforce concrete allows for total emissions savings. Direct comparison of the production-related emissions of 1 kg of steel reinforcement (2.3 kg CO_2 equivalents) with one kilogram of carbon fiber reinforcement (19.7 kg CO_2 equivalents) shows that carbon dioxide emissions are around 8.6 times higher.[10] However, for a conventional building product like a double wall, Scope et al. found that up to 22 times less carbon fiber reinforcement is required by weight instead of steel reinforcement.[8] In their life cycle sustainability assessment, they compare two steel-reinforced concrete variants of a double wall to two carbon fiber-reinforced concrete variants. Similarly to the reinforcement, the concrete for the carbon fiber-reinforced variants is also more energy-intensive to produce due to the high cement content, although up to 32.5 % concrete is saved compared to the steel-reinforced variants.[8] For the total double wall, embodied carbon emissions can be reduced by up to 25 % when using carbon fiber-reinforced concrete instead of steel-reinforced concrete.[8]

Although there are several extensive summaries addressing the technology of textile-reinforced concrete (e.g., [11–13]), there is a lack of summarising research literature focused on the textile reinforcement structures used in concrete and their current developments. Therefore, the aim of this paper is to summarize the state of the art of textiles used as concrete reinforcement as well as ongoing research in this area. This paper is focused on textile reinforcement structures utilizing continuous fibers. The topic of short fibers for concrete reinforcement is only briefly introduced since there have been several comprehensive reviews on this topic recently.[14–17] Also, this review paper is limited to textile reinforcements used within the concrete matrix and therefore does not include textile reinforcements applied to the outside of the concrete, such as lamellae or jackets, as described elsewhere, for example by Tatar and Milev.[18]

The use of technical textiles as reinforcement in concrete has been researched for a long period of time, with first patents being published in the 1980s.[19] In the late 1990s and 2000s, large research efforts in Germany led to the foundation of the new material combination, dubbed textile-reinforced concrete (TRC).[20,21] Other names for this composite material, especially in an international research

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context, include textile-reinforced mortar (TRM) and fabric-reinforced cementitious matrices (FRCM).[22]

The basic idea of TRC follows the established principles of steel-reinforced concrete.[5] The concrete matrix has a high compressive strength and can easily be cast into a multitude of shapes while using locally available materials. These advantages have led to concrete becoming the most important construction material and the second most used resource worldwide, just surpassed by water.[23] However, concrete has a comparatively low tensile strength, which can be mitigated using reinforcing materials with high tensile strength, such as steel or technical textiles. Steel-reinforced concrete has been researched and used for nearly two centuries and is one of the cornerstones of the modern construction industry. Steel-reinforced concrete construction is usually realized with various types of reinforcement elements, such as reinforcing steel bars and wires for one-dimensional (1D) reinforcements, welded wire meshes for two-dimensional (2D) reinforcements and reinforcement cages for three-dimensional (3D) reinforcements.[24] A few basic types of steel reinforcement for concrete according to the definition of the German Institute of Standardization e.V. (DIN) in DIN 488 are listed in Table 1.1.

Table 1.1: Characteristics of steel reinforcement elements following DIN 488[25–28]

Product form	Yield strength in N/mm²	Tensile strength in N/mm²	Elongation at break in %	Nominal diameter in mm	Manufacturing process	Surface condition
Reinforcing steel bar	500	550	2.5	6 – 28	Cold forming	Ribbed
Welded steel wire mesh	500	550	2.5	6 – 28	Cold forming and welding	Ribbed
Reinforcing steel wire	500	550	2.5	4 – 12	Cold forming	Smooth
Reinforcing steel wire	500	550	2.5	4 – 12	Cold forming	Profiled

Currently established textile reinforcements resemble these steel reinforcements in shape, function and application methods, with fiber-reinforced plastic rebars and textile meshes being the most common types of textile reinforcements. The beneficial property of common reinforcement textiles is their resistance to corrosion in contrast to steel reinforcements, which positively affects their long-term strength as well as the required thickness of the concrete cover.

Currently, the two main applications of TRC involve the retrofitting of existing structures[22,29–37] and the production of precast elements,[38–43] as TRC combines low weight and high strength with corrosion resistance. More specific examples of TRC precast elements are facades[44–51] and elements for simple buildings, such as pavillions[52–55] or garages.[39] Another prominent application of TRC is the construction of bridges.[37,56–61] Several bridges of different sizes, ranging from pedestrian to vehicular, have been constructed by means of TRC, some using precast elements, others being cast in situ. In addition, the CUBE in Dresden (Germany) will be the world’s first house to be built entirely with TRC.[62–65]

Within this paper, textile reinforcement structures used for concrete reinforcement are classified according to two criteria as shown in Figure 1.1, i.e. their production process and their dimensionality. The production processes are first divided into two categories: conventional textile production processes, using specialised textile machinery, and robotized production methods relying on industrial robots to produce the reinforcement structure. In both categories, various reinforcement textile production methods are used and are therefore discussed in this paper, as shown in Figure 1.1. The second criterion, the dimensionality, is defined by the dimensionality of the reinforcement effect that is provided by the textile structure. 1D textile structures only offer reinforcement in one direction, while two- and 3D textiles offer reinforcement in two or three directions, respectively.

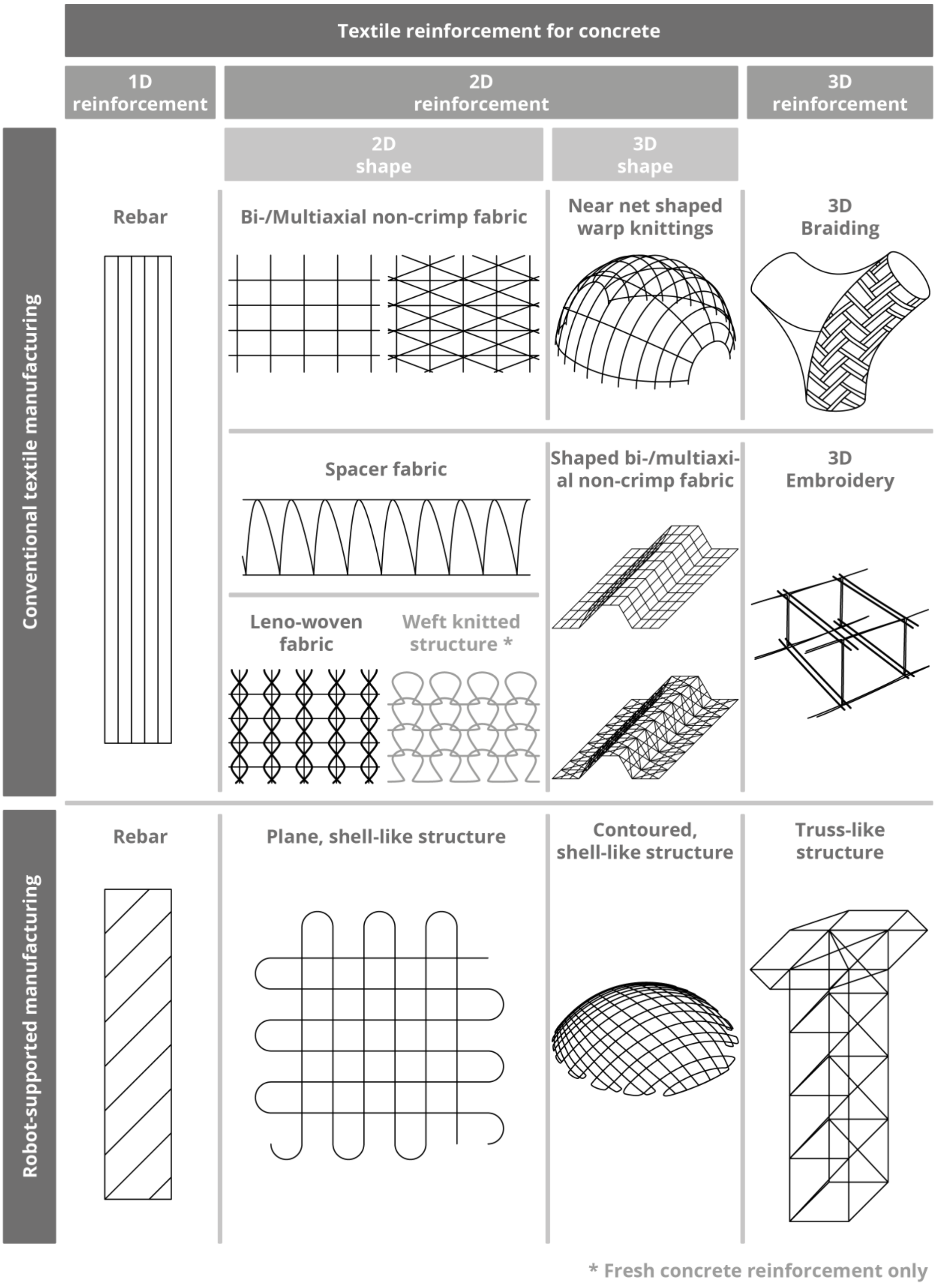

Figure 1.1: Schematic illustrations of different textile reinforcement types for concrete[12,66–74]

After an introduction to the materials used for the production of textile reinforcements for concrete, the structure of this paper follows the system established in Figure 1.1. First, textile reinforcements for concrete produced using specialized textile machinery are discussed, beginning with 1D structures, followed by 2D and 3D structures. Subsequently, textile reinforcements for concrete

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produced using industrial robots are discussed. Finally, the findings are summarized and promising new developments for the textile reinforcement of concrete are presented.

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2. Materials for textile reinforcement structures for construction applications

This chapter provides a summary of common man-made and natural-fiber-based textiles including their functional properties regarding the requirements of reinforced concrete components. Furthermore, this section addresses commonly used impregnation materials for textile reinforcement structures in terms of requirements, such as Young's modulus, inner and outer bond behavior, fire resistance as well as a protective barrier against chemical attacks of alkalis.[75] Impregnation is used synonymously with coating in the cited literature. All mentioned material specifications refer to the application of textile reinforcement in the construction industry. In addition, a short summary of the interfacial transition zone between textile reinforcement and concrete matrix is given, since this area is crucial for the load induction into the reinforcement.

2.1. Fiber materials

Fibers can be classified into chemical and natural fibers as well as a wide range of raw materials, as there are metal, ceramic and natural fibers in addition to man-made fibers, where synthetic polymer and inorganic fibers are further distinguished.[76] The class of technical fibers with diameters of a few micrometers comprises quasi endless fibers, so-called filaments, bunched together in various forms with up to 144,000 single fibers (144k).[77] Three fundamental reinforcement fiber types for concrete reinforcement are glass fiber (GF), basalt fiber (BF) and carbon fiber (CF) due to their highly anisotropic structure combined with high-strength but anisotropic mechanical properties. Initial efforts to replace steel with man-made fiber-based textile reinforcements started in the 1980s, when standard electric (E-) glass fibers were used to strengthen concrete components instead of reinforcing steel.[69,75] As the alkaline environment of concrete adversely affects the mechanical performance of reinforcement structures based on E-glass fiber, the advanced type of alkali-resistant (AR) glass fiber is superior to E-glass and even better than BF regarding its degradation resistance when exposed to an alkaline environment.[31,76,78–81] Following Bobeth et al.[82], Wulfhorst[72] and Ehrenstein[83], Table 2.1.1 gives an overview of the basic properties of selected fiber types for concrete construction applications.

Table 2.1.1: Properties of selected technical reinforcement materials[69,72,82–85]

Reinforcement material	Filament diameter in µm	Density in g/cm³	Tensile strength (roving) in MPa	Breaking strain in %	Young's modulus in GPa
E-glass	9 – 24	2.5 – 2.6	2,400	3.3 – 4.8	72 – 77
AR-glass	9 – 24	2.7	1,800 – 2,000	2.0 – 4.3	21 – 76
Aramid	12	1.5	3,400 – 3,600	2.0 – 4.0	80 – 186
Basalt	9 – 12	2.6	990 – 4,800	1.5 – 3.2	64 – 89
Carbon	5 – 10	1.8	3,000 – 6,000	0.35 – 2.1	240 – 500

Another advantage of AR glass fiber is its lower price per kilogram compared to CF.[86] The alkaline resistance of AR glass fiber is higher compared to that of E-glass fiber but lower than the chemical durability of CF.[69,78] Studies on the reinforcement of concrete structures with aramid fibers (AF) have also been sought through, it should be noted that AF loses considerable strength in alkaline environments.[87–89] Moreover, AF tends to absorb water, which leads to a deterioration of fiber stiffness.[83,82] Nonetheless, progress is driven by research continuously. Basalt fiber with diameters of 9 µm to 12 µm is a technical fiber type used to reinforce concrete components and characterized by

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high mechanical and chemical properties comparable with GF.[90–97] GF as well as BF consist of inorganic compounds.[76] Moreover, BF shows very high thermal resistance.[98] Carbon fiber with diameters of 5 to 10 µm is predominantly made of the synthetic polymer polyacrylonitrile (PAN) and offers beneficial properties for strengthening concrete constructions due to its highly anisotropic structure.[69,99–101] Moreover, CF offers the highest resistance to alkaline environments (inert)[69,102] and the highest Young's modulus as well as tensile strength in fiber axial direction in comparison with all mentioned fiber types within the scope of concrete reinforcement.[83] In addition, CF is characterized by the lowest breaking strain compared to other fiber types (Table 2.1.1). Figure 2.1.1 shows a selection of individual ready-to-use fiber materials as semi-finished materials for non-metallic textile reinforcements structures that have already been investigated in previous research projects with the aim of strengthening concrete components in place of steel reinforcements.

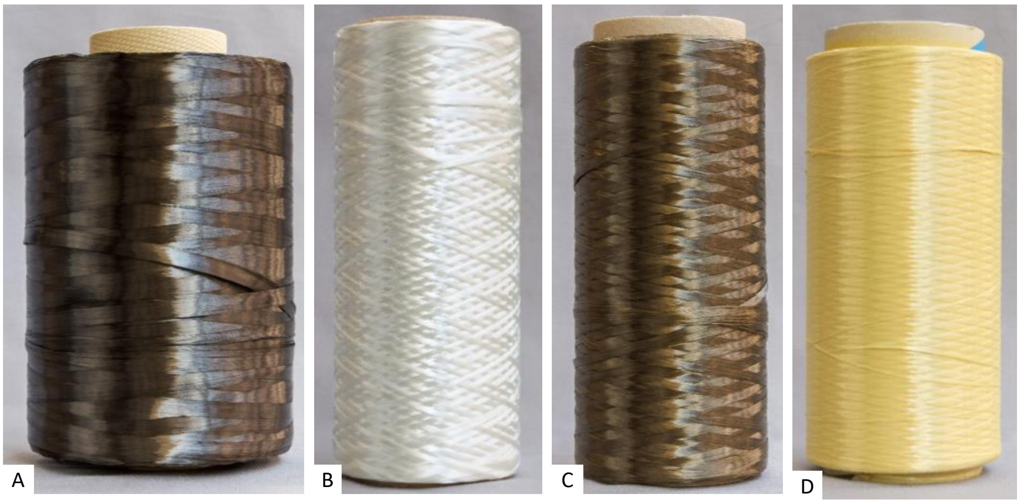

Figure 2.1.1: Selection of already investigated fiber materials for concrete reinforcement structures: A – Carbon fibers, B – Glass fibers, C – Basalt fibers, D – Aramid fibers

The class of polymer fibers, which is also applied for reinforcing concrete components, includes polyparaphenylene benzobisoxazole (PBO) fibers[79], polypropylene (PP) fibers[103–105] and polyethylene (PE) fibers.[106–109] All these fibers show an extraordinarily high chemical stability and therefore a highly inert fiber surface.[69] For the sake of completeness, however, it should be mentioned that concrete enriched with short fibers, e.g., polyvinyl alcohol (PVA), PP or E-glass fibers, are utilized in order to reduce crack formation and propagation as a result of concrete shrinkage, temperature effects, component stress and fatigue.

Short fibers, such as PP, PVA, high-density polyethylene (HDPE), AR glass, E-glass and steel fibers, in addition to the cementitious matrix contribute to enhancing the mechanical properties of concrete components, such as tensile strength, fracture toughness, resistance to fatigue, impact and thermal shock as well as flexural strength by forming a multiple crack formation.[110–112] Short fibers with their finite appearance are randomly oriented and supposed to be uniformly distributed throughout the concrete matrix, enhancing the tensile strength of the concrete component, even though they are not able to resist tensile stress to the same extent as endless fibers.[69] Therefore, in facade elements, sandwich components and very thin and slender concrete parts, appropriated short fibers are added to limit the crack width.[14] With regard to the increasing demand for sustainable solutions, natural fibers gain in importance for reinforcement materials in cementitious concrete[110], such as hemp fibers[113], flax fibers[114–116], jute fibers[117,118], sisal fibers[119], cellulose fibers[120] and coconut coir fibers[121,122], whereby coconut coir fibers have the strongest resistance to degradation in alkaline environments among all natural fibers.[123]

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2.2. Impregnation materials

In the field of impregnation materials for textile reinforcement structures for concrete applications, there are two substantial chemical categories: impregnation agents based on polymers, such as thermosetting or thermoplastic matrices and thermoplastic elastomers, as well as mineral-based matrices, as shown in Table 2.2.1. Related to the construction industry, impregnation is defined as a homogeneous soaking of liquid impregnation material into the roving to achieve an optimal load transfer from outer to inner filaments.

The functions of impregnation treatments are to increase the bond strength and durability of reinforcing fiber materials in cementitious concrete matrices.[124–127] In addition, the impregnation material ensures that the structural geometry can be maintained for the fiber orientation, thus improving the handling properties during the processing and protecting the textile reinforcement from external factors during transportation or processing.[125] However, these advantages only appear if the impregnation material has homogenously and fully infiltrated the fiber bundle, ensuring enhanced bonding between inner and outer filaments as well as between the entire roving and the surrounding concrete matrix.[125] Thus, an enhanced force transmission between filaments can be achieved compared to yarns without impregnation.[128] Furthermore, the impregnation stabilizes the textile formation along with improving the ease of application of textile reinforcement structures during the production processes. Ultimately, reinforcement fibers can sustain higher tensile forces so that their load capacity increases.[129]

Table 2.2.1: Properties of selected impregnation materials for textile-reinforced concrete application[130–143]

Impregnation category	Impregnation subcategory	Impregnation material	Glass transition temperature in °C	Processing temperature in °C
Impregnation based on polymers	Thermosetting matrix	Epoxy resin	81 – 225	18 – 180
	Aqueous dispersion	Based on acrylate	13 – 39	150
		Based on polystyrene	-5 – 33	150 – 160
		Based on styrene-butadiene	-8 – -5	130 – 160
		Based on polyurethane	< -30	120
Impregnation based on minerals	Mineral-based matrix	Granulated blast furnace slag	up to 500[a]	20

[a] In case of a mineral-based impregnation material the assessment basis is the temperature of usability.

Polymer-based coatings can be divided into aqueous polymer dispersions with thermoplastic solids – for instance acrylate, polystyrene, styrene-butadiene rubber or ethyl acrylate – and thermosetting matrices, such as epoxy resin.[141] Recent investigations show the high potential of mineral-based coatings particularly with regard to thermal capacity, minimizing the deterioration of commonly used polymer-based impregnations while also decreasing the load-bearing properties under elevated temperatures.[144–147] Other exceptional approaches enhancing adhesive bonding between filaments involve the prepreg technology, whereby fibers are pre-impregnated with an unconsolidated thermoset matrix, and the hybrid yarn (commingled yarn) technology.[148–150]

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2.3. Interfacial transition zone

Traditional steel reinforcement bars are usually connected to the concrete matrix by mechanical interlocking achieved by a tailored surface profiling, e.g., using ribbed steel. The load is induced into the steel reinforcement at the steel ribs and distributed through the steel bar, which is made of a single, solid and isotropic material.[151] Modelling of the bond strength of steel-reinforced concrete has been researched for decades and an international standard has been established.[152]

In case of textile reinforcements, the load induction from concrete to reinforcement differs from steel reinforcements in two key areas. First, the textile reinforcement is not made from a singular solid material. Textile reinforcements consist of hundreds to thousands of individual anisotropic filaments. Only the outermost of those filaments are in direct contact with the surrounding concrete matrix, since the concrete is too coarse to penetrate into the textile reinforcement.[153] The inner filaments are not in direct contact with the concrete matrix and load induction into these filaments is subject to a second, inner load induction. The ratio of inner to outer filaments highly depends on the thickness and shape of the textile reinforcement.[154] Second, for textile reinforcements, in addition to mechanical interlocking, load induction by substance bond and by frictional bond are relevant.[151] The type of bond that is most relevant depends largely on the type of textile reinforcement.

For 1D textile reinforcements, mechanical interlocking plays a very important role, since 1D textile reinforcements closely resemble the traditional steel reinforcement bars concerning in size dimension and often sport a tailored surface profiling enabling mechanical interlocking.[68,155] For 2D and 3D textile reinforcements, substance bond and frictional bond are more important than mechanical interlocking, since the surface of these textiles is macroscopically comparatively flat and does not allow for significant mechanical interlocking.[151]

In case of non-impregnated textiles, which are only used in edge cases, most of the load is induced via frictional bond. Depending on the fiber material, some substance bond might be achieved (e.g., with PVA[156]), but most fiber materials do not form a significant substance bond with the concrete matrix.[151] This frictional bond is comparatively weak and leads to low failure loads. In addition, uncoated textiles usually fail with a so-called pull-out failure, in which the load is not transferred to the inner filaments of the roving and only the outer filaments carry the load.[157] Impregnation of the textile reinforcements allows for an increased substance bond of the reinforcement with the surrounding concrete matrix as well as for a better load transfer to the inner filaments of the reinforcement.[141,157] If sufficiently stiff impregnation materials are used, some measure of mechanical interlocking can be achieved, further increasing the bond strength.[158] This can also be achieved by adding a sand coating to the outside of an impregnated textile.[100] Figure 2.3 shows the load transfer in coated and uncoated textiles.

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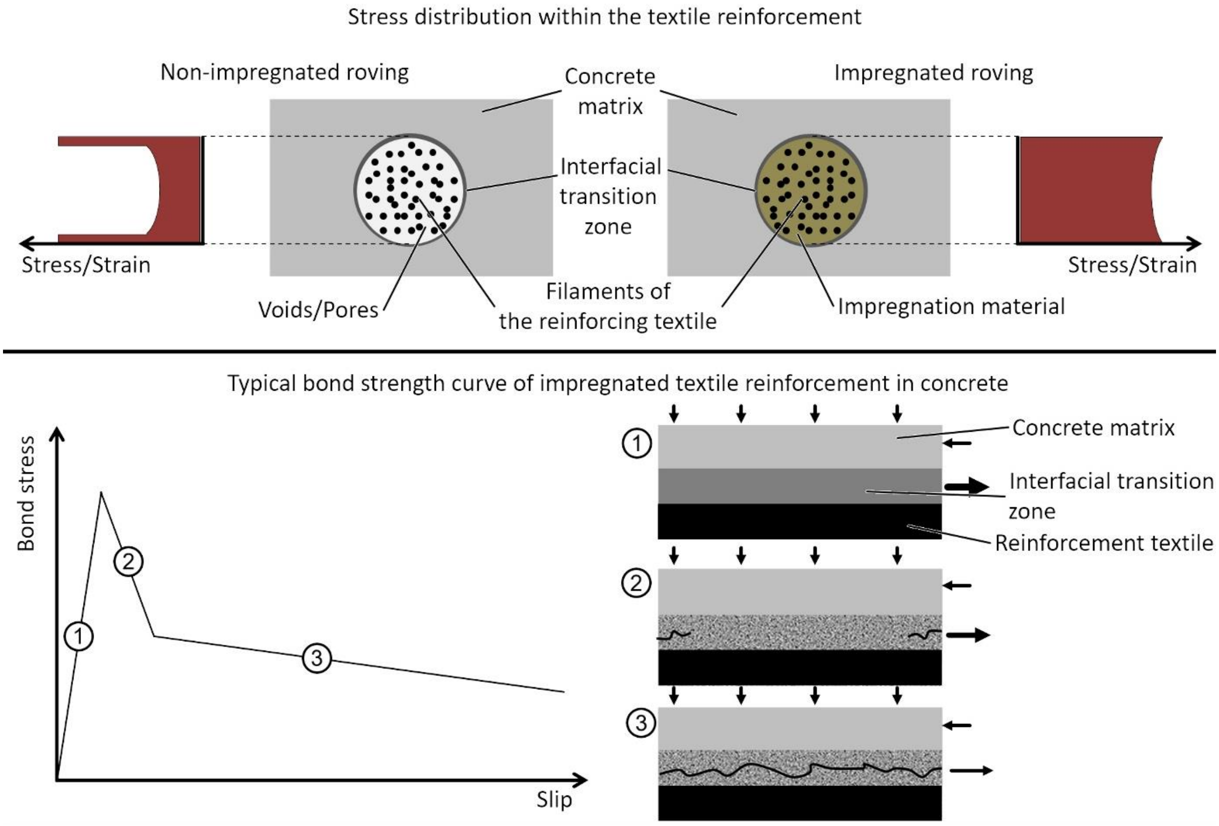

Figure 2.3: Interfacial transition zone of non-impregnated and impregnated textile reinforcements for concrete (top: difference in stress distribution within the roving following Cherif[159]; bottom: typical bond strength curve of impregnated textile reinforcements in concrete following Lorenz[157])

Based on the models used for the bond behavior of steel reinforcement, adjusted models for textile reinforcements have been developed. Richter et al. were able to show in experiments that multiple sectional linear ranges are a sufficiently precise description of the composite behavior.[160,161] Several different calculation and modelling methods for the bond behavior of textile reinforced concrete exist, which currently require complex tests for calibration.[162–165]

In experimental testings, Wendler et al.[166] have investigated the mechanical characteristics of selected impregnated reinforcement textiles, especially of non-crimp fabrics (see section 3.2), that find mostly application in construction. Experimental testing results show tensile strength of up to 3,500 MPa for carbon-fiber non-crimp fabrics with impregnation based on polymers.[166]

In addition, Valeri et al. investigated the bond behavior of TRC using non-crimp fabrics. The influence of different parameters was investigated within the experimental plan, namely: the influence of certain impregnation types, the amount of longitudinal and transversal reinforcement and the concrete cover. Experimental results of tested tensile TRC specimen show an ultimate nominal roving stress in a range of 1,000 to 1,600 MPa depending on reinforcement type and reinforcement ratio.[167] Furthermore, Valeri et al. found that the tensile failure of all TRC specimen tested arises without any apparent warning sign and in a brittle manner.[167]

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3. Textile reinforcement structures for construction applications

This chapter presents an overview of the wide range of common textile reinforcement structures already in use for concrete applications in the construction industry. The classification of these manifold textile reinforcement structures into one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) topologies enables a clear allocation according to their main reinforcement direction(s). New developments with a focus on robot-based manufacturing technologies and novel textile technologies currently under development are addressed in this section. In terms of fiber materials, this chapter is focused on reinforcements using carbon, AR glass and basalt fibers as they are the most commonly used materials. Within the comparatively new sector of non-metallic textile reinforcements for concrete components, standards are yet to be established so that currently, various textiles are employed for different applications. Nonetheless, a few types of textile reinforcement structures play a key role and are more commonly used than others. In general, textile reinforcement structures that are related to common steel reinforcement structures are very frequently used. Steel rebar is substituted by fiber-reinforced plastic rebar, while steel mats are substituted by 2D grid-like fabrics, which are either warp-knit or leno-woven. Since 2016, the first national technical approval published by Deutsches Institut für Bautechnik has universally regulated the procedure for reinforcing concrete with carbon-fiber warp-knitted reinforcement mats, which are bi- or multiaxial grids with regular orientation.[168] These reinforcement textiles in addition to other types are described in more detail below.

3.1. 1D textile reinforcement structures

The term 1D textile reinforcement refers to reinforcing bars – or simplified just rebars – based on fiber composite material with one preferred reinforcement direction.[169] The international application of rebars proves the element's potential of significantly increasing the tensile strength of concrete components.[170] Bridge constructions with highly stressed plates caused by deicing salt[171], such as the Shinmiya Bridge[172] in Japan and the Bridge Street Bridge[173] in the United States of America (USA), emphasize the international application field of 1D textile reinforcement topologies.

There have been comprehensive investigations into the tensile and bond-bearing behavior of carbon reinforcement mats in recent years. That is not the case for reinforced bars though, whose bond-bearing behavior is yet to be investigated in detail. Figure 3.1.1 illustrates a schematic overview of various kinds of rebars with varying surface finishes as a result of different manufacturing processes. Profiled rod-shaped fiber-reinforced plastic bars have to master the significant challenge of ensuring the transfer of (tensile) loads from external component stress on concrete to the reinforcement structures. In this context, the bond behavior is considerably influenced by the individual composite components – i.e., reinforcement fibers and matrix material – as well as the surface profile.

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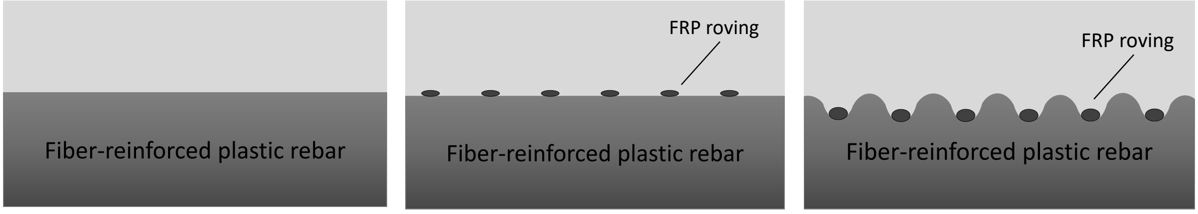
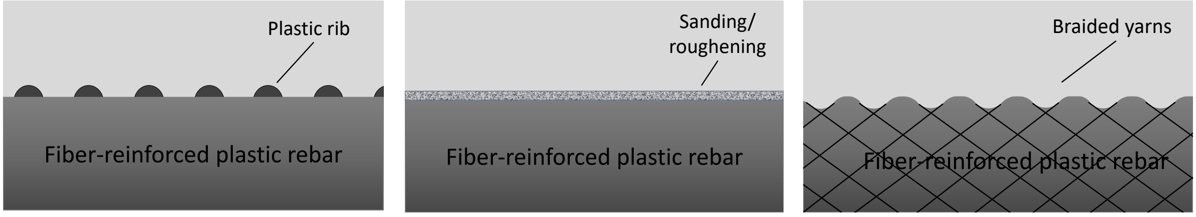
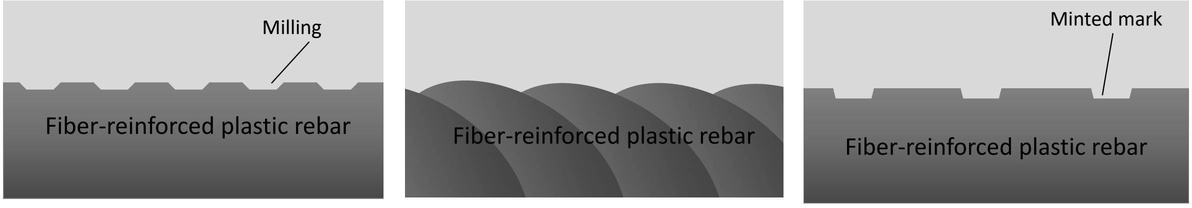


(a) Smooth profile (b) Softly wrapped (c) Tightly wrapped



(d) Plastic ribs (e) Sanding/roughening (f) Braided



(g) Milled (h) Twisted (i) Minted/form-pressed

Figure 3.1.1: Categorization of profiled textile reinforcement topologies such as fiber-reinforced plastic (FRP) rebars following Flemming et al.[174]

As shown in Figure 3.1.1, different manufacturing technologies can be used to increase the bond behavior by means of surface profiling.[175] Apart from the straight and smooth (a) 1D textile reinforcement structure, there are various types of postprocessed elements. Essential manufacturing methods for profiling include: soft (b) and tight wrapping (c)[175], adding polymeric ribs (d), sand-coating (e)[175], braiding (f)[176], milling (g)[175], twisting (h)[175] and minting/form-pressed (i).[175] In addition, profiled carbon yarns with an altering tetrahedral cross-section geometry, which are reshaped in freshly impregnated condition, can also be taken into consideration for substantial 1D reinforcement structures.[177]

Another new development in the area of 1D textile reinforcement structures are carbon fiber tapes. These tapes are spread rovings, and since the spreading process increases the contact area between fiber and concrete, subsequent coating processes are usually no longer required. Scheurer et al. report increases in bending strength of up to 125 % for tapes with a spreading factor of 2.2 compared to TRC beams reinforced with unspread rovings.[178]

3.2. 2D textile reinforcement structures

2D textile reinforcement structures offer reinforcement in multiple directions of a plane. Similar to conventionally used steel reinforcement grids, the main reinforcement directions of reinforcement textiles for concrete construction are usually perpendicular to each other. For the reinforcement of concrete, three types of reinforcement structures produced by means of textile machine technology are relevant in academia and industrial applications: grid-like non-crimp fabrics (NCF), grid-like woven fabrics and weft-knitted textiles.[11,179,180] These textiles, their production processes and their design are discussed in this section.

3.2.1. Grid-like non-crimp fabrics (NCF)

Grid-like NCFs are the most common reinforcement textiles used for concrete construction.[70] These textiles are produced using a warp-knitting process with a knitting thread connecting multiple layers of reinforcing fibers.[181] These reinforcing fibers are laid on top of each other and are, unlike fibers in woven fabrics, not crimped, leading to the designation "non-crimp fabric". Since the reinforcing fibers are not crimped, NCFs offer higher elongation stiffness compared to traditional fabrics.[70,72]

For applications in concrete reinforcement, the textile needs to be embedded in the concrete matrix, requiring the concrete to penetrate through the textile. Since concrete consists of aggregates with a size of several millimeters, large gaps in the textile are necessary. For example, in the case of the textile specified for the German national technical approval Z 31.10-182, the distances between reinforcing fibers are 12.7 mm in weft direction and 14–16 mm in warp direction.[168] As a general rule, the minimal gap opening needs to be three times the size of the largest aggregate in the concrete mixture to prevent a filter effect during concreting.[20] These gaps are realized using warp-knitting processes, enabling the precise production of grid-like textiles with defined spacing between the reinforcing fibers. The warp-knitting processes are either course-oriented or non-course-oriented. During a course-oriented production process, reinforcing yarn distance and stitch length coincide so that the knitting needle does not penetrate through the reinforcing fiber, but produces the loops around it.[72] Most grid-like NCFs used for concrete reinforcement are biaxial, meaning they consist of reinforcement fibers in production direction (0°, filler yarn) and perpendicular to the production direction (90°, weft yarn). The basic structure and an example of a biaxial grid-like NCF as commonly used for concrete reinforcement are shown in Figure 3.2.1.1 below. Hausding et al. also developed an extended warp-knitting process enabling the production of symmetrical, multilayered biaxial NCFs (e. g., fabrics with a layer build-up of 0°/90°/0°).[182]

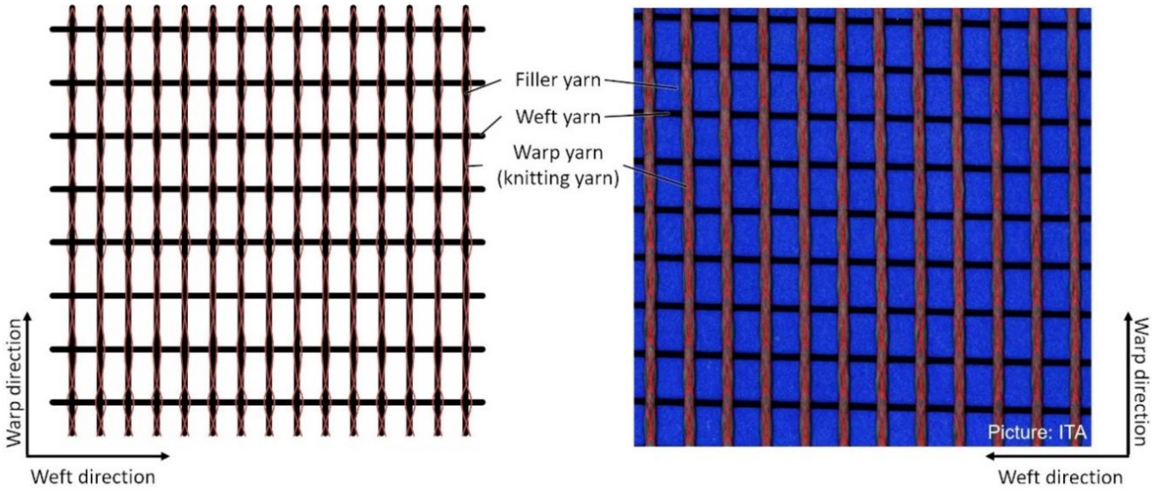


Figure 3.2.1.1: Structure of grid-like non-crimp fabric and example picture

Apart from the material selection, the most important parameters for the production of grid-like NCF for concrete reinforcement are the knitting parameters, especially stitch type and stitch length.[183] Increased stitch length leads to increased shear resistance of grid-like NCF[183] and also results in an increased mechanical performance of TRC elements.[104] While the number of possible stitch types is practically unlimited, especially on modern, electronically controlled machines, several stitch types are especially important, including pillar, tricot, counterlaid tricot and plain. These stitch types are shown in Figure 3.2.1.2 below.

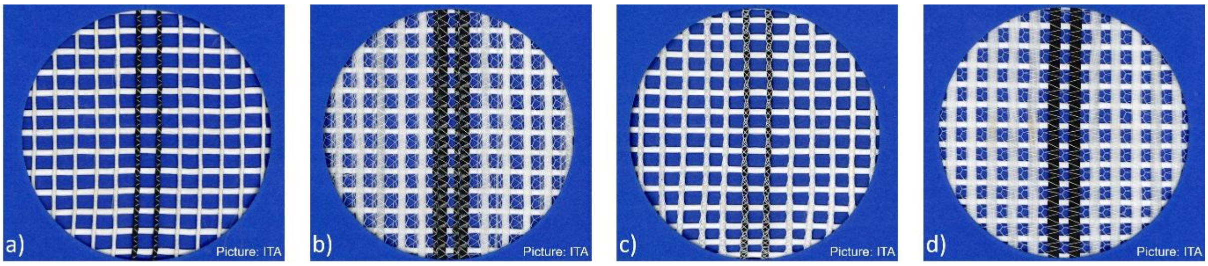


Figure 3.2.1.2: Different stitch types common in grid-like NCF for construction applications. [a] pillar stitch [b] tricot stitch [c] counterlaid tricot stitch [d] plain stitch

The stitch type influences various properties of the reinforcement textile and resulting TRC structure, starting with the shape of the cross section of the reinforcing fibers. This in turn affects the sleeve area in contact with the concrete matrix, which determines the load transfer from concrete to textile, ultimately influencing the mechanical performance of the reinforced concrete elements.[184] Several studies have reported increased pull-out strength and mechanical performance of specimens reinforced with grid-like NCF with wider stitch types, such as tricot or plain.[183,185–187] In all these studies, the textiles were used without additional coating. Perry et al. reported similar results for non-impregnated textiles, but different results for impregnated textiles.[184] In the case of impregnated textiles, stitch types with rounder cross sections, such as pillar or counterlaid tricot, seem to be beneficial.[184]

Grid-like NCF can be impregnated in offline or online processes. In offline processes, the textile is impregnated in an additional production step on a separate machine, while an online process integrates the impregnation into the textile production process.[125] A machine concept for the online impregnation of grid-like NCF was initially described and evaluated by Köckritz et al.[188,189] and further developed by Hahn.[125] Online impregnation of grid-like NCF is nowadays an established process in the textile industry for the production of concrete reinforcement textiles. An evaluation of impregnation parameters by Hahn et al. proved an increase in tensile strength of impregnated grid-like NCF of up to 10 % compared to standard parameters used in the industry.[190]

In an effort to develop highly drapable reinforcement textiles, Pidun investigated biaxial grid-like NCF with variable stitch types along the production length to enable bending of the textiles at specific locations to allow for the shaping of TRC elements during the curing of the concrete.[191] Similarly, Dittel et al. developed a reinforcement textile based on grid-like NCF with reinforcement only in weft direction utilizing flexible knitting yarns made of silicone to produce highly drapable textiles for doubly curved facade elements.[192]

An additional advantage for the production of grid-like NCF is the possibility to replace selected fibers in the structure. This enables the production of textiles with special properties in select areas. For example, replacing selected fibers in a glass textile with carbon fibers allows the use of these carbon fibers as sensor material.[193] Changes in the electrical conductivity of carbon fibers can be detected and allow their application as sensors in structural health monitoring, detecting strain and cracking[194–197] as well as water intrusion.[198,199]

Another development for grid-like NCF for construction applications based on multiaxial warp-knitting technology is the development of loop-shaped anchoring points at both sides of the textile done by Rittner et al.[200] The loop-shaped anchoring points reduce anchoring lengths to 100 mm or less, enabling a reduction of overlapping lengths in large structures, where multiple textiles are required, by more than 75 %.

Grid-like NCF can also be produced in an alternative production process eschewing warp-knitting, as reported by Hahn et al.[201] In this process, the layers of the textile are placed on top of each other and bonded using adhesives or impregnation processes. Initial results show an increase in breaking force at the bond points of 4–30 % compared to conventional, warp-knit grid-like NCF.[201]

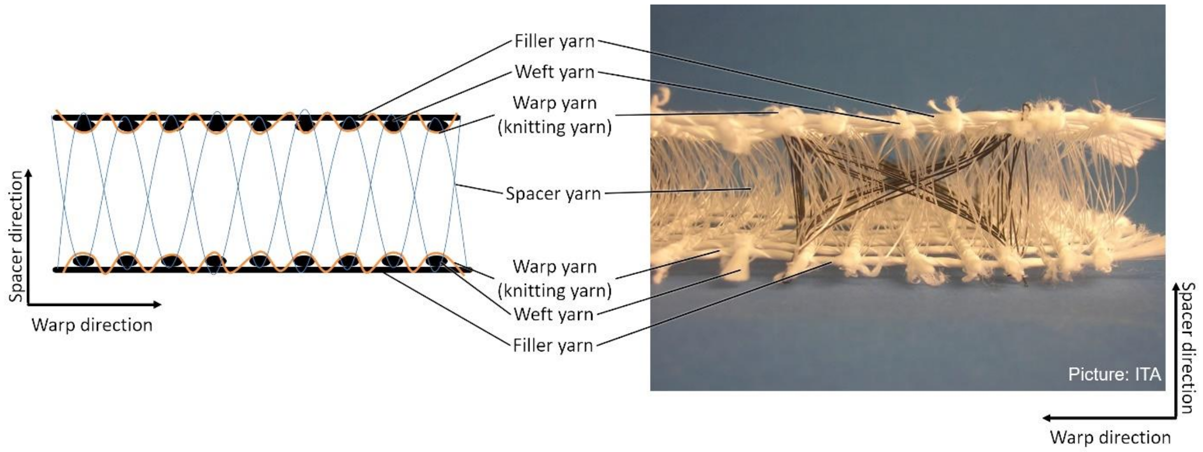
The production of TRC elements often requires shaped reinforcements in addition to flat reinforcement mats, for example L-shaped reinforcements in corner areas. The production of such 3D-shaped reinforcements is usually done in discontinuous processes, where the textile is coated, shaped and then cured in distinct steps on different machines.[202,203] A newly developed process by Hahn et al. enables the continuous in-line impregnation, shaping and curing of grid-like NCF.[204–207]

In addition to the commonly used biaxial grid-like NCF, the production of multiaxial grid-like NCF is feasible.[208] Based on such bi- and multiaxial grid-like NCFs, Sankaran et al. developed a numerically controlled delivery and doffing system for the multiaxial warp-knitting technology to produce grids with variable warp yarn lengths, which enables the production of 2D reinforcement textiles adapted for specific curved 3D shapes, such as the shells of a pavilion.[74,209–211]

3.2.2. Spacer fabrics

Warp-knit spacer fabrics are produced using double-bar raschel machines producing two layers of a warp-knit textile connected by spacer yarns.[212] The individual layers are similar to the 2D , grid-like NCFs described above and consist of reinforcement yarns in 0° and 90° directions as well as a knitting yarn connecting them. The distance between the layers can be adjusted not only between textiles, but also on the fly during production.[213] The basic structure and an example of a warp-knit spacer fabric as used for concrete reinforcement are shown in Figure 3.2.2.1 below.

While spacer fabrics offer a textile with a 3D yarn architecture and are often referred to as 3D textiles, the spacer yarns are comparatively thin polymer yarns that do not offer significant reinforcement for concrete applications. Therefore, spacer fabrics offer two layers of 2D reinforcement.



Picture: ITA

Figure 3.2.2.1: Basic structure and example of a warp-knitted spacer fabric as used for concrete reinforcement

Roye et al. analyzed different warp-knitted spacer fabrics for concrete applications and compared their resistance to compressive forces.[213,214] They reported a decrease in compression resistance with a decreasing spacer yarn angle[213] and with decreasing amount of spacer yarn[214], as well as a dependency of compression resistance on spacer yarn material.[214] Haik et al. evaluated the suitability of spacer fabrics for concrete reinforcement and found them to be highly beneficial.[215] Depending on the type of fabric construction, they found the performance of spacer fabrics to be highly anisotropic.[215] Similarly, El Kadi et al. compared the performance of spacer fabrics and equivalent 2D textiles, revealing that there is no difference in tensile strength of TRC elements, but a higher

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bending strength when using spacer fabrics.[216] Spacer fabrics are also employed in Concrete Canvas, a special type of geosynthetic cementitious composite mat consisting of a spacer fabric filled with concrete powder, which is hardened on-site by adding water.[217] Han et al. investigated different spacer fabric geometries and their applicability for Concrete Canvas, suggesting the use of a solid outer layer.[218] Han et al. also analyzed the influence of spacer fabric geometry on the drying shrinkage of Concrete Canvas, with drying shrinkage mainly depending on the spacer yarns.[219] Li et al. investigated different spacer fabric geometries used in Concrete Canvas and developed a lattice model predicting the tensile behavior of Concrete Canvas based on the geometry of the 3D spacer fabric.[220] Recent development efforts focused on specialized spacer fabrics easing the combination of multiple textiles during construction. By reducing the distance between the reinforcement layers of the spacer fabric at the sides of the textile, multiple textiles can be overlapped without increasing the resulting thickness of the element.[221]

3.2.3. Grid-like woven fabrics

Weaving has been used to produce fabrics for more than 5,000 years and is the most common production method for fabrics today.[72] Woven fabrics consist of warp and weft threads which are interlaced during production, usually at right angles.[222]

Woven fabrics were among the first textiles considered as reinforcement textiles for concrete in the 1990s. For example, Peled et al. analyzed plain woven fabrics made from polyethylene monofilament yarns and reported an improvement in textile-concrete bond (compared to straight yarns) due to the crimped structure of the textile providing mechanical anchoring.[223] They also determined an optimal yarn density above which the concrete matrix cannot penetrate into the textile, reducing mechanical performance.[223] Similarly, Perez-Pena and Mobasher used woven polypropylene and AR glass meshes as effective reinforcements for concrete.[224]

While initial analyses used very fine concrete mixtures or cementitious matrices, later concrete developments with coarser aggregates required larger mesh openings to enable concrete penetration into and through the textile reinforcement structure. Since the maximum mesh opening is limited in conventional woven textiles, leno-woven textiles are employed to overcome these geometrical limitations. With leno-woven fabrics, at least two warp yarn systems are employed: straight and leno yarns.[225] In contrast to standard woven textiles, warp and weft yarn are not always interwoven, but can be connected via the leno yarns.[226] This enables the production of a woven textile with straight reinforcement yarns in warp and weft direction.[226] Additionally, due to this structure, woven fabrics with low warp and weft densities and therefore large mesh openings can be produced.[225,227] The basic structure and an example of a grid-like woven fabric as used for concrete reinforcement are shown in Figure 3.2.3.1 below. Grid-like woven fabrics were used in TRC in several studies, in which they were found to be effective reinforcement textiles.[228–230]

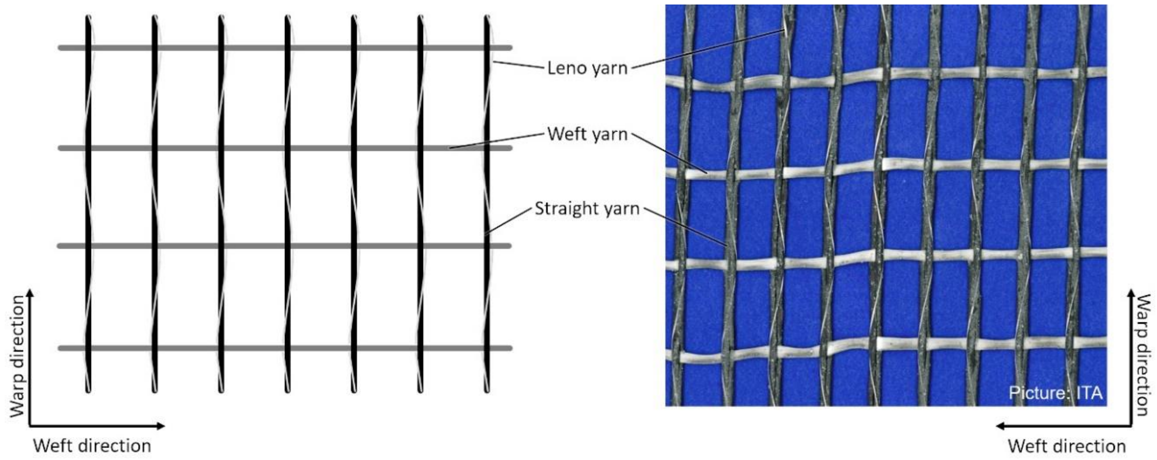

Figure 3.2.3.1: Basic structure and image of a grid-like woven fabric

Compared to conventional leno-weaving machines, machines for the production of grid-like woven fabrics require some alterations. Hausding et al. exchanged several key machine components (e.g., thread heddles / warp beams) to enable the processing of high-performance fiber materials like carbon and AR-glass.[228] Lenz et al. increased the amount of warp-yarn twist that can be introduced on leno-weaving machines as well as production speeds, enabling cheaper textiles with larger mesh openings.[231] And Weise et al. further modified the weaving machines to enable the processing of coarse high-performance fibers (> 2,400 tex) and to reduce the crimp of the reinforcing warp yarn.[225]

Another application of woven fabrics for concrete reinforcement is the fabric formworks suggested by Brennan et al.[232] Woven textile structures can be used as lost formwork during concrete production, where they are either employed only as a flexible formwork, enabling highly curved, nonlinear structures, or as formwork and reinforcement in one.[232]

3.2.4. Weft-knitted structures

Weft-knit fabrics are produced from one or several thread systems by stitch formation, meaning the threads are formed into loops and connected with adjacent loops.[72] Since this production process leads to a comparatively flexible textile with very small gap sizes, weft-knit textiles are an unusual choice for the pure reinforcement of hardened concrete. However, weft-knit fabrics can be employed in concrete construction for the reinforcement of fresh concrete. In that case, weft-knitted structures are used as stay-in-place formworks, also dubbed KnitCrete.[66] Figure 3.2.4.1 below shows the basic structure and an example of a weft-knit textile.

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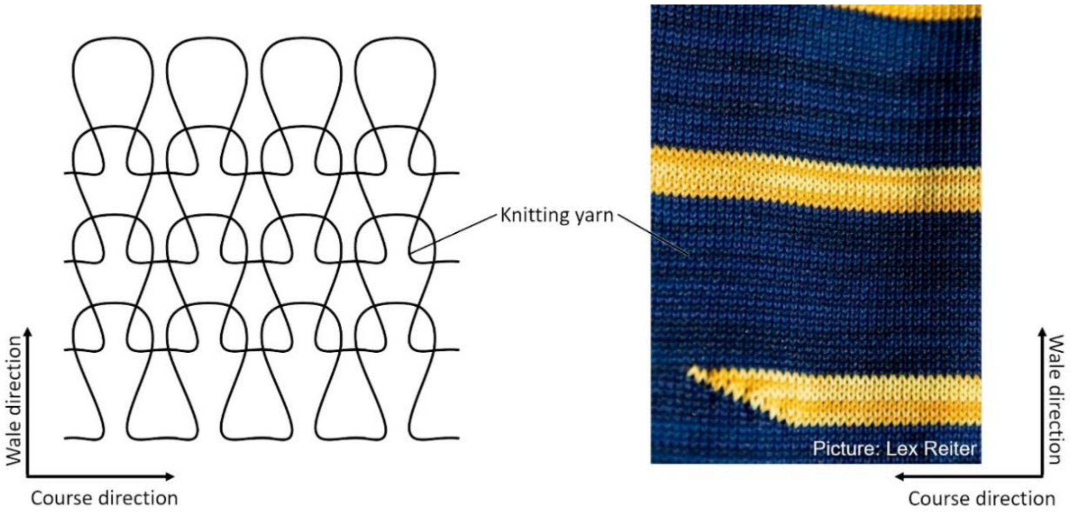

Figure 3.2.4.1: Basic structure and image of a weft-knit fabric utilized to reinforce fresh concrete (KnitCrete[66])

Utilizing double-bed flat-knitting machines, Popescu et al. produced several stay-in-place formworks for concrete structures.[66,233–236] Using a double bed machine enables the production of a weft-knit textile with two sides for different purposes. While one side has an aesthetically pleasing design (color/structure), the other side is used for the inclusion of reinforcing cables by providing anchoring points and hooks.[66] The distance between the two sides of the textile is adjusted by means of balloons.[66]

3.3. 3D textile reinforcement structures

3D textiles as defined in this paper offer textile reinforcement in all three spatial dimensions. This type of reinforcement is comparatively rare and has so far only been investigated in a few research projects. In the case of most TRC applications, various 2D textiles are combined to produce a 3D reinforcement since the production of 3D textiles is comparatively expensive.

One possibility for 3D textile reinforcement are 3D concrete-filled fiber-reinforced plastic branchings, which can be produced using a newly developed technological braiding process obtaining triaxial braidings. The utilized radial braiding machine is used to manufacture branched, knot-like, 3D textile structures with altering knot geometries and appropriated surface coverages, whereby the focus is also on adding continuous stationary reinforcing threads with an axial alignment coinciding with the normal force direction.[237] In comparison to plain concrete specimens as reference, the generated concrete-filled fiber-reinforced plastic knot structures show an enhanced load-bearing capacity through load-adapted fiber arrangements inspired by natural role models.[237]

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Picture: Matthias Egger

Picture: ITKE, University of Stuttgart

(a) 3D reinforcement embroidery
Institute for Design and Material Science
University of Innsbruck (UIBK)

(b) 3D reinforcement braiding
Institute of Building Structures and Structural Design (ITKE)
University of Stuttgart

Figure 3.3.1: Non-metallic 3D textile reinforcement structures with strengthening function in all three spatial dimensions[237,238]

Another possibility for the production of 3D reinforcement textiles involves technical embroidery. This process allows the controlled placement of yarns in any direction, enabling the production of load-adapted reinforcement.[238] The reinforcement yarns are embroidered onto a soluble carrier textile, which is subsequently removed. The structure is then spread out, coated and consolidated. Similar to spacer fabrics, the resulting textiles consist of two layers of reinforcement placed at a defined distance to each other. However, the distance is not controlled by using an additional yarn system, but by the reinforcement yarns themselves.[238]

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4. New developments in robot-supported manufacturing technologies for construction applications

Textile-reinforced concrete is gaining attention for its potential for producing geometrically sophisticated and complex structures in research and the construction industry.[239–241] Hence, its scope is increasingly being extended so that even geometrically sophisticated three-dimensional (3D) concrete components with free-formed outer shapes are reinforced with state-of-the-art manufacturing processes, e.g., the previously mentioned knitting, weaving and warp-knitting processes. However, in most cases, the production of these kinds of reinforcement structures is associated with a high level of waste, especially when reinforcement shows a complex, highly branched inner structure with gradual contours. The conventional textile manufacturing processes cannot offer a flexibly adaptable machine technology to easily modify the main textile reinforcement structure toward the preferred direction without time-consuming machine and process modifications as well as without rework.

Therefore, special robot-based machine technology paves the way for novel resource-saving and cost-efficient textile reinforcement structures. Von Zuben et al. developed six-axis robot technology which is capable of producing planar and grid-like reinforcements using freshly impregnated carbon fiber heavy tow (CFHT).[67] Even though presently, planar structures and two-dimensional (2D) component geometries can already be realized and are applied for 2D stress states, this robot-supported technology constitutes a crucial bridge toward complex multi-branched reinforcement topologies.[242–244] This technology is characterized by the fact that the robot manipulates the fiber placement tool and the workpiece carrier is stationary, as shown in Figure 4.1 (a).

Furthermore, there are even robot-support manufacturing technologies enabling the production of 3D reinforcement topologies according to the definition given above in Section 3c – 3D textile reinforcement structures. The 3D coreless filament winding technique is a translative cross winding technology enabling the fabrication of 3D trusses for reinforcement utilization by Minsch et al.[245–247] Initially, this technology was developed for the production of automotive operating materials in energy-reduced manufacturing processes.[248] The producible carbon fiber reinforcement structures have mechanically high-performance properties, though containing the winding elements within the fiber-reinforced plastic structure for the rest of the component's life. This production technology is usable for truss-like reinforcement structures of any kind and suitable for producing reinforcement structures with a focus on concrete construction components. In this case, an industrial six-axis robot handles the CFHT, whereas the workpiece carrier is fixed and only the fiber placement tool is working. The translative cross-winding technology processes freshly impregnated fibers (thermosetting resin) to simple spatial structures with no gradual fiber orientation.

Another novel production technology by Michel and Mechtcherine et al. is the winding technique by means of a winding core, which realizes simple, rotationally similar and shell-like fiber structures with no gradual fiber orientation.[71,249] This technology uses pre-impregnated CFHTs and it is applicable for concrete parts with a low degree of complexity as reinforcement cages. The six-axis robot technology is characterized by manipulating the workpiece carrier, as the fiber placement tool remains dormant, as shown in Figure 4.1 (b).[71] Here the solid and fluid media are located on the ground, which enables the free guidance of the workpiece carrier with the impregnated fiber structure increasing the degrees of freedom of the robot.

The manufacturing technologies in Figure 4.1 form the basic technologies in the robotic production of textile reinforcement structures, with a process difference in terms of yarn impregnation and a difference in the manipulation of the tool and workpiece carrier. In addition, other robot-assisted

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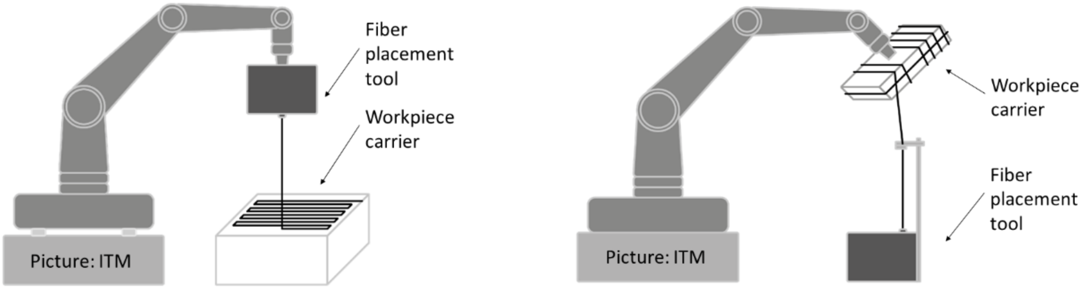
manufacturing processes exist for textile reinforcement structures, which are to be regarded as derivatives of the two basic technologies.



(a) Robot manipulates fiber placement tool
Technische Universität Dresden, Germany

(b) Robot manipulates workpiece carrier
Technische Universität Dresden, Germany

Figure 4.1: Classified robot production technologies for manufacturing textile reinforcement structures for concrete construction application[67,71]

A new approach of producing large-scale shell elements is the robotized production by means of collaboratively used robot systems, consisting of six-axis robots, drones and climbing robots (Research Pavilions; BUGA Fiber Pavilion 2019).[250,251] The manufactured 3D textile topologies have a membranous outer appearance exclusively using prepregs. Here, the workpiece carrier is fixed and the robots place the pre-impregnated fibers in gradual fiber orientation matching the load-adapted design approach of construction components. To date, this technology has been used for creative-architectural application within the construction industry rather than for the reinforcement of concrete. Even if this technology is currently applied to produce components with an architectural focus, the manufacturing principles can be analogically transferred to a production scheme for 3D textile reinforcement topologies with regard to concrete parts.

The robot-supported manufacturing technology needs to meet the requirement in order to provide3D textile reinforcement topologies with spatial branchings and a load adapted fiber orientation. In particular, the enhanced flexibility to place fibers with the use of six-axis robots must be taken advantage of in order to produce highly complex fiber structures, for instance in the use of textile reinforcements for corner areas, reinforcement cages or load-adapted design components.

5. Conclusions

Since the 1990s, high-performance textile materials have been investigated for use in reinforcing concrete components and the industrial applications are steadily growing.[252–257] Various types of textile reinforcement structures exist, which can at the most basic level be divided into 1D, 2D and 3D structures. For 2D reinforcements, an additional distinction is made between 2D and 3D shape.

In conventional concrete structures, the concrete accounts for by far the largest share of the global warming potential. If this share can be reduced, the greatest effect on sustainability is achieved in the overall balance.[9] For that reason, the ambitions of the research and the industries involved are to substitute steel reinforcements for concrete applications with tailor-made technical textiles. So, the first national technical approval published to universally regulate the procedure for reinforcing concrete with carbon-fiber warp-knitted reinforcement mats in Germany can be seen as an interim success. Textile reinforced concrete (TRC) offers several advantages in comparison to steel-reinforced concrete, such as corrosion resistance, which has a positive effect on the longevity of the reinforced concrete component. In addition, concrete consumption is considerably reduced as a result, since the thick concrete cover that would otherwise protect the steel reinforcement against corrosion can be reduced. This, in turn, has a positive effect on the environment because carbon dioxide emissions are reduced due to the lower cement consumption. In addition, the possibilities of diverse and creative shaping can expand the architectural design scope when TRC components with low thicknesses in the range of one to five centimeters are used.

Meanwhile, almost all common textile technologies have been scientifically examined or industrially used to pave the way for the concrete reinforcement of technical textiles. Manufacturing technologies such as wrapping, braiding, twisting and spreading for 1D textiles, warp- and weft-knitting as well as weaving for 2D reinforcement structures, and braiding as well as embroidery for 3D textile structures have the ability to reinforce specific concrete components in the construction industry. The review shows that technical textiles with continuous and non-crimped fibers (e.g., non-crimp fabrics) have higher load-bearing potential for reinforcing concrete components than technical textiles with ondulated fiber structures (e.g., woven and knitted fabrics). Possibly for this reason, technical textiles such as bi- and multiaxial fabrics (warp-knitting technology) have been more successful than warp-knit spacer fabrics, weft-knit fabrics and grid-like woven fabrics in industrial construction applications. Moreover, compared to the other technological textile manufacturing processes, the warp-knitting technology is significantly more productive regarding the production volume.[69] However, the full potential of technical textiles is not being fully exploited, as the currently used textile reinforcement structures predominantly reflect the steel reinforcements. There is more potential in TRC, especially for geometrically complex structures. The fibers need to be placed according to the main load direction of the final concrete component. Only if the fiber orientations correspond to the load direction the reinforcement is able to fully exploit its anisotropic material properties, especially the high tensile stiffness and strength. Potential utilization can be achieved in textile-reinforced concrete components by using load transfer mechanisms specifically in the area of non-straight trajectories or principal stress courses and consequently reducing local material usage due to reduced oversizing. Even highly productively produced conventional reinforcement textiles such as non-crimp fabrics can be postprocessed to generate load-adapted 3D textile reinforcement topologies. In order to meet the ever-increasing requirement for increasingly complex component contours in the construction industry as well as the demand for more efficiently produced and resource-saving textile reinforcement structures, further research is needed into innovative and flexible manufacturing technologies producing load-adapted 3D textile reinforcement structures.

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Developed robot-supported textile manufacturing technologies can already produce 3D textile reinforcement topologies with the characteristic of a membranous structure. These highly flexible robotic manufacturing processes show the potential to produce novel and innovative design approaches for material-minimized concrete constructions. Further development is necessary to take full advantage of TRC by robotically manufactured, biologically inspired textile reinforcements with spatially branched structures and according to a load-adapted fiber orientation throughout the whole textile reinforcement structure.

Thus, a key strategy to tackle cement-related CO_2 emissions is to minimize the use of cement and the efforts resulting from component transport as well as to enhance the concrete components' longevity by realizing textile-based and resource-saving concrete construction approaches. Already these novel design methods within the construction industry along with the appropriate textile manufacturing processes for textile reinforcement topologies have a high potential to manage one of the main drivers of the greenhouse gas carbon dioxide: the excessive global production of cement.

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Declaration of Conflict of Interests

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