Actual applications and potential of textile-reinforced concrete

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Abstract

Textile reinforcements for concrete members are mesh-like structures with fibres made of alkali-resistant glass or carbon. The main advantage of those reinforcements is – in contrast to conventional steel reinforcements – their non-corrosive behaviour, thus, reducing concrete covers significantly. Only 10mm - 15mm are necessary for a proper bond between textile and concrete resulting in member thicknesses of only 20mm - 30mm, which highly reduces material costs. By impregnating those textiles with epoxy-resin or styrene-butadiene-rubber tensile strengths of more than 3,000 MPa can be achieved in the concrete member, which is about five times higher than steel reinforcements. Furthermore, only with the impregnation it is possible to produce shaped and dimensionally stable reinforcements, which are already be used in an industrial scale in precast-concrete factories.

The paper presents the main properties of the high-performance reinforcements as well as actual applications of textile-reinforced concrete like façade and sandwich panels (from small-sized up to large-sized panels with an panel area of more than 12m²). Furthermore, applications for road and pedestrian bridges are presented as well as for modular buildings and precast-concrete garages. In Germany, for all of those constructions general technical approvals are in progress, which are also be describes within this paper.

INTRODUCTION

Due its versatile shaping, steel-reinforced concrete is considered one of the most important construction materials in the building trade. But in addition to the advantages – including a high load capacity and comparatively straightforward processing at low cost in addition to shaping – there is also a major disadvantage: The reinforcement is prone to corrosion. Concrete is highly alkaline and forms what is known as a passive layer on the steel, protecting it against corrosion. Substances penetrating the concrete from the outside (carbonisation) can lower the alkalinity over time (depassivation), so the concrete reinforcement steel loses its protection and the steel reinforcement starts to corrode. This leads to spalling of the concrete, reducing the permanency of the structure as a whole and leading to structural failure in extreme cases. Structures from the 1950s to 70s in particular are often at risk today, since the standards in effect at that time required far too little concrete coverage from today's perspective. As a result, the carbonisation front reaches the surface of the concrete reinforcement steel much more quickly. This is illustrated by numerous cases of damage over the last few years. The standards that are in effect today require far more concrete coverage in order to prevent corrosion of the reinforcement. According to current standards, the minimum requirement is 35 mm for exterior building elements, leading to an overall thickness of approximately 100 mm for facade cladding panels by way of an example.

If the concrete reinforcement steel is now replaced by non-metallic reinforcement, for example mesh reinforcement made of glass or carbon fibre, a thickness of only a few millimetres is sufficient to ensure permanency and a strong bond between the concrete and reinforcement. What is known as textile concrete makes it possible to produce facade cladding panels with a thickness between 20 and 30 mm, which saves up to 80 % in concrete. This has a direct impact on the transportation costs for prefabricated concrete components, which can be reduced by 80 % as well. Much smaller mounting elements are also sufficient for installation, which results in further cost savings.

Textile concrete is already being used in new construction today, and also to reinforce existing building elements. In addition to the fact that they are not susceptible to corrosion, glass and carbon fibre reinforcements set themselves apart in particular with their high strength which is up to six times higher compared to concrete reinforcement steel. The first section of this article describes the material characteristics that are most important for the building trade. In the second section, the current projects are described which illustrate the performance of these reinforcements.

CONSTRUCTION MATERIALS: TEXTILE REINFORCEMENT AND CONCRETE

Hair-thin filaments (continuous filaments) made of alkali-resistant glass (AR glass, ARG) or carbon (CAR), as shown in Figure 1 (to the left), form the base material for the textile reinforcements. They have a diameter between 5 and approximately 30 µm, depending on the material. From thousands to tens of thousands of these filaments are combined into what are called rovings. Then the rovings are processed into lattice-like non-woven fabrics on textile machines. Bundling the filaments with their small diameters causes microscopic hollow spaces to form between the fibres, so small that even the finest concrete particles cannot penetrate them. The concrete would only reach the outer filaments (blue area in Figure 1, middle), while the concrete does not reach the core filaments (red area). This means that only the outer edge filaments would absorb the load. The core filaments on the other hand remain free of strain, resulting in a very low load factor of only 30 to 35 % for the rovings.

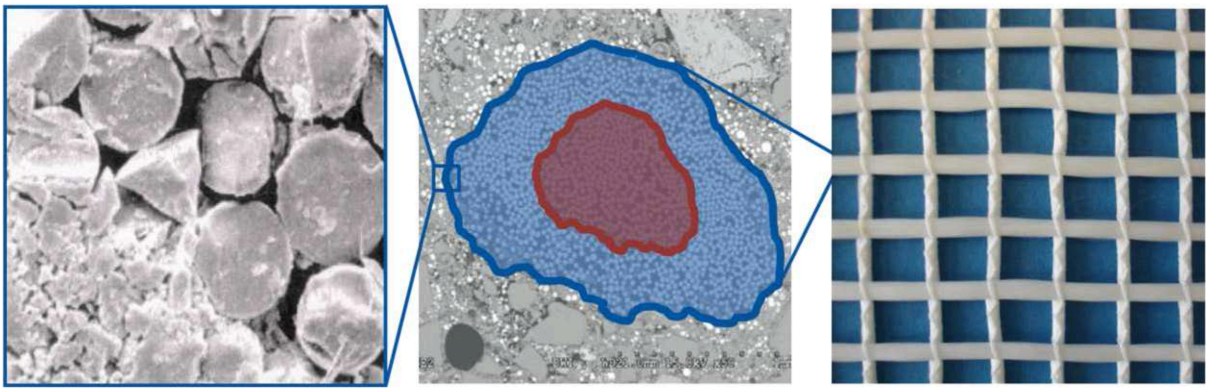
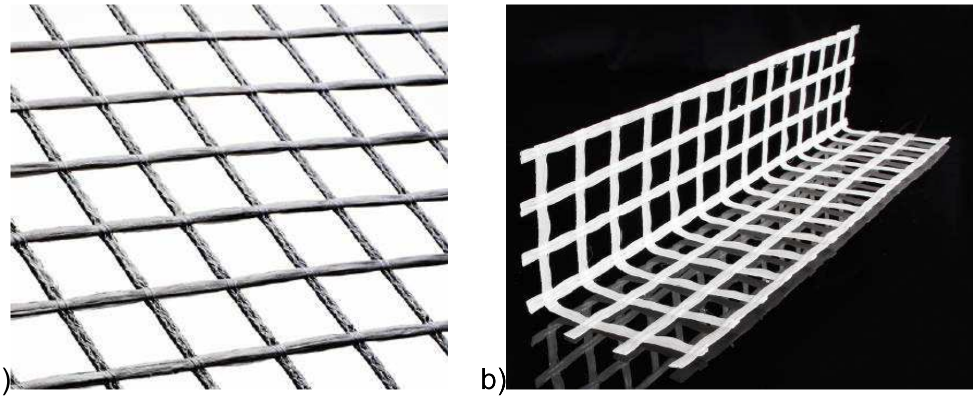


Figure 1. *Filament [1], roving [2] blue:outer filaments, red: inner filaments, non-woven fabric [1]*

To use textiles efficiently, they have to be impregnated. The impregnation mix is far finer than the concrete, can penetrate the core of the roving and is able to activate the inner filaments for load dissipation as well. Impregnation with epoxy resin (EP) or styrene-butadiene (SB) has proven particularly effective for improving the quality of the composite material. Impregnating the glass or carbon reinforcement therefore makes it possible to systematically achieve the required characteristics, such as tensile stress at break and permanency. In addition to the high tensile stress at break, epoxy resin impregnation is particularly well suited for the production of robust, dimensionally stable reinforcement (Figure 2a) – important factors for the workflows in prefabricated component plants and concreting. Furthermore, moulded reinforcements such as angles, U-profiles (Figure 2b) but also free-form curved surfaces can be fabricated exclusively with epoxy resin impregnates today. Moulded reinforcements are needed for numerous applications, for example soffits for facade cladding panels or land and web reinforcements for T-beam bridges.



a) b)

Figure 2: *a) Flat carbon textile (epoxy resin impregnate); b) Moulded reinforcement as L-angle (AR glass, epoxy resin impregnation); image source: www.solidian.de*

On the other hand, reinforcements that can be rolled up are frequently used for renovations as well. Roll-up reinforcements can for example be produced by means of styrene-butadiene impregnation. The table that follows provides a qualitative overview of the key characteristics of reinforcements with various fibres and impregnation materials. Additional characteristic values of the various reinforcements are listed in the application example in Section 3.

Table 1: *Key characteristics of reinforcements with various fibres and impregnation materials*

Characteristic	ARG/SB	ARG/EP	CAR/SB	CAR/EP
Tensile stress ([3], Figure 3)	o	+	++	+++
Concrete bonding behaviour ([3])	o	+++	o	++
Forms of reinforcement: flat / moulded	flat	flat / moulded	flat	flat / moulded
Handling	can be rolled up	inherently stable	can be rolled up	inherently stable
Inherent stability for pouring of concrete	-	++	-	++
Suitability for prefabricated components	o	+++	o	+++
Suitability for reinforcements	+++	++	+++	++
Cost per m²	+++	o	++	o

ARG/SB: AR glass fibres with styrene-butadiene impregnation
ARG/EP: AR glass fibres with epoxy resin impregnation
CAR/SB: Carbon fibres with styrene-butadiene impregnation
CAR/EP: Carbon fibres with epoxy resin impregnation

+++ Optimum characteristic
++ Very good characteristic
+ Good characteristic
o Average characteristic
- Not suitable

Figure 3 specifies the stress and strain behaviour of the four most common material combinations, based on tests with building elements. The tests in question are tensile tests performed on reinforced concrete tensile specimens. One can see that the level of tensile stress at break which is achieved depends on the combination of the fibres and impregnation material, and can be over 3000 N/mm². The stiffness on the other hand largely depends on the fibre material.

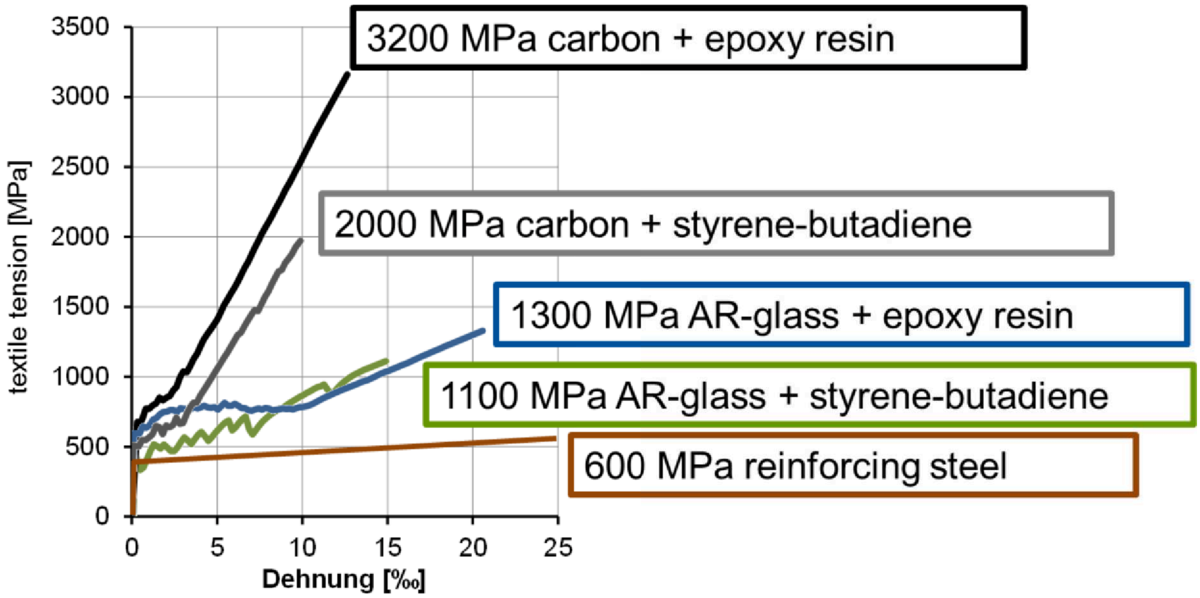


Figure 3: *Effect of impregnation on tensile stress at break: Comparison of different textile reinforcements (curves were determined on composite material (expansion mat) under tensile stress); data sources: [3]*

The opening width of the textile reinforcement is determined by the largest grain size of the concrete that is used. In particular in the casting process, the opening width must not be too small since a screening effect otherwise results, creating a separating layer in the building element. Today's textile reinforcements have comparatively large opening widths in excess of 30 mm. This means that special concrete known as fine-grained concrete is not required. Conventional, standardised concrete with a maximum grain size of 8 mm can be used in the casting process instead. A conventional formulation follows DIN 1045-2 [4] for example. No special approvals (case-by-case approval, general building authority approval) are therefore required for the concrete itself.

FIELDS OF APPLICATION

Thanks to their material characteristics, glass and carbon reinforcements are already being used in numerous fields of application in the building trade, for example as reinforcement for facades, sandwich elements and for bridge building. Generally possible fields of application are:

- Ventilated facade systems in small, midsize and large formats
- Sandwich walls
- Modules (e.g. garages, transformer stations)
- Storage units (tanks, silos and similar)
- Bridges (new construction and maintenance)
- Free-form surfaces
- Load-bearing shell structures
- Balcony slabs
- Building elements with high chloride exposure (e.g. parking garage ceilings)
- Maritime building elements
- Load-bearing structure reinforcements [5]
- Concrete remediation, sprayed concrete applications

In addition to comprehensive theoretical and experimental studies of the load-bearing behaviour and the use of textile concrete within the scope of the two special fields of research 528 (Dresden Technical University) and 532 (RWTH Aachen), which were subsidised over twelve years by the "Deutsche Forschungsgemeinschaft" (German Research Association, DFG), the innovative composite material has already been used successfully in numerous pilot projects. Performance and the suitability for practical applications have been proven. Projects in facade construction, bridge building and structural reinforcement have been realised to date [5]. In general, the use of carbon and AR glass reinforcements makes sense wherever lightweight, slim and durable building elements (thickness 10 mm and up) are required, or when transportation costs have to be reduced by using lightweight prefabricated components. High-performance reinforcements made of AR glass or carbon are also suitable when the conservation of resources in construction is a concern (see [6]), the standards for permanency are high or for building elements with a high exposure to chloride (for example structures in coastal areas, maritime structures, parking garages, bicycle/pedestrian overpasses and vehicle bridges etc.). In the non-load-bearing field, the construction of concrete furniture is another field of application for textile concrete.

A few select examples from facade construction and bridge building are presented in the following.

FACADE CLADDING PANELS

One example for a small-format, ventilated curtain wall can be seen on the health and education centre (GEBIZ) of the company Groz-Beckert in Albstadt (Figure 4).

Figure 4: *Small-format ventilated curtain wall in Albstadt (Baden-Württemberg)*

The slabs were produced by the company Hering Bau in formats up to 600 mm x 1200 mm. The epoxy resin impregnated AR glass reinforcement soligrid® Q120-GEP-38 was used (Figure 5, Table 2).

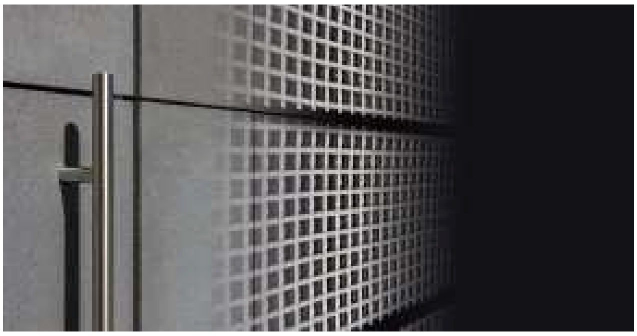


Figure 5: *Visualization of AR-glass reinforcement inside the panel*

Table 2: *Characteristics of the soligrid® Q120-GEP-38 reinforcement*

Characteristic		**Value**	**Unit**
Fibre material		AR glass	-
Impregnation material		Epoxy resin	-
Fibre cross-section	0° / 90°[1)]	121 / 121	mm²/m
Dimension between strand centre lines	0° / 90°	38 / 38	mm
Strand cross-section	0° / 90°	4,62	mm²
Tensile stress at break (average)[2)]	0° / 90°	1420 / 1533	N/mm²
Tensile stress at break (characteristic value)	0° / 90°	697 / 749	N/mm²
Tensile stress at break (rated value)	0° / 90°	465 / 499	N/mm²

1) The information 0° / 90° refers to the production direction of the reinforcement:
0° = parallel to the production direction
90° = perpendicular to the production direction

2) Average value from 20 samples

Around 370 of non-woven fabric was precisely cut to size in 1,660 individual mats by the company solidian, which allowed the workflows in the prefabricated component plant to be optimised. The result is a tremendously thin-walled facade construction with a thickness of just 20 mm, which is approved for wind loads up to 2.2 kN/m² [7], [8]. Similar to the installation of natural stone, the slabs are mounted with undercut anchors together with aluminium rails attached on the back (hanging profile system).

From an architectural perspective, a facade look with a reduced number of joints compared to small-format slabs is often demanded. One application example for this is the facade with a total area of approximately 400 m² for a restaurant building in the "SchieferErlebnis" park landscape, which was opened in 2014 in Dormettingen. A large-format ventilated curtain wall (Figure 6) with element dimensions of up to 1.5 m x 4.1 m and a building element thickness of 50 mm was used here. The epoxy resin impregnated carbon textile soligrid® Q140-CEP-38 (Table 3) was used as the reinforcement. A force of 200 to 230 kN/m (rated value) per running metre can be absorbed by the reinforcement, which approximately corresponds to the load-bearing capacity of a conventional Q524 concrete reinforcement steel mat ($_{,d}$=228 kN/m).

Based on the slab thickness of 50 mm, conventional fasteners for steel-reinforced concrete construction could be used. Facade cladding panels with a rated force of 6.75 kN were used in the upper section. The wind loads in the lower section are absorbed by two pencil-shaped wind pressure / wind suction safeguards.

Figure 6: *Ventilated curtain wall (SchieferErlebnis, Dormettingen)*

Table 3: *Characteristics of the soligrid® Q140-CEP-38 reinforcement*

Characteristic		**Value**	**Unit**
Fibre material		Carbon	-
Impregnation material		Epoxy resin	-
Fibre cross-section	0° / 90°[1)]	142 / 142	mm²/m
Dimension between strand centre lines	0° / 90°	38 / 38	mm
Strand cross-section	0° / 90°	5,42 / 5,42	mm²
Tensile stress at break (average)[2)]	0° / 90°	2621 / 2934	N/mm²
Tensile stress at break (characteristic value)	0° / 90°	2122 / 2428	N/mm²
Tensile stress at break (rated value)	0° / 90°	1415 / 1619	N/mm²

1) The information 0° / 90° refers to the production direction of the reinforcement:
0° = parallel to the production direction
90° = perpendicular to the production direction

2) Average value from 20 samples

SANDWICH ELEMENTS

The benefit of sandwich elements is the high degree of prefabrication, since complete wall cross-sections (supporting shell, thermal insulation, facing) can be produced in advance in a prefabricated component plant. Weight reductions can once again be achieved by reinforcing the facing with AR glass mesh, so that a thickness of just 30 mm is required for the external leaf. The internal leaf can be made of conventional steel-reinforced concrete, since minimising the concrete cross-section would not be productive due to buckling of the wall because of the high floor loads (Figure 7). The external leaf on the other hand, next to its net weight, is largely exposed only to horizontal wind loads which means it is mainly subject to bending stress. Calculating the bending load bearing capacity of the external leaf is based on familiar models from steel-reinforced concrete construction [3].

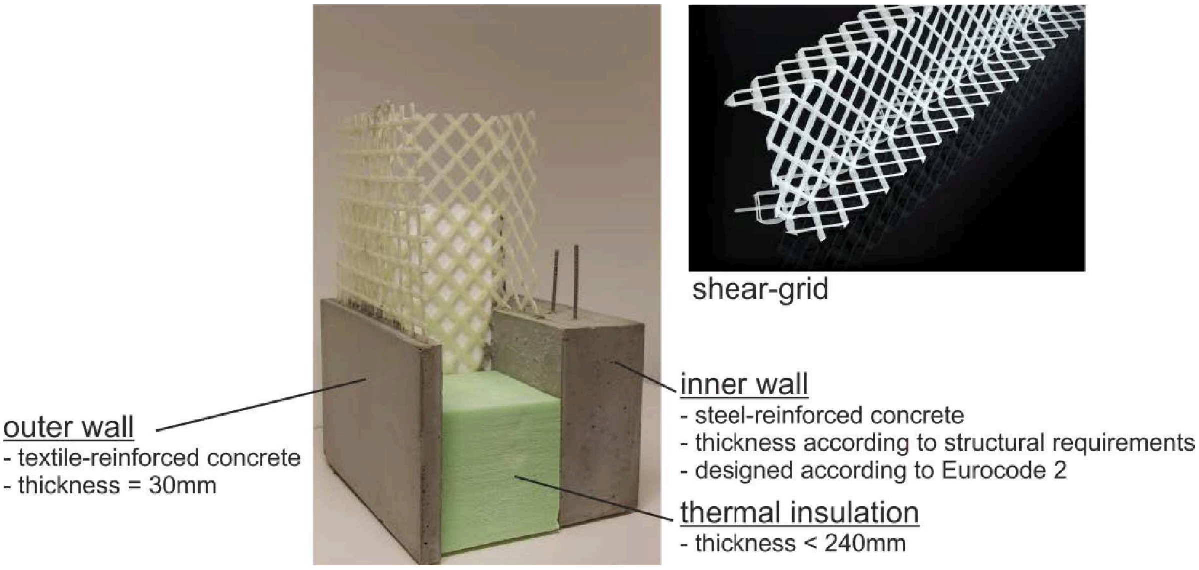


***Figure 7**: Sandwich wall with thin facing*

The internal and external leafs are connected by non-metal sliding lattice, which is made of epoxy resin impregnated AR glass fibres as well (Figure 7). Since the thermal conductivity of glass fibres is low, thermal bridging can be minimised in comparison with conventional connecting elements made of stainless steel and the thermal transfer of the entire building element is reduced. The straightforward installation of thermal insulation is another advantage: In contrast to single-point connecting elements where it is necessary to drill through the thermal insulation, this usually very elaborate process step is eliminated with the sliding lattice since the thermal insulation can simply be inserted between the sliding lattice sections (Figure 8).

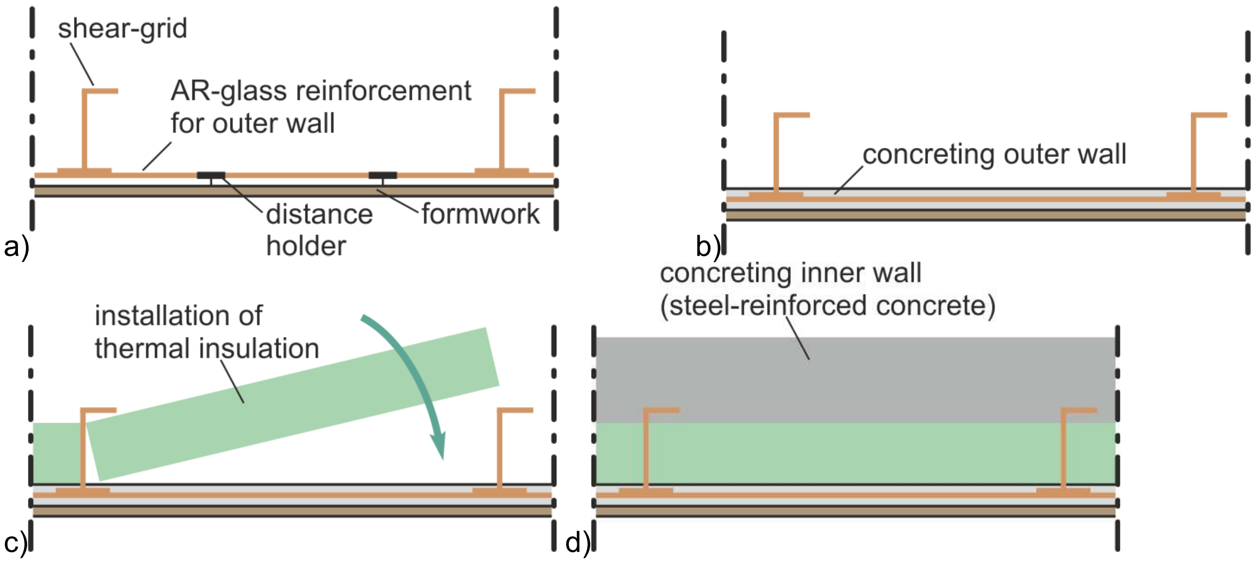


Figure 8: *Sandwich wall construction: a) Installation of the reinforcement (facing); b) Pouring concrete for the facing; c) Installing the thermal insulation; d) Pouring concrete for the supporting shell*

BRIDGES

Figure 9: *Pedestrian overpass in Albstadt*

The pedestrian crossing in Albstadt (Figure 9) with a length of 97 m is an example from the field of bridge building. The superstructure for the pedestrian crossing is made from prefabricated components and consists of six individual elements with a maximum length of 17.2 m. The span is 15.0 m. Through a combination of AR glass reinforcement and pre-stressing without lamination, a T-beam cross section with a height of 0.435 m and therefore a slenderness of 1:34 could be achieved (Figure 10). In addition to the bending characteristics, the AR glass reinforcement contributes to the transverse load-bearing capacity in the longitudinal direction of the bridge. In the transverse direction of the bridge, loads are dissipated exclusively through the AR glass reinforcement.

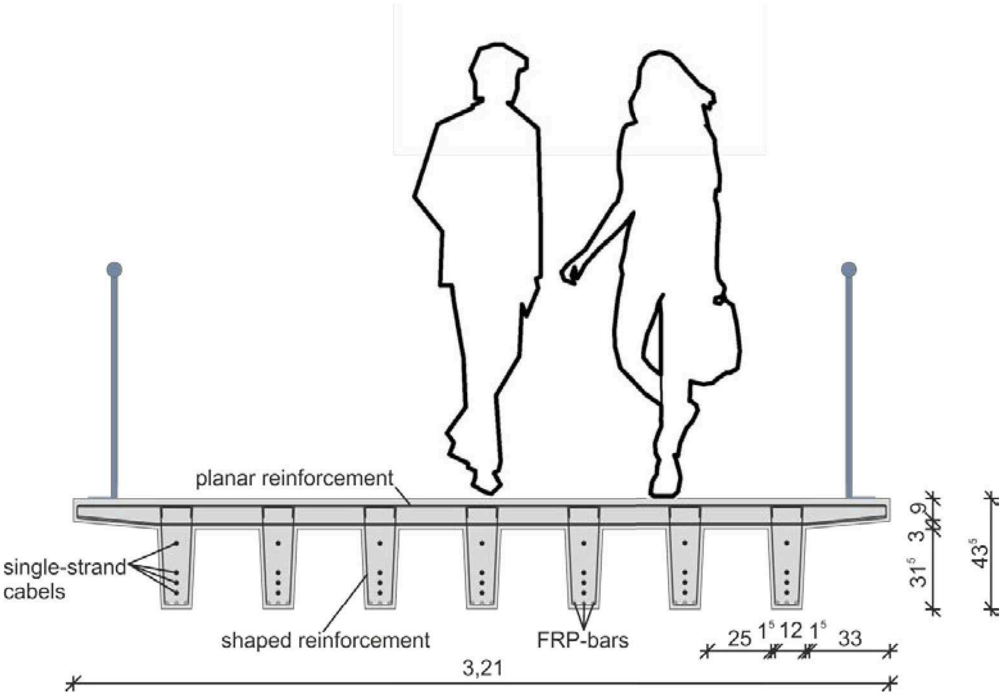


***Figure 10**: Cross-section*

The key benefit of this bridge construction is that the weight of the superstructure is reduced by approximately 40 % compared to the conventional construction method with steel/pre-stressed concrete. The bridge construction is also more permanent, since the reinforcement cannot corrode even if the exposure to de-icing salt is high.

INDUSTRIAL FABRICATION AND GENERAL BUILDING AUTHORITY APPROVAL

After research and development in the field of textile reinforcements was mainly conducted at universities in the form of fundamental research in the last few years, industrial enterprises are now positioning themselves to manufacture reinforcements made of AR glass and carbon. One such company is solidian GmbH, a wholly-owned subsidiary of Groz-Beckert, which is represented in the market since January of 2014. Representing virtually the entire value chain from dimensioning and application consulting to industrial textile production to after-sales service, solidian produces high-performance reinforcements made of AR glass and carbon filaments. The company develops, produces and distributes the innovative glass and carbon lattice structures under the brand name soligrid®. In addition to flat reinforcements, solidian has specialised in the fabrication of moulded reinforcements and even free-form surfaces.

To date, using building elements made of textile concrete for load-bearing components in Germany is only possible with approval on a case-by-case basis or with general building authority approval. This is why solidian is currently working on three general building authority approvals for which applications were submitted to the Deutsches Institut für Bautechnik (DIBt). One of these is for sandwich elements with a textile concrete facing in a thickness of 30 mm, which is reinforced with an AR glass mesh, and non-metallic sliding lattice for the connection between the internal and external leafs. This sliding lattice reduces thermal bridging on the one hand, which otherwise occurs when conventional connectors made of stainless steel are used. For another, the installation of thermal insulation can be significantly simplified as a result. The internal leaf is made from steel-reinforced concrete in the conventional manner, so that greater vertical floor loads can also be dissipated, and can be dimensioned according to DIN EN 1992-1-1.

The second approval application is for a garage made of prefabricated components with wall and ceiling thicknesses between 40 and 60 mm. Weight reduction is the primary motivation here, since reducing the thicknesses allows a weight of just 11 tons to be achieved so that two garages can be transported on a tractor-trailer without special permits. An application for a pedestrian crossing and bicycle bridges with a maximum span of 20 m, which is entirely free of steel, is being processed as well. Once again the reduction in weight makes it possible to use prefabricated components for construction. In particular, the fast exchange of old and new bridges is enabled when new structures are built to replace old municipal bridges.

SUMMARY

With textile high-performance reinforcements, the building trade has materials available to it today which are suitable for constructing thin, slim and lightweight concrete building elements which conserve resources and simultaneously exhibit high permanence. Since textile reinforcements made of AR glass or carbon do not corrode, concrete coverage can be minimised which results in weight reductions and material savings, in particular for exterior building elements. The use of textile reinforcements is also sensible wherever the structure is exposed to large amounts of chloride, e.g. parking garages, bridges and maritime structures. With an average tensile stress at break over 3000 N/mm², the field of application for the reinforcements is not limited to structural applications. They are also suitable as static load-bearing reinforcements in particular. Since textile concrete is not standardised, its application is regulated through case-by-case approval or general building authority approval today, which is currently in progress.

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