

The Application Potential of Textile-Reinforced Concrete

by H.N. Schneider and I. Bergmann

Synopsis: Textile-reinforced concrete (TRC) is a composite material taking advantage of non-corrosive nature of fiber materials such as alkali-resistant glass (AR-glass), carbon, or aramid for designing slender and filigree structural elements. Compared to short cut fibers, textile reinforcement provides a higher degree of effectiveness because the fiber bundles are arranged in the direction of the main tensile stresses. These properties make TRC a promising construction material suitable for a wide range of structural or cladding applications. The material can be produced in plate or panel form, or as a lattice structure, each of these forms requiring different production and connection techniques. This investigation aims at identifying appropriate applications for TRC. These include façade, housing, and load-bearing systems made using slender TRC elements. Geometric and structural modifications are necessary to improve the performance of thin-walled building components made of textile-reinforced concrete. Using selected applications, this paper outlines the main principles of component design in relation to type of load, method of production, and connection details.

Keywords: alkali-resistant glass fibers; application; carbon fibers; lightweight structure; precast concrete; textile-reinforced concrete

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RESEARCH SIGNIFICANCE

TRC is a new composite material which opens up new fields of application for concrete as a building material. In recent years, the most favored fiber reinforcement materials have been alkali-resistant glass and carbon. Their different material properties result in differences in the load-bearing behavior of the composite. These have to be considered when deriving applicable design methods for TRC-structures which are important for a successful application.

INTRODUCTION

The main structural and architectural design characteristics of textile-reinforced concrete are influenced by the type of material used for reinforcement, the load-bearing mechanism, the method of production and the connection detail applied. On the one hand, the use of AR-glass or carbon-fiber as reinforcement enables the construction of very thin-walled elements, just 10-30 mm (3/8"-1-3/16") thick. Different from steel-reinforced concrete there is no need to ensure a minimum cover over the reinforcing bars to protect against corrosion. On the other hand, the textile materials used for reinforcement are generally available as sheets which are easy to form and which can be adapted to the geometry of the element. When textile-reinforcement is used in combination with concrete matrices of high fluidity, elements with very free forms can be created.

The textiles that were used in this research are shown in Table 1. Some important properties of these materials are also shown. The performance and durability of AR-glass and carbon reinforcement differs. While carbon and aramid generally do not corrode within the concrete, AR-glass loses some of its strength due to long-term weathering (Orlowsky and Raupach 2006). In addition, the tensile strength of carbon is two to three times higher than that of AR-glass (Hegger et al. 2007).

Another key influence, however, is the production technique. The various production methods currently used lead to limitations with regard to the shape of elements, as they either exclude certain geometries or only permit certain degrees of reinforcement. For example the laminating technique, enabling very highly reinforced components with 15-20 layers of textile reinforcement, is much more restricted in terms of element geometry than other methods of production. Pouring offers greater freedom in designing shapes. However, this method only allows relatively low reinforcement ratios. Using the pouring technique, only three to four layers of textile reinforcement can be integrated into the cross-section, thus excluding its use in many load situations.

A good example here is the diamond truss which was constructed at RWTH Aachen University in February 2005 (Schneider et al. 2006). Only the pouring process was capable of producing the complex component geometry involved. Because the overall structure is a load-bearing frame that is generally only subject to compression forces, only two layers of reinforcement were needed in the elements. The diamond truss gives an example of an application in which load, production technique and form all fit together very well.

It is still easier to produce two-dimensional, level shapes in textile-reinforced concrete, a criterion that emerges from the reinforcing textile itself and from the method of production. However, flat, panel-like components are usable only in a very limited range of applications, as flat component geometry is not suitable for transverse loading conditions. Therefore, one concept in the development of applications and components is to modify or combine the flat geometric shapes in manners that enhance the performance of the component, in particular with regard to load-bearing.

The options for modifying these geometries can be divided into four categories as shown in Table 2. While profiling

elements is a technique applied on steel-reinforced concrete very effectively, it has to be considered that textile-reinforced concrete cannot resist tensile forces in a concentrated manner. Thus wide tension zones have to be integrated into the cross-section. The combining or adding of single components to larger elements, e.g. in combination with other materials as examined on sandwich panels, can lead to very promising applications. Folding and bending appear to be very appropriate modifications of the flat-shaped material in order to develop load-bearing structures. The textile reinforcement can suitably be applied in flat arrangements on these forms because of their broad tension zones. For some of these categories examples of application for textile-reinforced concrete are set out in the following.

APPLICATIONS OF TEXTILE-REINFORCED CONCRETE

During the last years we have been working on very different structural concepts in TRC, as shown in Table 3. The structures differ by form and load bearing behavior. The forms that can be realized might be planar, single-folded and curved or double-curved. Planar beams and sandwich panels represent section-active systems which are very common in building construction because of their ability to transfer load laterally without deforming (Engel 1997). Surface structures can be differentiated between being surface-active and vector-active. The former is interesting because of its most effective bearing mechanism, the surface being parallel to the direction of the acting force. The latter structures appear to be constituted by triangulation and they result in small vector forces. Finally we have started to examine the possibilities of segmentation and prestressing. For all structures we only consider to apply precast elements, since the fine-shaped components cannot easily be produced under common site conditions.

Cylindrical barrel shell: Already by the mid 20th century lightweight, prefabricated structural shells were used for roofs structures for industrial purposes. By folding and bending these shells it was possible to achieve a high load-bearing capacity and spans of up to 24 m (approximately 79'). When applying textile-reinforced concrete, surface structures are also indicated because of the material's properties. The simple folded-plate structure represents a combination of beam and roof covering with many different types of application. In the case of the long barrel shells the shell effect of thin concrete structures comes into play.

After examining barrel shells in a shallow form with spans up to 8 m (26' 2-15/16"), we have further optimized the structure with an almost semi-circular cross-section. Barrel shells with a length of 10 m (32' 9-13/16") were designed to span the distance of 7 m (22' 9-5/8") and to cantilever 1.5 m (4' 11") on both ends (Fig. 1). The element features a structural depth of 70 cm (2' 3-9/16") and a width of 1.74 m (5' 8-1/2"). When combined in roof structures, these elements can produce very interesting and attractive appearances.

The dimensioning process undertaken at the Institute of Structural Concrete at the RWTH Aachen University calls for six layers of AR-glass reinforcement. Along the lower edges, eight layers of a glass fabric having a cross-sectional area of 70 mm²/m (0.033 in²/ft) are required to bear the tension forces. Ten layers of glass fabric are required immediately above the bearings.

These very highly reinforced components with a semi-circular cross-section are to be produced by the shotcrete technique. A first section of the shell with the length of 1.5 m (4' 11") was built at the Institute of Building Materials Research, Aachen University, in order to examine the conditions for this production process. Each coating of 2 to 3 mm (1/16" to 2/16") thickness, consisting of one layer of glass reinforcement, was laminated on the cylindrical formwork (Fig. 2). The process was continuously controlled by using a gage. A first promising prototype was produced and the experience gained can be applied to longer structural elements (Fig. 3). The application of shotcrete will be an important production technique for numerous single and double-curved constructions.

V-section arched shell: If greater spans are required, the compression arch is a logical form to use. To ensure that the shell is as thin as possible and to avoid deformation or buckling under loading, an undulating, wave- or V-form cross-section is recommended. A fine example of a compression arch with a wave-form cross-section was erected for the parcel sorting hall in Munich in 1968 (Mokk 1968). The impressive structure spans 146.8 m (481' 7-1/2") with a structural depth of 2.75 m (9' 1/4") and a rise of 27.3 m (89' 6-13/16"). Prefabricated segments were joined together to create wide span arch members. The extremely favorable load-bearing behavior of the double-curved shell allowed the thickness to be reduced to only 8.5 cm (3-3/8"). The undulations are divided into two identical, almost flat elements. Regarding the view of the simplified manufacturing process and a minimum use of materials the structure is very much optimized.

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Following the same principles, a V-section arched shell with a span of 25 m (82' 1/4"), a structural depth of 52 cm (1' 8-1/2") and a crown height of 5 m (16' 4-7/8") requires a minimum material thickness of 2 cm (13/16"). The simple provisional dimensioning process calls for a double layer of carbon reinforcement (cross-sectional area of 220 mm²/m, 0.104 in²/ft) (Schneider et al. 2004).

The wave- or V-section arch is resolved into a polygonal form and assembled from almost flat, planar elements. The longitudinal joints should be reinforced and cast in order to ensure the necessary bending rigidity (Fig. 4). While the textile mesh extends beyond the edges of the building component, it is overlaid with a second reinforcement within the grouting cross-section (Fig. 5). The pre-jointing of for example five by six elements to form an 8.5 by 2.2 m (27' 10-5/8" by 7' 2-5/8") arch segment simplifies the assembly process on site. This construction system is characterized by great lightness in relation to large spans and is suitable for higher quality applications (Fig. 6).

Segmented, prestressed plates: In further considerations on the development of load-bearing structures in textile-reinforced concrete, we looked at breaking down the area of the component into segments. Smaller segments with an area of 1 to 2 m² (10.76 to 21.52 ft²) as shown in Figure 7 simplify the production process. The individual segments can be cast or injected vertically into closed formwork. These practical individual sections also offer advantages in terms of transport and assembly. To fit them together to form the larger structure, they are fastened to each other and prestressed by means of steel cables or carbon rods which also enables the load-bearing performance to be influenced.

A first successful application of such a segmented and prestressed structure is a little pedestrian bridge which was realized by a Collaborate Research Center at the University of Dresden (Curbach et al. 2006). The bridge is compound of ten elements with a weight of 500 kg (1102.3 pounds) each and a length of 90 cm (2' 11-7/16"). The construction spans the distance of 9 m (29' 8-5/16") and reaches only 20 percent of the weight in comparison to a similar steel-reinforced structure (Fig. 8).

In order to be able to put together structural plates like long barrel shells or shell arches from individual prefabricated elements, an even compression has to be achieved on the edges along which the sections are to be jointed by prestressing. For this, an even distribution of tendons in the cross-section is necessary so that no tension forces can occur along these edges in any load situation. For the initial design, thin tendons with a diameter of approx. 1.5 cm (5/8") were chosen and an outer diameter of the plastic sheath of 2 cm (13/16") (Fig. 9). A minimum of 6 cm (2-3/8") of concrete cross-section has to be planned for encasing this sheath. The prestressing tendons influence the geometry of the cross-section. Depending on the design of the component, it is possible to integrate the tendons. Alternatively, the tendons can be clearly traced on the outside or inside of the shells, or on both. At the ends of the tendons the concrete cross-section has to be increased up to 12 cm (4-3/4") in order to carry the anchorage forces. Thus the method of prestressing textile reinforced concrete structures generates a very specific form (Fig. 10).

Wave shaped beam and shell arch: For simply folded or curved roofing components the segmented ridged structural shell is one option for cross-section design. The 2 m (6' 6-3/4") wide, 45 cm (1' 5-11/16") high elements are compressed together by 4 tendons at their center of gravity. The concrete cross-section of 6 cm (2-3/8") needed for the prestressing can be integrated into the corrugated shape (Fig. 11). Towards the edges and at the high point of the shell, a thickness of only 2 cm (13/16") can be realized. Initial calculations by the Institute of Structural Concrete, RWTH Aachen University, show that two layers of AR-glass are necessary as textile reinforcement (cross-sectional area of 320 mm²/m (0.151 in²/ft)) with up to 5 layers being required for some areas under higher load (Fig. 12).

The double-curved shell arch has a high rigidity. At a rise of 35 cm (1' 1-3/4") the arch spans 12 m (39' 4-7/16"). The 14 elements have dimensions of 120 cm (3' 11-1/4") by approx. 90 cm (2' 11-7/16") (Fig. 9). Smaller edge elements take up the thickening for the prestressing anchor (Fig. 9). As with the corrugated shell girder, 2 to 6 layers of textile reinforcement are necessary. The thickness of the shell is 2 cm (13/16") increasing to 6 cm (2-3/8") at the tendons. The position of the tendons can clearly be identified on the bottom view. Tendons and grooves structure the shell surface. Thus, both segmentation and prestressing influence the design and articulation of the shell construction and that leads to an elegant double-curved example for these structures (Fig. 10).

Prestressing requires a higher material thickness due to the high compression force applied to the elements. In order to see whether it could be an appropriate principle for textile reinforced concrete further investigations should be taken.

Segmented spheric shell: Considering the complexity of doubled-curved prestressed structures, we tried to combine the advantages of segmentation with a load-bearing behavior that allows the textile reinforcement and screwed or adhesive joints to bear the occurring tensile forces. Heinz Isler, a Swiss engineer, successfully developed elegant wide-span structures with compression forces only (Ramm and Schunck 2002). Numerous shell roofings with minimal thickness and little steel-reinforcement were constructed as a whole on site. Jörg Schlaich also realized an impressive shell construction made of glass fiber reinforced concrete (GRC) at the Federal Garden Exhibition in Stuttgart (Fig. 13) (Schlaich and Menz 1977). For the production of the eight precast elements with a length of 15.5 m (50' 10-1/4"), a width of 10 m (32' 9-13/16") and a height of 5 m (16' 4-7/8") a fabrication on site was installed. The single constituents as shown in Figure 14 were jointed by grouting. The span distance of 30 m (98' 5-1/8") with a minimal thickness of 15 cm (5/8") led to a fine elegant example of light-weight shell structures (Fig. 13).

Following these principles, textile reinforced concrete can provide an opportunity to generate a similar elegance with precast elements. A spheric shell with outer measurements of 7.20 by 7.20 m (23' 6-1/2" by 23' 6-12") and a height of 3.25 m (10' 7-7/8") was designed at our Institute. We broke down the cupola into 36 segments in order to yield practical individual sections (Fig. 15). These offer advantages in terms of production, transport and assembly.

First dimensioning at the Institute of Structural Concrete prescribes a cross-section of 1.5 cm (5/8") thickness up to 12 cm (4-3/4") at the four bearings. An AR-glass reinforcement with a cross-sectional area of 210 mm²/m (0.099 in²/ft) is necessary to bear the tensile forces.

The formwork for nine single elements, which are repeated four times to form the whole, is CNC-milled. The production technique of shotcrete is to be applied. The edges of the elements are jointed by screwing, adhesion and grouting. Due to its complex geometry the joining technique and production of the double-curved shell structure is subject of further research work (Fig. 16).

SUMMARY

The applications of textile-reinforced concrete elements as described demonstrate that it is possible to create high-performance components using this innovative material. Forming and combining precast units yields a wide variety of component designs. The joining of the elements requires further research, in particular, when larger forces at the junctions have to be transferred. The free formability of the two material components – concrete matrix and textile fabric – has been utilized in number of applications. The diamond truss and plate structures linked by tendons are good examples demonstrating formability of the TRC material for creating complex shapes and component designs. To fully exploit the design potential of the textile reinforced concrete, fabrication techniques for producing TRC elements need further research and development.

ACKNOWLEDGMENTS

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REFERENCES

- Curbach, M.; Jesse, D.; Weiland, S., 2006, "Marktpotential Brückenbau – die erste textilbewehrte Segmentbrücke von der Idee bis zum Bauwerk," FBF Betondienst GmbH (ed.), *Tagungsband zu 50. BetonTage*, pp. 54-56.
- Engel, Heino, 1997, *Tragsysteme. Structure Systems*, p. 134, 172, 212.
- Hegger, J.; Voss, S.; and Bruckermann, O., 2007, "AR-Glass and Carbon Fibers for Textile Reinforced Concrete – Simulation and Design," ACI SP 244-4 *Thin Fiber and Textile Reinforced Cementitious Systems*, American Concrete Institute, pp. 57 – 76.

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Mokk, László, 1968, *Montagebau in Stahlbeton*, vol. 2, pp. 171-174.

Orlowsky, J. and Raupach, M., 2006, "Modelling the Loss in Strength of AR-Glass Fibres in Textile-Reinforced Concrete," *Materials and Structures (RILEM)* 39, No. 6, pp. 635-643.

Ramm, E. and Schunck, E. (eds.), 2002, *Heinz Isler, Schalen*, 3rd ed.

Schlaich, J. and Menz, W., 1977, *Glasfaserbeton-Schale auf dem Bundesgartenschau Gelände in Stuttgart*, Fraunhofer IRB Verlag.

Schneider, H.N.; Bergmann, I.; and Schätzke, C., 2004, "Leichte Betontragwerke," *Detail*, issue 7/8, 2004, pp. 844 – 854.

Schneider, H.N.; Hegger, J.; Schätzke, C.; and Voss, S., 2006, "Stabnetze aus Textilbeton," *Betonwerk- und Fertigerteiltechnik*, 72. Volume, No. 03-2006, pp. 34-40.

Table 1 — Examples of textile reinforcements

	Name	Material	Grid spacing [mm]/(in)		Areal weight [g/m ²]	Cross-sectional area [mm ² /m]/(in ² /ft)	
			0°	90°		0°	90°
	MAG_04_03	Carbon	8 (0.31 / 5/16)	8 (0.31 / 5/16)	400	105 (0.049)	105 (0.049)
	MAG_07_03	AR-Glass	8 (0.31 / 5/16)	8 (0.31 / 5/16)	400	105 (0.049)	105 (0.049)
	2D_02_06	AR-Glass	4,2/8,4 (0.16 / 0.33)	8,4 (0.33 / 5/16)	400	70 (0.033)	52,5 (0.025)

Table 2 — Categories of geometric modification of components

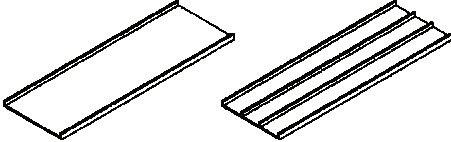
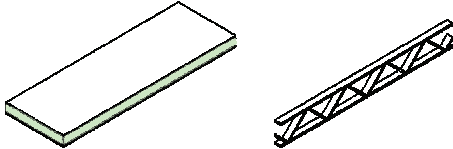
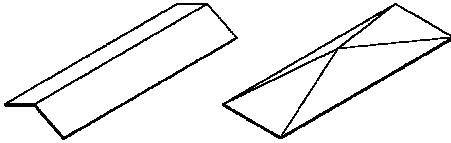
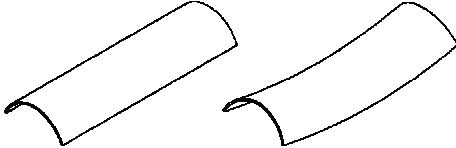
Component geometry	Category
	Profiling Left: simple Right: multiple
	Combining Left: composite Right: lattice structure
	Folding Left: simple Right: multiple
	Bending Left: simple Right: multiple

Table 3 — Examples of examined lightweight load-bearing structures

Form		Structure	Planar beam section-active	Sandwich section-active	Surface structure		Prestressed, segmented structure	Suspended structure form-active
					Folded plate surface-active	Lattice framework vector-active		
Planar	Uniaxial							
	Multiaxial							
Single folded/curved	Single folded							
	Single curved							
Double curved	Synclastic							
	Anticlastic							

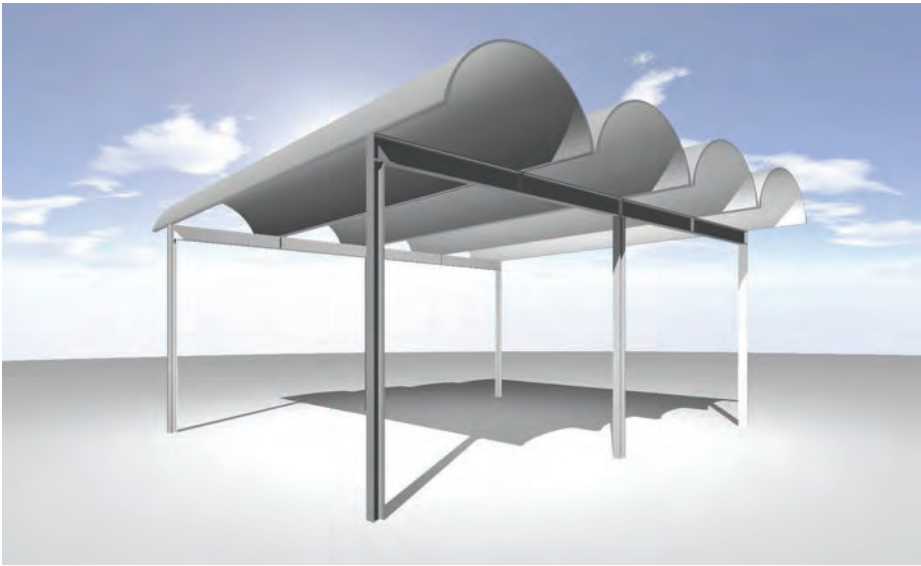


Fig. 1 — Semi-cylindrical barrel shell



Fig. 2 — Shotcrete applied on the semi-cylindrical barrel shell

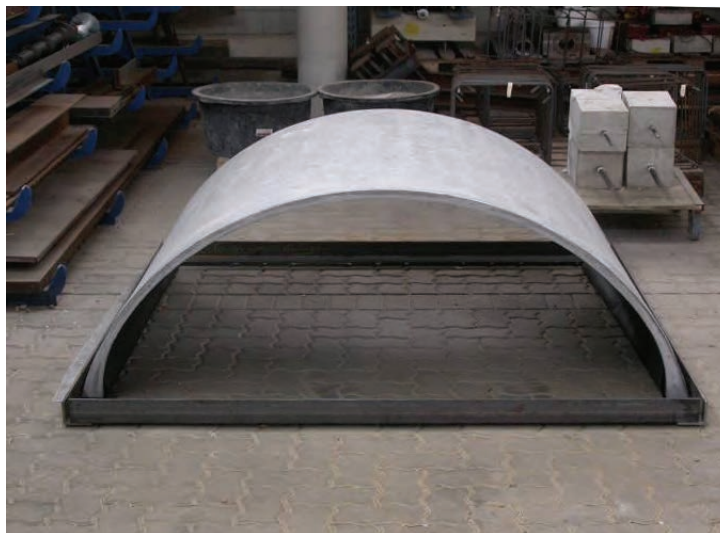


Fig. 3 — Prototype of the semi-cylindrical barrel shell

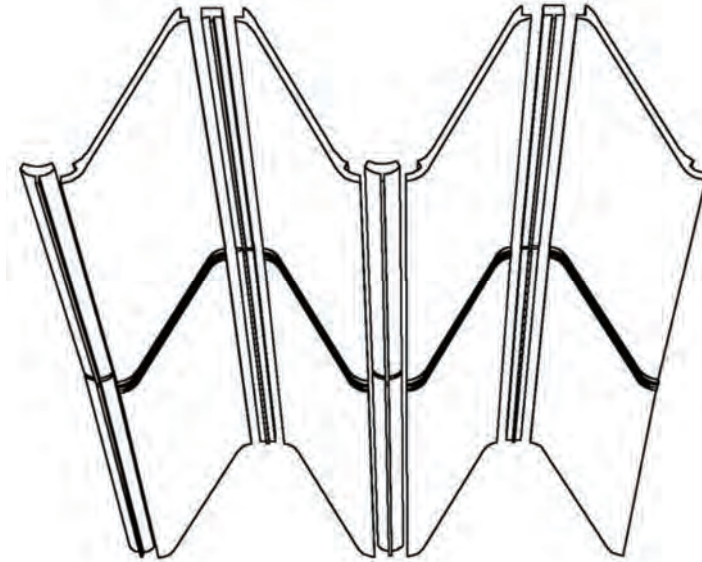


Fig. 4 — Exploded view of the grouted joints of the V-section shell-arch

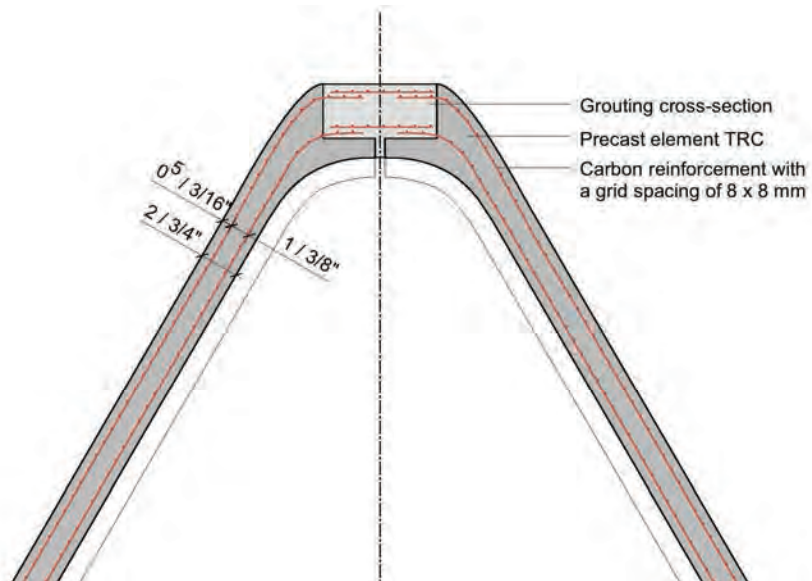


Fig. 5 — Detail of the grouted joints of the V-section shell-arch

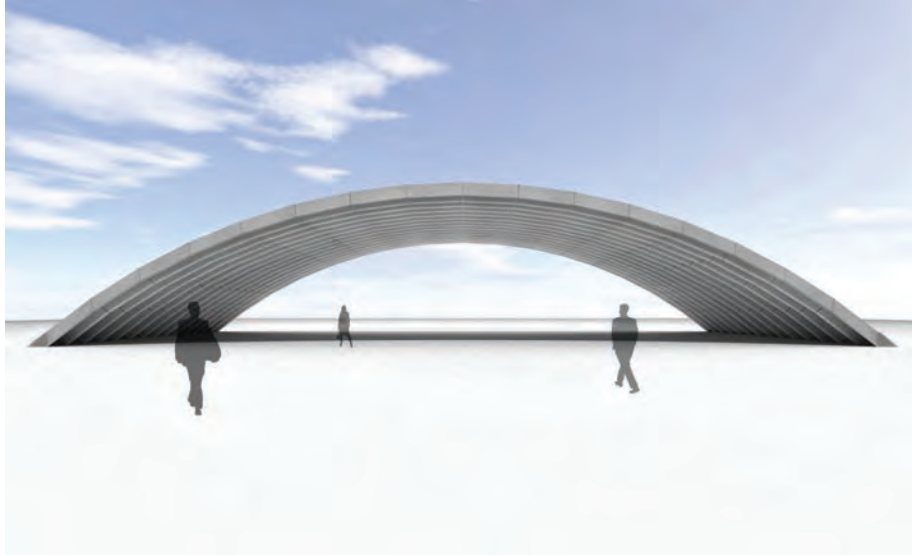


Fig. 6 — Perspective view of the V-section shell-arch

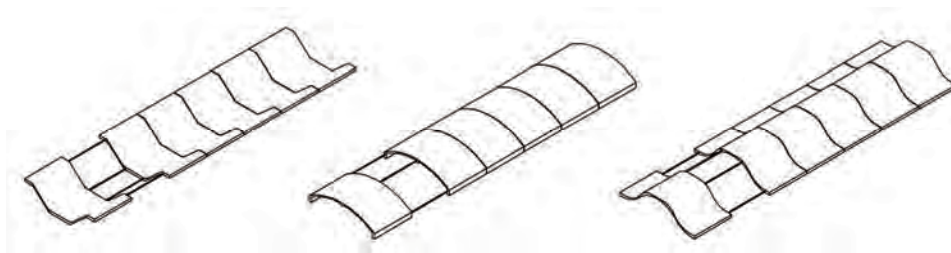


Fig. 7 — Segmented, prestressed girder shapes



Fig. 8 — Segmented, prestressed pedestrian bridge at the University of Dresden

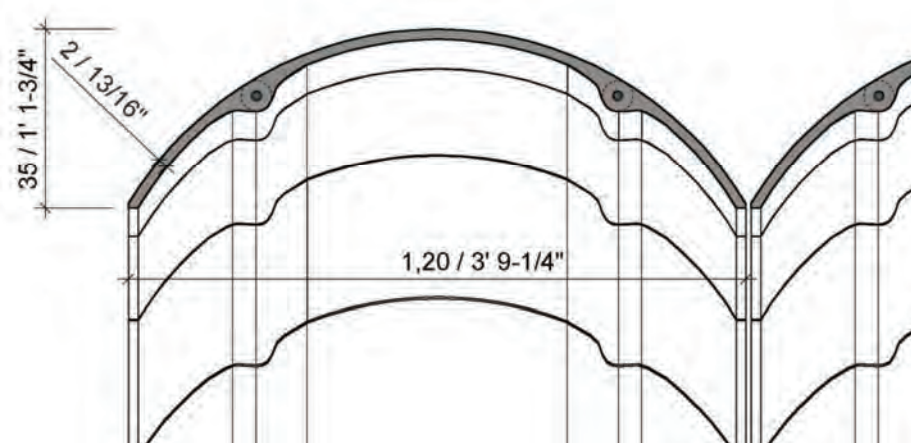


Fig. 9 — Details of the double-curved shell arch, segmented and prestressed

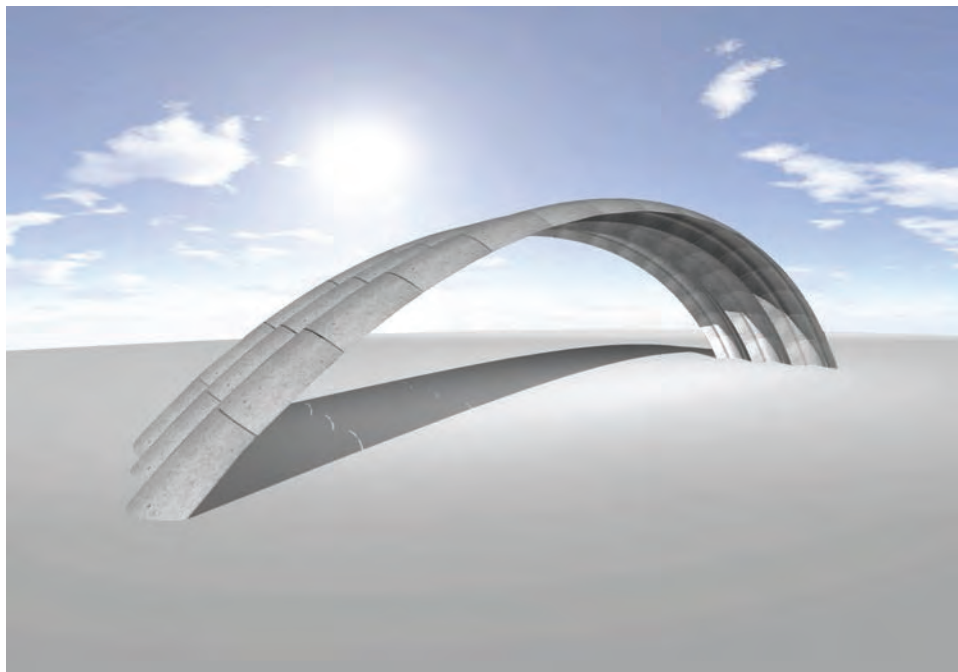


Fig. 10 — Perspective of the double-curved shell arch

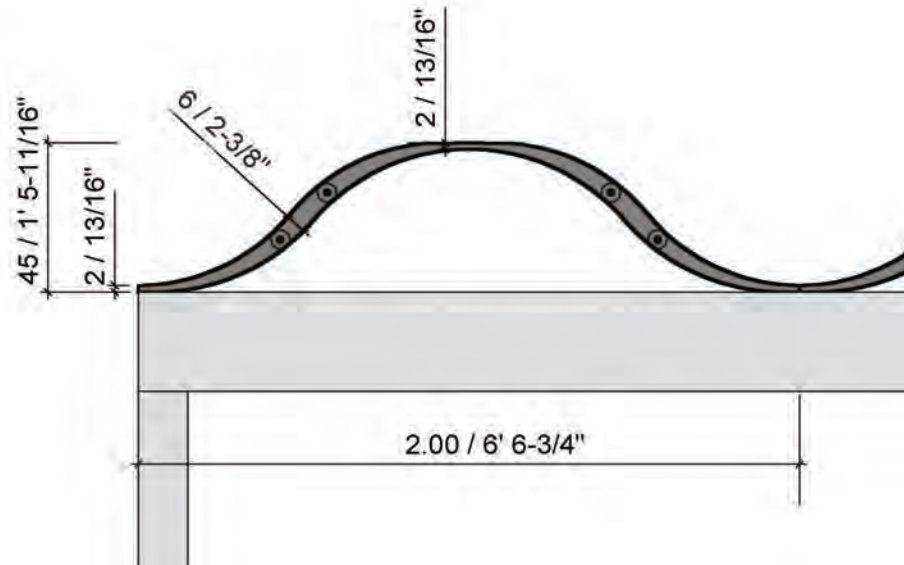


Fig. 11 — Details of the wave-shaped beam

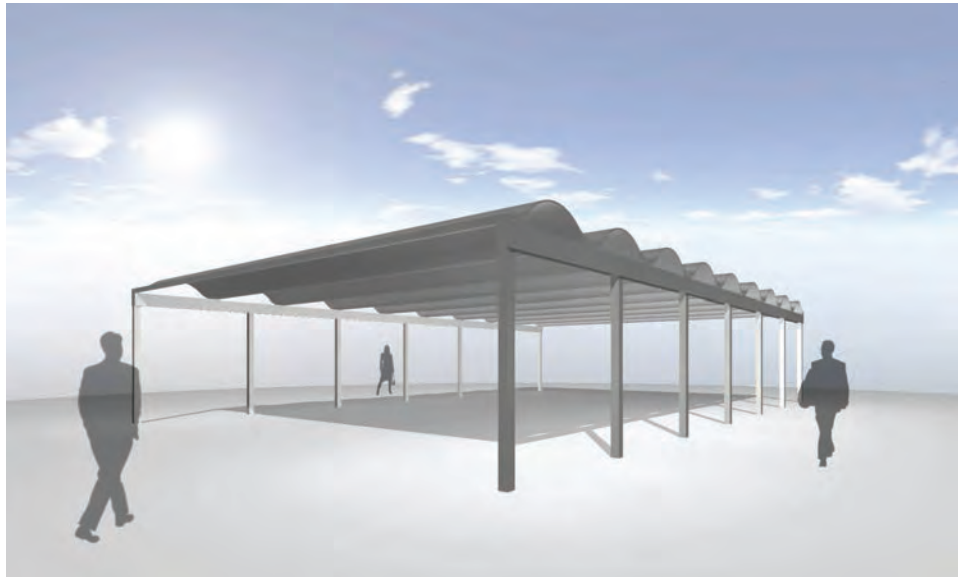


Fig. 12 — Perspective of the wave-shaped beam



Fig. 13 — Garden exhibition shell roof by Jörg Schlaich, Stuttgart 1977



Fig. 14 — One of the eight GRC elements by Schlaich during the assembly

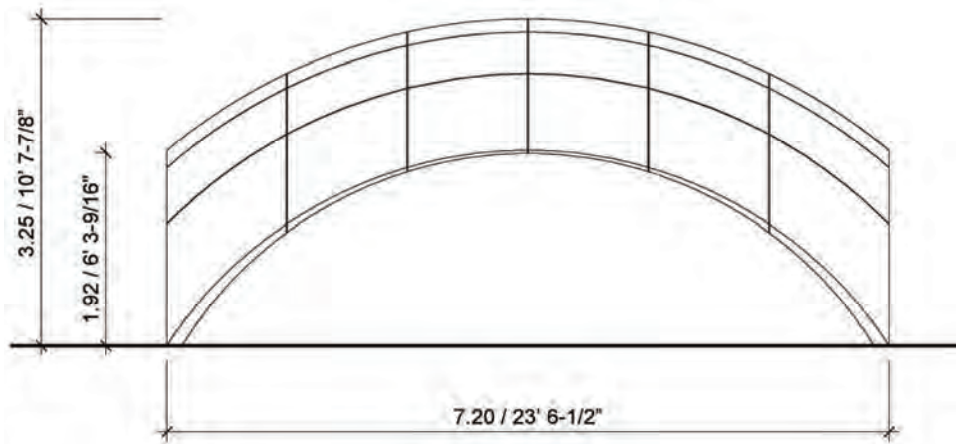


Fig. 15 — View of the segmented, spheric shell

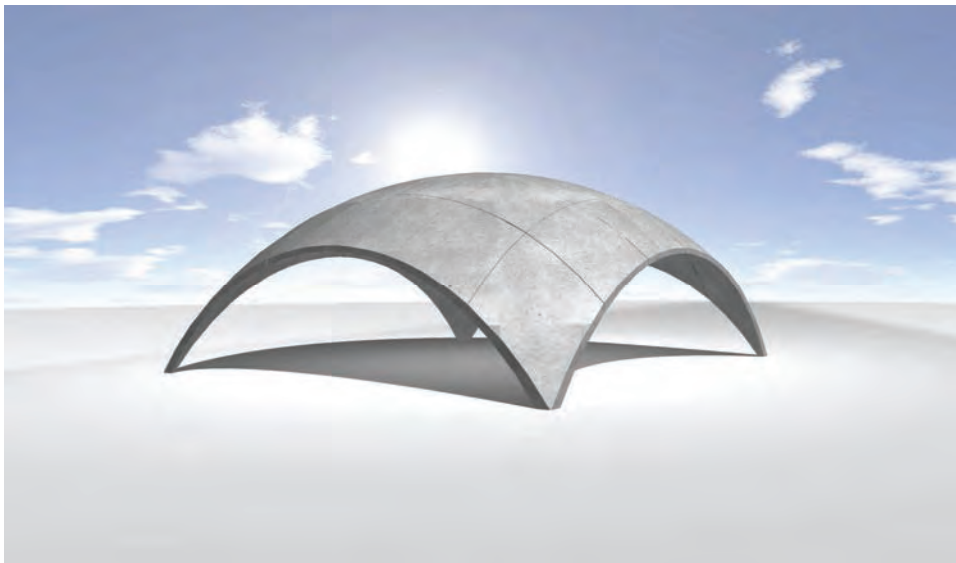


Fig. 16 — Perspective of the segmented, spheric shell

Possibilities of Textile Manufacturing for Load-Adapted Concrete Reinforcements

by A. Roye, T. Gries, T. Engler, G. Franzke, and C. Cherif

Synopsis: Incorporation of short fibers as reinforcement in concrete as popularly practiced at the moment provides only a low level of improvement in composite mechanical properties. The application of directed endless fiber reinforcement (i.e. textiles), so far utilized only in some limited special areas, has a high growth potential for use as reinforcement in concrete and promises several new fields of applications. In order to fulfil the reinforcement function, particular heavy-duty filament yarns are required in concrete composites. Their utilization in a multitude of possible applications can be practical only if prefabricated textile reinforcements with desired construction and properties can be manufactured efficiently. Modern textile production processes are now available with which extensive as well as spatial thread alignments in the production process can be implemented to produce novel textile reinforcement for applications in concrete. This paper provides an overview of the relevant textile formation methods for reinforcement textiles. A review of testing methods to characterize textile properties is also provided.

Keywords: technical textiles; textile-reinforced concrete; textile reinforcement

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TEXTILE FIBER MATERIALS

Commercial Heavy-Duty Filament Yarns

For the effectiveness of textile reinforcements, high fiber strength as well as a high Young's modulus are necessary, lying far above the one of the concrete matrix. If not, the rigidity of the composite would drastically decrease in case of crack formation. The choice of the textile reinforcement depends on whether the reinforcement material resists the alkaline environment of concrete in a durable manner and without losing its essential properties. As different fibers provide a particular creeping over the years, the properties especially the long-term properties have to be investigated properly. The fiber material must not only be inexpensive but also offer the required textile technological processability.

These requirements are particularly achieved by chemical fibers made of AR glass (alkaline-resistant glass, Figure 1) as well as those made of carbon (Table 1). These yarn types are commercially available as filament yarns, whereas regarding concrete reinforcement, yarn finenesses between 300 and 2500 tex (1 tex = 1 g/km) are applied. AR-glass filament yarns with sufficient tension strength show a slightly more convenient price performance ratio.

Determination of Filament Yarn Strength

In order to determine the stress-strain behaviour of filament yarns, two testing methods are available being fundamentally distinctive in the clamping of yarn samples and the covering of different application areas.

The test set-up with special sample holder (Figure 3) sensitively reacts to the properties of the filament-filament boundary surface and it can activate the compound properties between the single filaments [1]. It is technically easy feasible, free from subjective influences and it is especially suitable for the material characterisation and the quality monitoring of unprocessed filament yarn samples with a minimum length of 950 mm. With the help of the deployment of an external length changing detector a precise expansion measurement for the determination of e-modules is ensured.

The tension testing of yarn samples with resin bedding (Figure 4) is conceived for a free clamping length from 10 to 500 mm (0.39 to 19.69 inches) which are mainly applied with short manufactured fiber materials, being taken from

the prefabricated textile structure. With the help of this variant of power division it is possible to test yarns, whose textile character was for instance changed distinctively by a surface modification.

The cross-sectional area of the yarn for both testing methods is calculated by the gravimetrical determined filament yarn fineness and the yarn density, being measured in the hydrometer.

Special Combined Yarns

Apart from the already described chemical fiber yarns, combined fiber yarns are applied for reinforced textiles as well. According to the present state of technology, combined fiber yarns are mainly used as friction spinning fiber yarns. These yarns perform as a hybrid structure and they consist of different materials. Thus, the core of the friction spinning hybrid yarns consists of AR-glass or carbon filament yarn among others and the covering of a thermoplastic, as well alkali-resistant fiber material. The covering material can be added in a further production step causing a shape-retaining fiber structure.

Further combined fiber yarns are so-called co-extruded yarns. In this case, the core yarn is sprayed all over using a polymer. Co-extruded yarns do have a very plane surface, so that the compound to the concrete matrix is not very good. In order to increase the mechanical anchorage, additional spiral fibers can be wound around the drawn core yarn (Figure 5).

MANUFACTURE OF REINFORCEMENT TEXTILES

General

Reinforcement textiles for concrete products can consist of a face or a spatial structure. For both groups of reinforcement elements a multitude of textile plane generation procedures are available, with which a number of different requirements regarding the textile structure are feasible. Aside from the achievable structure properties concerning the method choice, the productivity as well as the expenditure for necessary adaptations of the machine and process guiding is relevant. Latter mentioned are caused by an inconvenient processing behaviour of applied heavy-duty filament yarns. At present, mainly non-crimped fabrics in connection with the knitting technique as well as the weaving technique are used. The opening width of grid-like textiles is adjusted according to the maximum particle of the fine matrix. They can amount from a few millimeters to several centimetres.

Non-Crimped Fabrics

Non-crimped fabrics result from the superimposed formation of several thread systems into several directions. The pre-non-crimped fabric systems are fit together to a plane by a material or tensional locked connection in the intersection points of the threads. The fixation of thread layers can also result from an additional binding yarn system. The designation of non-crimped fabrics is derived from the thread orientations. A differentiation of bi-axial as well as multi-axial non-crimped fabrics is usually driven.

With the help of the non-crimp technique, the thread material can be drawn exactly into the direction of the withstanding load [3]. This feature differentiates the non-crimped fabrics particularly from fabrics.

Furthermore, the thread lay mechanisms can be adjusted according to the particular product. A special variant is represented by the so-called round non-crimped fabrics (Figure 6). The thread layers of the round non-crimped fabrics are fixed by welding (ultrasonic welding) of a thermoplastic thread component [4]. For this purpose, a single thread layer with thermoplastic share is sufficient. The diameter of the non-crimped fabrics is determined by the diameter of the ultrasonic welding unit. Round non-crimped fabrics are for example applied for the reinforcement of hollow profiles (tubes, cable chutes). By slitting or recasting they are additionally suitable for plate-shaped component parts as well as for the reinforcement of t-profiles.

Warp Knitting

In warp knits, the textile face firstly consists of a mesh structure. The desired mesh structure can be formed by diverse bindings or markings. Thus, closed as well as much opened structures can be generated.

The possibility to integrate reinforcements into the textile by an additional thread input enables the manufacture of grid-like reinforcements, equalling the non-crimped fabrics with regard to their principal build-up (cf. non-crimped fabric). The single threads of one layer are arranged parallel to each other in a drawn way, like in the case of non-crimped fabrics. Normally, the special feature of biaxially reinforced textile structures is that all reinforcement threads are integrated in a mesh-oriented manner. For this purpose, they must be integrated in the moment of mesh generation.

With the same mesh generation method, pre-layed thread layers can be fixed (Figure 7). In contrast to the mesh-oriented input, the reinforcement threads are punctured partially [5]. This results in a 10% reduction of firmnesses of the concerned threads as well as a reduced drapeability, but a higher shifting stability, too. The application of the process, called “sew-knitting”, offers the advantage to consolidate up to 8 arbitrary-oriented thread layers to a multiaxial reinforcement (Figure 8). The integration of prefabricated textile fabrics is additionally possible. At the same time, the momentary most productive processing methods for open grid structures are available through the “sew-knitting technology”.

Moreover, special sew-knit technology disposes of warp racking devices. With their help, the reinforcement threads entering the machine can be positioned variably into the work flow direction as a yarn sheet or as an individual thread in transverse direction of the textile. Load-compatible thread-laying in the area of power flow points or breakthroughs in the textile face are thus feasible (Figure 9). The producible special structures are denominated as sew-knitted variable non-crimped fabrics.

The mesh-generation concerning the sew-knitting leads principally to a one-sided covering of the reinforcement threads, being arranged according to the warp yarns. Thus, different large contact surfaces are generated in-between the thread material and the concrete matrix depending on the warped flank. Current research results in connection with an additional material connective fixation (cf. solidification) of mesh as well as reinforcement threads show an increasing significance of this effect. For the generation of new mesh structures, enclosing the reinforcement thread, an approach described under [6] is taken up in current research projects. With the development of appropriate binding-technical as well as processing-technological solutions, basics for symmetrical non-crimped fabric alignments are created (Figure 10). This means that amongst others, reinforcement threads are integrateable into the work flow direction of the machine, both on the under-side as well as at the upper-side of the non-crimped fabric. Thus far, the manufacture of such structures at sew-knit machines is not possible.

Spacer Warp Knit Fabrics

For the processing of spacer fabrics the “double needle bar raschel technology” is used which is a special variation of warp knitting. Thus, two warp knitted surfaces can be manufactured simultaneously in a defined distance and be interlinked directly. Especially for the application as a concrete reinforcement, open gridnet like surfaces maintaining AR-glass or carbon is used [7].

With an adjustable thickness of the spacer fabrics between 20 and 160 mm (0.79 to 6.30 inches) three-dimensional reinforcement grids for concrete products such as sandwich boards can be produced efficiently. In this case, both surfaces are positioned near to the surface. The pile threads serve as an integrated distance holder. The producible hollow space can fulfil the function of additional rear ventilation.

In order to form contoured spacer fabrics, variable surface distances are feasible. This is possible due to the independent manufacturing of each surface. Thus, the surface structure can be arranged differently concerning different materials and different binding types as well as reinforcement fiber density can be chosen.

A further type of three-dimensional warp knit fabrics is available in the form of circular knits (Figure 13). Due to the circular knitting based on the knitting technology as well, hose-shaped textiles are producible and of interest concerning the reinforcement of cylindrical component parts [8]. Two-dimensional reinforcement textiles for tubular concrete component parts are applied as a spiral winding or in sections. According to this, the disadvantages lies in textile overlaps, limited component part length as well as restricted reinforcement directions. In contrast, the hose-shaped circular knits with drawn and optionally arranged fiber layers enable a load-compatible reinforcement of long tube strings. The diameter of the circular knits is determined by the size of the knitting needle bed and can be varied.

Woven Fabrics

For the reinforcement of concrete elements, mainly flat fabrics and partially multi-layer fabrics are applied, too. Conventional flat fabrics consist of two fiber systems, being arranged in a crossed, rectangular manner from the perspective onto the flat fabric. The crossing happens via shed formation of the fibers in the working direction of the machine (warp fibers). Using the open shed, cross threads (weft threads) are inserted. The shaping of crossings is called fabric binding. It can be formed multi-functionally and influences the fabric properties significantly. The binding furthermore decides how often a yarn is crossed at a certain length, too. The connection of warp and weft threads to define a textile structure is solely based on friction at the crossing points. An additional fiber system generating a mesh structure for the fixation of the reinforcement fibers does not exist.

Flat fabrics are utilised principally for the purpose of crack-width limitation of plasters. Furthermore, they serve as a reinforcement of foam plates, gypsum and wood elements as well as sound and thermal insulation elements in sandwich constructions. The used fabrics can be distinguished in half-cross leno and full-cross leno fabrics (Figure 14). For the on-site processing an additional stabilisation of the cross fabric is necessary by the treatment with a plastic matrix. This so-called handling optimisation (coating) simultaneously secures the resistance of the predominantly applied e-glass material to chemical influences.

The processing of filament yarns made of AR-glass or carbon turns out to be very difficult with the conventional weaving technology. In particular the high load of the fiber material regarding the shed formation leads even under the application of special laces to serious yarn damages in form of splicing and filament breakings. Differing from the conventional way to manufacture leno fabrics with leno heddles, a novel proceeding enables the shed formation by a system of rotating discs [9]. The principle of the disc turner simultaneously offers the advantage of manufacturing leno fabrics with much bigger lattice spacing. At the same time it succeeds to increase the shifting strength as compared with conventional leno fabrics, thus ensuring the manageability for subsequent process steps, as well without coating.

Multi-layer fabrics consist of several fabric layers, connected by binding yarns. With the help of these yarns the individual unidirectional layers can be kept at a fixed distance. The construction of the individual layers is variable and it can be constructed separately. Multi-layer fabrics are characterised by fiber systems in the three space coordinates. Concerning concrete reinforcement they have a rather low application potential.

Reinforcement of Sew-Knitted Fabrics

For a simple handling of sew-knitted non-crimped fabrics during the processing and for a complete use of the reinforcement function, the geometry of textile structures must be ease in handle and processing. This particularly affects reinforcement textiles which are to be applied for concrete curing. The necessary form stability requires an additional fixation of structures. This can generally be realised by bonding or coating as well as by thermo-bonding of inserted thermoplastic supporting structures or by laminating with thermosets (Figure 15). The required process technology has to be integrated directly into the processing technology (non-crimped fabric or knitting technology). The requirements towards layer geometry and arrangement of reinforcement fibers can be fulfilled in this way. If the solidification happened subsequently outside the machine, disadvantageous layer-shifting of reinforcement fibers would occur.

A further important aim concerning the stabilisation strategy is to activate all filaments in the yarn bundles by adhesive forces of the coating. The increase up to the utilisation of theoretical yarn strengths is ensured by test results with subsequently epoxyd-resin-immersed fabrics and non-crimped fabrics. The textile character of such reinforced structures mostly gets lost, caused by the high coating mass content of up to 30 weight-percent (Figure 16). The knowledge of current fundamental analysis regarding the fiber as well as the boundary layer optimisation is therefore based on aqueous dispersions (polymer dispersions on the basis of self-interlinking carboxyl styrol-butadiene-copolymer) with clearly poor coating shares [10]. Thus, it turns out that the filament's strength reserves can be mobilised with roughly 8 mass-% of this kind of coating in a very high dimension [11]. The knowledge being obtained at the yarn forms the basis for the stabilisation of reinforced textiles (Figure 17).

Both above mentioned aims can be realised by a coating solution integrated in the textile production process [12]. The online-coating of sew-knitted non-crimped fabrics simultaneously forms the basis for the adaptation of

reinforcements to later applications. Thus, the structure stabilisation can be designed for the reinforcement of spatial component parts in the direction of adjusted drapeabilities

Manufacture of Ready-Made Textile Reinforcements

Due to the defined working widths of the textile machine technology, the necessary textile widths for the building projects must be generated by online cutting shortly after the textile production process. Especially for the above mentioned sew-knitting technology, modular cutting devices developed for this purpose are available, enabling a pre-ready-made manufacture of variable structure widths without gradation. A cutting to size can also happen after the textile production process (offline).

The prefabricated manufacture, thus the cutting to size and assembling of textile structures to form-shaped semi-products, requires the development of novel joining techniques, because of the grid design. In principle there are two joining processes available for concrete applications: adhesive bonding by polymers and a mechanical bonding by sewing processes (e.g. one-sided sewing processes)

Textile Resting Methods

For a constructional application, reproducible textile properties must to be ensured. A precondition is thus the identification of the characteristic value at the textile. The development of adequate testing methods in conformity with the open, grid-like design of the reinforcements does not only serve as a monitor for the textile quality. It simultaneously offers a basis for further development and modulation regarding the textiles. Aside from the structure's rigidity, the quantitative evaluation of usability is of interest (Figure 18).

One possibility to measure the usability of textile reinforcement structures offers the testing of form stability (Figure 19). For the acquisition of form stability of technical textiles, techniques for the determination of drapeability (spherical workability without fold generation) are known. The usability of open grid-structures, however, can not be assessed sufficiently with the help of this testing method. The analysis of this construction-technologically relevant property is therefore used with the help of a particular, novel testing method for the determination of the shifting stability. The latter mentioned is based on the flat torsion of a layer-oriented fixation of the textile structure. With the help of supplementary equipment, translatory shiftings are realized and occurring forces are measured. The drag being resisted by the textiles against the twist as well as the shift is taken as a measurement for the shifting-stability. Structure-specific differences, resulting from binding, construction or adhesion properties can thus be represented differently.

Additionally, the bending behaviour is assessed for the evaluation of usability of reinforcement textiles. In this case an individually developed bending test method is applied (Figure 20). The vertical reference block placement enables a clearly better distinction of the bending behaviour in contrast to conventional test set-ups with a horizontal sample bearing.

CONCLUSIONS

The application of heavy-duty filament yarns as an alternative or in combination with conventional steel concrete reinforcements is only effective with a multitude of possible applications in form of textile solutions. Textiles provide "ready-made semi products" for the reinforcement. With the help of the textiles, the fiber material can be positioned easily in a reproducible way in the component part. An inexpensive production of reinforcement textiles with good properties enables the knitting technology with weft insertion. This technology provides biaxially as well as multiaxially oriented textiles. In future, the efficiency of these reinforcement textiles will be increased. Therefore it is necessary to design the textile according to the demands required in the building industry.

For the use of high-stability textiles in term of rough application, the coating of the textiles seems to be important. The solution of this task, a machine-internal coating technology is favoured on the one hand, enabling the regulation of coating-independent textile properties. On the other hand, the reinforcement as well as the connection fibers can be arranged more symmetrically by a novel textile production process. With the help of these textiles which are to be developed, the possibility exists to improve the load insertion in the concrete matrix.

The realisation of novel three-dimensional textiles traces particular applications, with which the textile construction of the component part geometry is adaptable. Apart from the reinforcement, the deformation behaviour of spacer fabrics represents a central point in the current developments. The aim is to ensure the positioning of the reinforcement in the component part. New approaches for the further development of 2D- and 3D-textiles reinforcement textiles emerge from the application of new fiber materials and of course from new applications in the building industry.

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REFERENCES

- [1] Abdkader, A., Offermann, P.; Jesse, F.; Curbach, M.: Textile reinforced concrete with AR glass filament yarns. In: Industrial Fabrics Bulletin (2003) 3, S. 50-54.
- [2] Kolkman, A.; Stockmann, P.; Al-Masri, A.; Gries, Th.; Wulfhorst, B.: Textilien zur Bewehrung von Betonbauteilen. In: Bauen mit Textilien 4 (2001) 2.
- [3] Waldmann, M.; Schierz, M.; Franzke, G.; Offermann, P.: Directional Dependent Yarn Tensioning Regulation for the Production of Multi-Axial Reinforcement Structures : 14th International Conference on Composite Materials. San Diego, CA, 2003 July, Paper 2194.
- [4] Gries, Th., Roye, A.: Dreidimensionale Bewehrungsstrukturen für dünnwandige Bauteile. In: Curbach, M. (Edt.): Textile Reinforced Structures. Proceedings of the 2nd Colloquium on Textile Reinforced Structures (CTRS2), Dresden : Sonderforschungsbereich 528, Technische Universität Dresden, 2003.
- [5] Hausding, J.; Engler, Th.; Franzke, G.; Köckritz, U.; Offermann, P.: State of the Art and Perspectives of Textile Reinforcements of Concrete Components : ACI Spring Convention, New York, 2005.
- [6] Schutzrecht DE 101 63 730 C1 (2003-10-09). Karl Mayer Malimo Textilmaschinenfabrik GmbH.
- [7] Roye, A.; Gries, Th.: Three-dimensional and online-shaped textile production with double needle bar raschel machines and weft insertion for concrete applications : ACI Spring Convention, New York, 2005.
- [8] Bischof, Th., Wulfhorst, B.: Rundgewirke mit multiaxialen Stehfäden für neue Anwendungsgebiete. In: Technische Textilien 42 (1999) 2.
- [9] Stockmann, P.; Wulfhorst, B.: Dreidimensionale Textilien zur Bewehrung von Betonbauteilen. In: Konferenz-Einzelbericht: Textilbeton, 1. Fachkolloquium der Sonderforschungsbereiche 528 und 532, Aachen, 2001, S. 45-57.
- [10] Gao, S. L.; Mäder, E.; Abdkader, A.; Offermann, P.: Sizings on Alkali-resistant Glass Fibers: Environmental Effects on Mechanical Properties. In: Langmuir 19 (2003) 6, pp. 2496-2506.
- [11] [Offermann, P.; Köckritz, U.; Abdkader, A.; Engler, Th.; Waldmann, M.: Anforderungsgerechte Bewehrungsstrukturen für den Einsatz im Betonbau. In: Curbach, M. (Edt.): Textile Reinforced Structures. Proceedings of the 2nd Colloquium on Textile Reinforced Structures (CTRS2), Dresden : Sonderforschungsbereich 528, Technische Universität Dresden, 2003.
- [12] Köckritz, U.; T.; Franzke G.; Waldmann, M.; Offermann, P.: The Sustainable Structural Stabilisation of Open Grid Warp Knits. In: 11th International Conference on Composite / Nano Engineering (ICCE-11). Hilton Head Island, South Carolina, 2004 August.

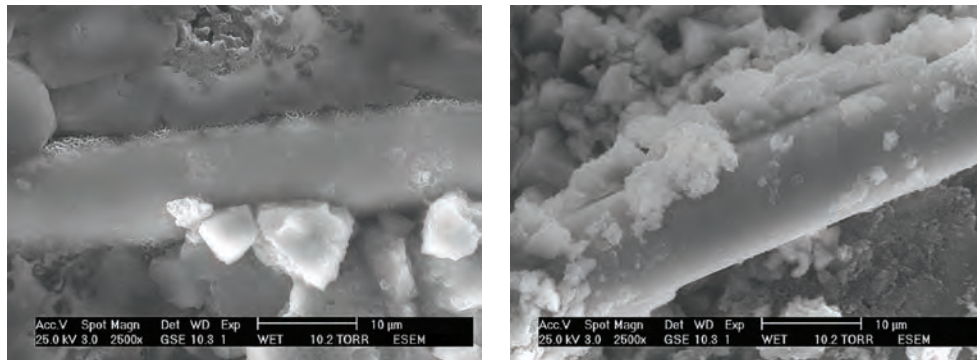
Table 1: Yarn Characteristics

Yarn Name	Producer	Fineness [g/km] *	Diameter of fibers [μm] *	Amount of fibers [tex]	Strength of fiber [N/mm²] **	Strength of yarn [N/mm²] **	E-Modulus of yarn [kN/mm²] **
Alkali-resistant glass yarns							
AR310S-800/DB	Nippon Electric Glass, Japan	310	13.5	800	2271	990	80
AR620S-800/TM		620	13.5	1600	2079	1051	81
AR1100S-800/TM		1100	16	2000	2061	574	81
AR2500S-800/DB		2500	24	2000	1574	444	77
LTR ARC 320 5325	Saint-Gobain Vetrotex, Spain	320	14	800	1892	1409	75
LTR ARC 640 5325		640	14	1600	1917	1372	71
LTR ARC 1200 5325		1200	19	1600	1936	1315	73
LTR ARC 2400 5325		2400	27	1600	1710	1210	72
Carbon filament yarns							
Tenax HTA 5131 400	Tenax Fibers GmbH	400	7	6000	3071	1566	211
Tenax HTS 5631 800		800	7	12000	3070	1125	217
T300JB-6000		396	7	6000	kein Test	1266	203

* Data from producer

** Practical test results from "Institut für Textil - und Bekleidungstechnik der TU Dresden"

Unit Conversions: 1 N/mm² = 145.03 psi; 1 kN/mm² = 145.03 x 10³ psi1 μm = 3.93701 x 10⁻⁵ inches; 1 tex = 1 g/km



(a) Significant damage of E-glass after 6 weeks

(b) No damage at alkali-resistant glass type after 1.5 years

Figure 1: Different behavior of glass filaments in portland cement matrix



Figure 2:
Yarn finenesses

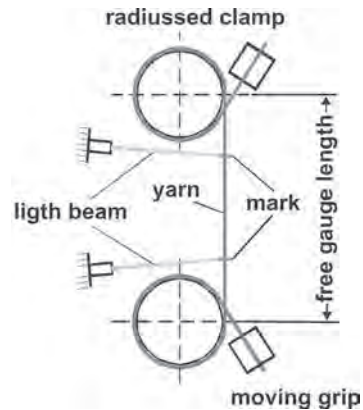


Figure 3:
Layout of test equipment



Figure 4:
Embedding in resin



Figure 5:
Cabled yarn

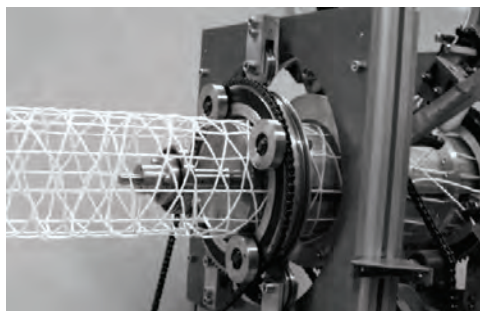


Figure 6: Production of circular textiles

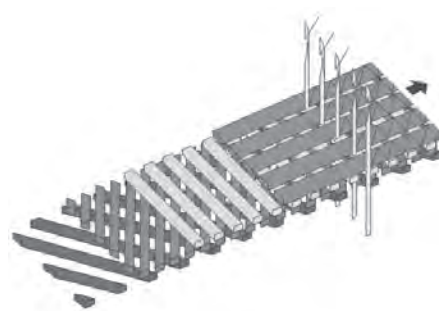


Figure 7: Multi-axial multi-ply fabrics

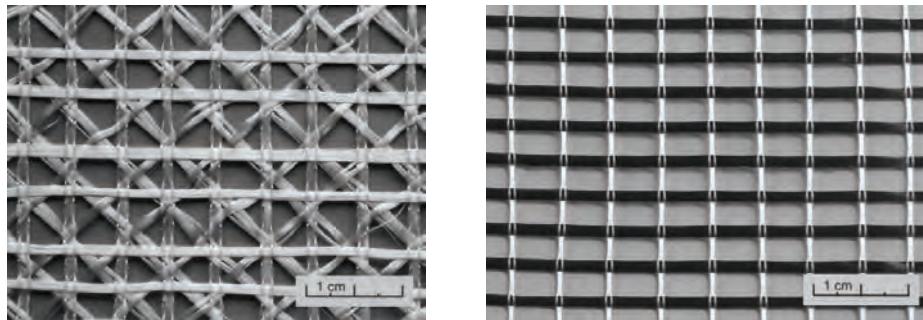


Figure 8: Examples for sew-knitted textiles

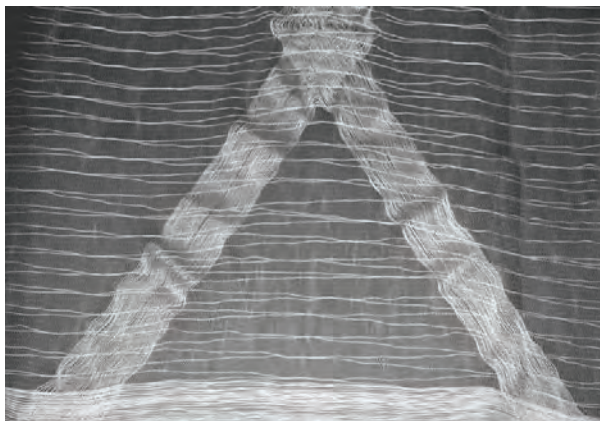


Figure 9: Sew-knitted fabric with local reinforcement for a triangular shaped concrete element



Figure 10: CAD model of a warp knitted textile structure

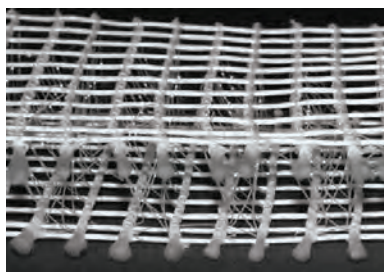


Figure 11: Spacer fabric with constant surface distance

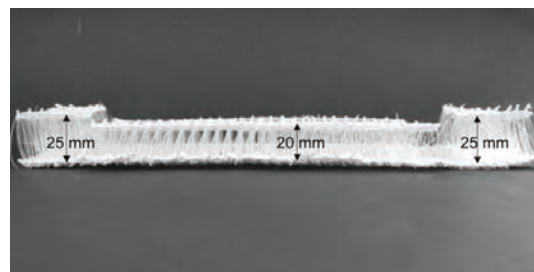


Figure 12: Spacer fabric with varying surface distances

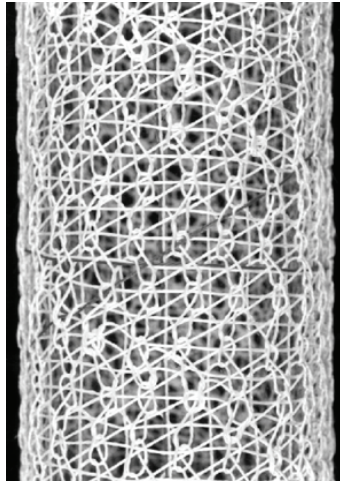
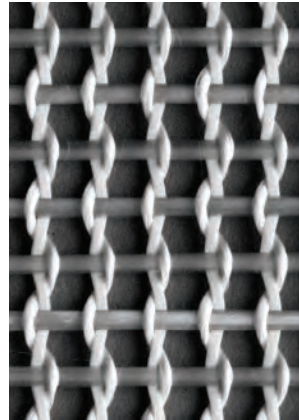


Figure 13: Circular knit with weft insertion, diameter 80 mm



(a) $\frac{1}{2}$ turn / weft



(b) 4 turns / weft

Figure 14: Leno woven structures

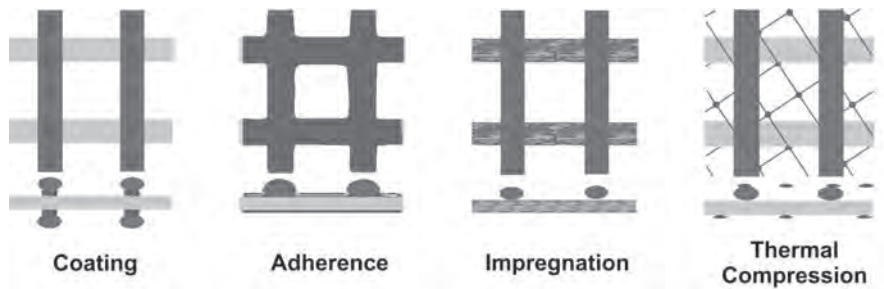


Figure 15: Processes for fixation of grid net-like textile structures

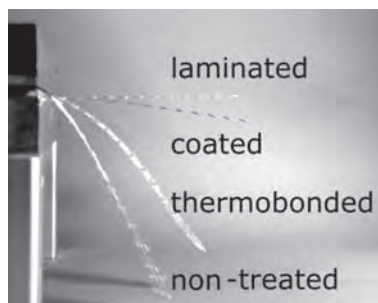


Figure 16: Bending behavior of coated structures



Figure 17: Example of industrial used coated reinforcement textile



(a) Retrofitting of steel-reinforced concrete piles by textile-reinforced concrete



(b) Realization of curved surfaces

Figure 18: Practical uses of textile reinforcements



Figure 19: Determination of handling behavior

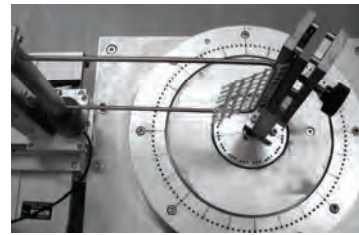
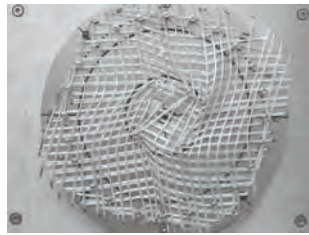


Figure 20: Investigation of bending behavior

Integrated Formwork Elements Made of Textile-Reinforced Concrete

by W. Brameshuber, M. Koster, J. Hegger, and S. Voss

Synopsis: The aim of this research project was to develop a textile-reinforced concrete ceiling board that remains as part of the ceiling after completion. The lost formwork element was designed to carry the load of a 200 mm (7.87 inch) thick layer of fresh concrete. The influence of different reinforcement textiles was examined. The load bearing capacity and the serviceability were investigated by 4-point bending tests. The bond to the top concrete layer was examined by bending tests carried out on composite beams consisting of the formwork element with a top concrete layer. To test the load-bearing capacity when the element is used as part of a one-way spanning slab, composite slabs of three formwork elements with steel-reinforced top concrete were cast and tested. The resistance to fire of the integrated formwork elements was investigated by conducting standardized fire tests. The results from this investigation demonstrate that the developed textile reinforced concrete formwork element successfully achieved the designed load-bearing capacity and serviceability requirements.

Keywords: ceiling boards; integrated formwork elements; textile-reinforced concrete

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RESEARCH SIGNIFICANCE

Due to its specific properties the new composite material textile reinforced concrete opens new fields of application. One possible application consists in the use of component integrated formwork elements. The serviceability of the developed formwork elements is demonstrated by several tests. The main results of these tests are represented.

INTRODUCTION

A considerable proportion of the total costs in concrete construction is attributable to the labor cost for set-up and shuttering work which traditionally consists of erecting a plywood sheeting supported by a stiff scaffolding that has to be removed after hardening of the concrete. The expenditure can be significantly reduced by using a formwork, which becomes part of the structural member (also commonly referred as “lost formwork”) and therefore dismantling later on is superseded. Formwork elements made of textile reinforced concrete are particularly suitable for this purpose since they can be produced with a significantly reduced wall-thickness as compared to steel-reinforced concrete where a certain concrete coverage thickness of the steel is needed to prevent it from corrosion. For this reason they are comparatively lightweight and can be laid by hand or with the aid of light hoisting devices. In contrast to traditionally cast components whose surfaces often do not fulfil the contractor’s requirements the pre-fabricated formwork elements have by default the quality of fair-faced concrete. A subsequent treatment of the surface is not needed which further reduces the total costs. Further on the fine grained concrete usually used for the textile reinforced formwork elements is very dense which exerts positive influence on the durability of the component.

GEOMETRIC DESIGN OF THE FORMWORK ELEMENT

The formwork element developed and tested in the context of the research project (Brameshuber et al. 2004) is based on experiences reported earlier in Brameshuber et al. 2001a and Brameshuber et al. 2001b. The formwork element was designed to meet the following requirements:

- It should be usable as a continuous girder, i. e. it should be able to carry positive as well as negative bending moments.
- The cross-section should have a large geometrical moment of inertia to assure a maximum load bearing capacity in conjunction with the resulting deflection being as small as possible.
- The height of the formwork element should be as low as possible to ensure an arrangement of the transverse reinforcement of the later concreted ceiling slab.

- The cross-section of the formwork should assure a positive-locking to the later placed top concrete layer. This is necessary to avoid flaking in case of fire.
- The formwork element should be thin-walled to reduce its weight in order to be placeable by hand or with the aid of a light hoisting device.

These requirements led to the hat-shaped cross-section (Ω -profile) of the formwork element displayed in Figure 1.

CONCRETE TECHNOLOGY

The complex shape of the Ω -profile in conjunction with the small wall-thickness of 10 mm (0.39 in) makes great demands on the rheology of the concrete used. The concrete has to be flowable enough to completely fill the mold and ensure a full penetration of the fabric. The latter is necessary to guarantee an optimal bond between the textile and the concrete. Preliminary tests revealed that the required slump flow measure according to the German standard DIN EN 196 need to be at least 370 mm (14.6 in) to meet both requirements. This in conjunction with a water to binder ratio of 0.4 to fulfil the demands with regard to the mechanical properties and durability was achieved by optimization of the particle size distribution curve of the binder in conjunction with a superplasticizer – stabilizer combination. The stabilizer was necessary to prevent the mixture from segregation and reduce bleeding. The detailed composition of the fine grained concrete can be taken from (Brameshuber et al. 2004). The mixture features a binder content of 1000 kg/m³ (1686 lb/yd³) and a maximum grain size of 0.5 mm (0.02 in). Table 1 provides the properties of the fresh and the hardened concrete used in the investigation.

FABRICS

Although concrete has a high compressive strength, its tensile strength amounts approximately only one tenth of its compressive strength. Therefore textile reinforcement is arranged to carry and transfer the tensile forces via bonding into the surrounding concrete. The fabrics used as reinforcement for the Ω -profile were made of alkali resistant (AR) glass. Table 2 shows a selection of them. Fabric 1 has a tri-directional structure with yarns in 0°- and $\pm 45^\circ$ -direction. Textiles 2 to 4 are bi-directional layer fabrics. For the latter fabrics so-called friction spun hybrid (FSH) yarns were developed. These yarns consist of a core of AR-glass and a coating of polypropylene (Figure 2). Since the polypropylene lagging is very fine-fibered it has a high suction capacity and therefore excerpts water from the concrete. This dehydration can be circumvented when the polypropylene is previously melted at temperatures from 180 °C (356 °F) to 200 °C (392 °F) for about 10 minutes. At this temperature the polypropylene liquefies and a compact covering is formed which stops the absorption of water. Further on the liquefied polypropylene permeates into the AR-glass core of the yarn and glues the individual filaments together when it cools down resulting in a monolithic strand with improved bonding properties. The yarns in fabric 3 and 4 consist of three thinner FSH yarns which are subjected to the friction spinning process as core material for a second time. This production technique results in a greater proportion of polypropylene being available for gluing the core filaments. A second advantage results from the fact that the three yarns provide a fluting to the strand which further increases the bond to the concrete (Figure 3). The fabrics 1 and 4 are laminar textiles whereas textiles 2 and 3 are contoured spacer fabrics consisting of cover layers of bi-directional layer fabrics of FSH yarns and pile yarns made of aramid. The contoured spacer fabrics can simply be reshaped to fit the shape of the formwork element (Figure 4). Placement and fixing of the textile in the casting mold of the Ω -profile is therefore very easy to conduct.

FABRICATION TECHNIQUE

The casting mold to fabricate the formwork elements consists of an outer formwork made of plastics and an aluminum core to provide the hollow core of the desired hat-shaped component. The core consists of six aluminum hollow sections which are mounted flush to plastic end pieces. The whole assembly is held together by three steel rods and wrapped with a polyethylene foil to prevent the concrete from leaking in. After removing the rods the core can easily be dismantled which facilitates the demolding of the finished Ω -profile.

The attachment of the reinforcement textile in the mold was achieved by applying a slight prestressing through the abutting faces of the casting mold. Figure 6 shows the finished formwork element.

TESTING OF THE FORMWORK ELEMENT BY 4-POINT BENDING TESTS

The formwork element was intended to be used as a continuous girder to carry the load of a 200 mm (7.87 in) thick layer of fresh concrete. The load bearing capacity and the serviceability were investigated by 4-point bending tests both for positive (moment of span) and negative (moment at support) bending moments. The underlying static system is displayed in Figure 7.

The results of the bending tests for positive bending moments are displayed in Figure 8. The tests were controlled by crosshead displacement at a rate of 3 mm/min (0.12 in/min). The formwork element with the mere AR-glass fabric 1 achieved the lowest load bearing capacity in conjunction with the largest deflection of the tested fabrics. This results from the fact of a poor penetration of the concrete into the core filaments of the yarn. The bigger the diameter of the yarn the less interior filaments are reached by the concrete resulting in a decreased efficiency of the yarn with increasing diameter. In case of the FSH yarns the melted polypropylene coating penetrates into the AR-glass core and glues its filaments to produce a monolithic strand upon cooling down. The contoured spacer fabric 2 made of FSH yarn therefore reveals an improvement in both the modulus of rupture and deflection. Finally the fabrics 3 and 4 which were also made of FSH yarn where three thinner yarns are knit to one strand provide an enhancement in the ultimate load of 250% compared to fabric 1. The ultimate bending moment of the Ω -profiles with fabric 3 and 4 were 4.08 kNm (3009.4 lbf ft) and 4.46 kNm (3289.7 lbf ft), respectively. Since the design of the formwork element according to the German standard DIN 1045-1 yield a design bending moment of 1.25 kNm (922.0 lbf ft) the safety factor amounts 3.6 and 3.3, respectively. Thus only the fabrics 3 and 4 made of FSH yarns resulted in a sufficient load bearing capacity. Due to the fact that fabric 3 was easier to place in the casting mold than the laminar fabric 4 the further investigations were confined to formwork elements with fabric 3 as reinforcement.

TESTING OF COMPOSITE BEAMS CONSISTING OF THE FORMWORK ELEMENT WITH A TOP CONCRETE LAYER

The bond between the Ω -profile and the top concrete layer was investigated by 4-point bending tests carried out on composite beams. The cross-section of the beams is represented in Figure 9 and the test set-up is shown in Figure 10. The components were tested 5 days after the pouring of the top concrete layer in a deformation controlled manner with a constant deformation rate of 0.5 mm/min (0.02 in/min). In four tests the Ω -profile was placed in the tensile zone (test series one) and in four tests it was placed in the compressive zone (test series two). Within each test series the effect of keying the surface of the Ω -profile and placing additional epoxy resin on it before pouring the top concrete layer has been investigated.

In Figure 11 the load-deflection curves of tests with the formwork element placed in the tensile zone are displayed. All beams had nearly the same load bearing capacity of about 50 kN (11241 lbf). The calculated shear capacity of the joint according to the German standard DIN 1045-1 was 40 kN (8993 lbf), taking into account a safety factor of 1.5. Decisive for the failure of the beam was the excess of the top concrete's shear strength (Figure 12). The keying of the Ω -profile's surface caused no effect on the load behavior. Furthermore, no relative displacement between the formwork element and the top concrete layer has been detected. Therefore, a positive locking bond between both can be assumed. The results of the tests with the formwork element placed in the compressive zone (test series two) also agreed with the predicted results.

TESTING OF SLABS CONSISTING OF THREE FORMWORK ELEMENTS WITH A TOP CONCRETE LAYER

The influence of the formwork elements on the transversal distribution of an applied single load was investigated by three bending tests carried out on composite slabs. The slabs consisted of three formwork elements with a reinforced top concrete layer. The test set-up is shown in Figure 13 and Figure 14. Comparing the measured load bearing capacity with the calculated one yielded a safety factor of 2.3 against failure, whereas the load bearing capacity of the formwork elements has not been taken into account. Thus, the formwork elements ensured a sufficient transversal distribution of the imposed single load.

DESIGN MODEL

Based on the results of the experimental investigations, a design model for the formwork element has been derived. Decisive for the design of the element were the load assumptions of the German standard DIN 4421. In axial direction of the formwork, the bending moments resulting from the weight of the fresh concrete and the building activities are decisive for the calculation of the required textile reinforcement. The required content of textile reinforcement in transversal direction is determined by the required shear strength.

Calculation of the Bending Capacity

The calculation of the formworks flexural strength is based on the design method suggested in DIN 1045-1. According to this the maximum strain of the textile reinforcement is restricted to 1%. The tensile strength of the reinforcement, detected in appropriate tension tests as described in DIN 1045-1, has to be reduced by a factor in order to correctly estimate the flexural strength of the formwork element. The reason for this is the reduction of the tensile strength of the fabric due to the arising lateral pressure at crack edges. For the fabrics described in chapter 3.2 this reduction factor amounted to 0.75. The tensile strength $\sigma_{\max,fl}$ of the reinforcement for determining the formwork element's flexural strength is obtained by

$$\sigma_{\max,fl} = k_{fl} \cdot \sigma_{\max,t} \quad (1)$$

where

k_{fl} reduction factor when the component is subjected to bending
here: $k_{fl} = 0.75$

$\sigma_{\max,t}$ tensile strength of the reinforcement investigated by tensile tests according to DIN 1045-1

The flexural strength of the formwork results from (Figure 15)

$$M_{cal} = F_{t,fl} \cdot z_{t,fl} + F_{t,web} \cdot z_{t,web} \quad (2)$$

where

M_{cal} flexural strength of the formwork

$F_{t,fl}$ tensile strength of the textile reinforcement in the flange: $F_{t,fl} = \sigma_{\max,fl} \cdot a_{t,fl}$
with $a_{t,fl}$: square area of textile reinforcement in 0°-direction

$z_{t,fl}$ lever arm

$F_{t,web}$ tensile strength of the textile reinforcement in the web: $F_{t,web} = \sigma_{\max,fl} \cdot a_{t,web}$
with $a_{t,web}$: square area of textile reinforcement in 0°-direction in tensile zone

$z_{t,web}$ lever arm.

Calculation of the Shear Strength

In order to calculate the shear strength of textile reinforced concrete (TRC) a design method has been derived according to (Görtz 2004). In this rule the shear bearing capacity consists of two parts:

- a concrete part V_c
- a frame-work part V_f

The load bearing capacity of the tension strut of the underlying truss is calculated by

$$V_f = a_{sw} \cdot f_{y,res} \cdot z \cdot \cot \beta_r \quad (3)$$

where

a_{sw} cross-sectional area per unit of shear reinforcement

$f_{y,res}$ resulting load bearing capacity of the textile reinforcement

z inner lever arm

β_r angle of the shear crack.

A detailed description of this design method of TRC under shear loading is given in SFB 532.

The correlation between the calculated and the measured ultimate bending moments is depicted in Figure 16.

TESTING OF THE FIRE-RESISTANCE OF COMPOSITE BEAMS CONSISTING OF THE FORMWORK ELEMENT WITH A TOP CONCRETE LAYER

The behavior of the composite system consisting of an Ω -profile with a top concrete layer in case of a fire exposure was investigated at the Institute of Construction Materials of the University of Stuttgart by fire-resistance tests according to the German standard DIN 4108. Figure 17 shows the formwork element with assembled steel-reinforcement before pouring the top concrete layer. During the furnace test the sample was subjected to a fire action for a period of 90 minutes. The maximum furnace temperature amounted to 1017 °C (1862.6 °F). Thermocouples were affixed to the test sample at different positions in order to monitor the temperatures during the fire resistance test (Figure 18). The temperatures measured by the thermocouples are shown in Figure 19.

Although an intense cracking occurred at the bottom flange of the formwork element exposed to the flames the bond to the top concrete stayed intact (Figure 20, Figure 21). Since the AR-glass reinforcement features a high temperature stability no flaking occurred and therefore there is no risk of parts falling off in case of fire. The bottom flange maintained its protective role and prevented the inner steel-reinforcement from a direct fire attack.

All tested samples achieved a fire-resistance grading of F 90 according to DIN 4102.

SUMMARY AND CONCLUSIONS

It has been shown that the designed load bearing capacity and the serviceability of the developed formwork elements made of textile reinforced concrete is achieved by using textiles made of friction spun hybrid yarns. The hat shape of the formwork elements assures a positive-fit to the top concrete layer without the necessity of further measures to improve the bond between both.

The fire resistance tests revealed that in case of fire exposure no flaking occurs and that the bottom flange of the Ω -profile retains its protection capacity to the steel reinforced top concrete layer. A fire resistance grading period of F90 according to the German standard DIN 4102 has been achieved. The developed formwork element is therefore appropriate to many applications in domestic construction.

ACKNOWLEDGEMENT

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REFERENCED STANDARDS AND REPORTS

DIN German Institute for Standardization

- DIN 1045-1 Concrete, reinforced and prestressed concrete structures - Part 1: Design and construction, 2001-07-00
- DIN 4421 Falsework; Calculation, design and construction, 1982-08-00

RWTH Aachen University

- SFB 532 Collaborative Research Center 532, Textile Reinforced Concrete - Foundation of a new technology, work and results report, 2004

CITED REFERENCES

- Brameshuber, W.; Brockmann, J.; Rößler, G., 2001a, July 16-18, "Textile Reinforced Concrete for Formwork Elements - Investigations of Structural Behavior", *Proceedings of the 5th International Conference on Fibre-Reinforced Plastics for Reinforced Concrete Structures, Cambridge, Great Britain*, ed. C. J. Burgoyne, V. 2, pp. 1019-1026

Brameshuber, W.; Brockmann, J.; Röbler, G.; Hegger, J.; et al, 2001b, April 23-24, "Textile Reinforced Concrete for Formwork Elements", *11. International Techtextil Symposium for Technical Textiles, Frankfurt, Germany*, lecture 335

Brameshuber, W.; Gries, T.; Hegger, J.; Reinhardt, H.-W.; Koster, M.; Barlé, M.; Voss, S.; Krüger, M., 2004, "Praxisgerechte Weiterentwicklung eines bauteilintegrierten Schalungssystems aus Textilbeton", Institute for Building Materials Research, RWTH Aachen University, Research Report No. F 771

Görtz, S., 2004, "Zum Schubbrissverhalten von Stahlbeton- und Spannbetonbalken aus Normal- und Hochleistungsbeton", PhD-Thesis, Institute for Structural Concrete, RWTH Aachen University

Table 1 — Properties of the fresh and hardened concrete

Fine Grained Concrete					
1	2	3		4	
Fresh Concrete	Slump Flow	m	in	0.38	14.57
	Apparent Specific Gravity	kg/m ³	lb/yd ³	2119	3572
	Air Void Content	%		0.3	
	Water Retention	-		good	
Hardened Concrete after 7 d	Young's modulus (dyn.)	N/mm ²	lbf/in ²	28900	4191591
	Compressive Strength			66.0	9572
	Splitting Tensile Strength			5.3	769
	Bending Tensile Strength			6.6	957
Hardened Concrete after 14 d	Young's modulus (dyn.)	N/mm ²	lbf/in ²	31000	4496170
	Compressive Strength			75.4	10936
	Splitting Tensile Strength			6.0	870
	Bending Tensile Strength			8.0	1160
Hardened Concrete after 28 d	Young's modulus (dyn.)	N/mm ²	lbf/in ²	32400	4699223
	Compressive Strength			76.9	11153
	Splitting Tensile Strength			6.2	899
	Bending Tensile Strength			8.5	1233

Table 2 — Reinforcement Textiles (Selection)

Fabric	Type of Fabric	Percentage of Reinforcement 0°-direction	Percentage of Reinforcement 90°-direction	Percentage of Reinforcement ±45°-direction	Tensile strength of yarn in 0°-direction
-	-	mm ² /m (in ² /yd)	mm ² /m (in ² /yd)	mm ² /m (in ² /yd)	mm ² /m (in ² /yd)
1	2	3	4	5	6
1	tri-axial layer fabric	70.5 (0.10)	-	33 (0.05)	446 (0.63)
2	contoured spacer fabric	194 (0.27)	51 (0.07)	-	581 (0.82)
3	contoured spacer fabric	246 (0.35)	116 (0.16)	-	895 (1.27)
4	cover layer of 3	246 (0.35)	116 (0.16)	-	895 (1.27)

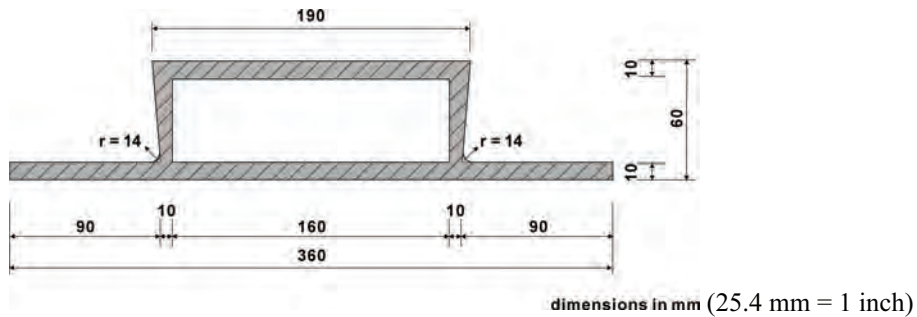


Figure 1 — Cross-section of the formwork element (Ω -profile)

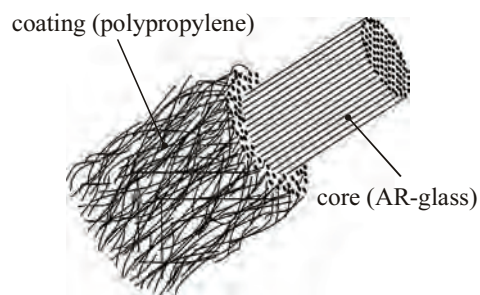


Figure 2 — Friction spun hybrid (FSH) yarn

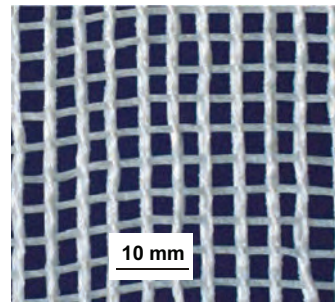


Figure 3 — FSH yarn fabric with three yarns woven to one strand (Fabric 3, 4)

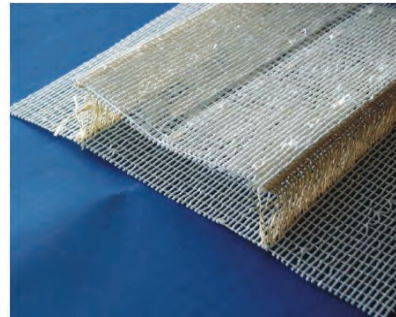
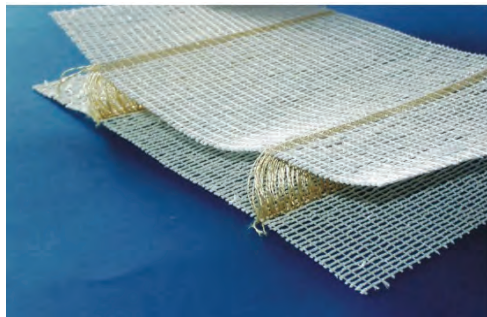


Figure 4 — Reshaping of the textile (Fabric 3)

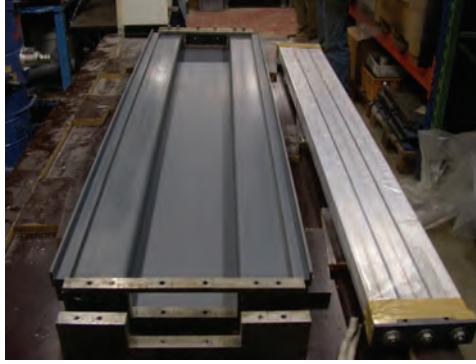


Figure 5 — Casting mold for the Ω-profile with aluminum core



Figure 6 — Finished Ω-profile

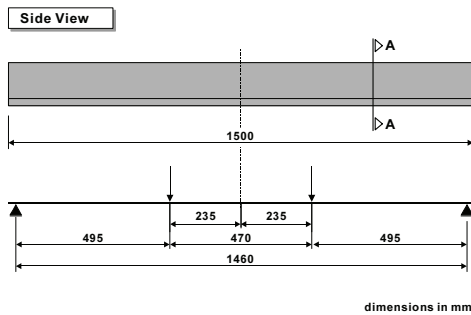


Figure 7 — Static system of the 4-point bending tests for positive bending moments (25.4 mm = 1 inch)

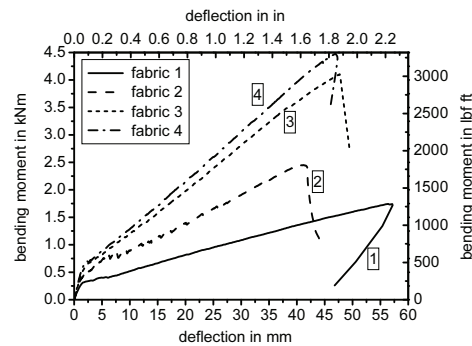


Figure 8 — Results of the 4-point bending tests

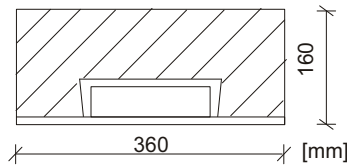


Figure 9 — Cross-section of the composite beams (25.4 mm = 1 inch)

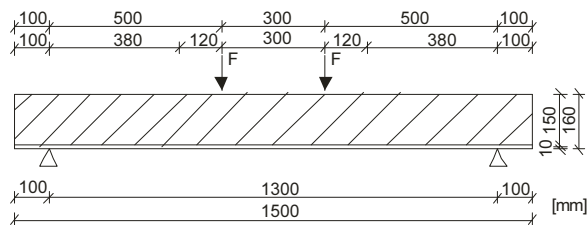


Figure 10 — Set-up of 4-point bending tests carried out on the composite beams (25.4 mm = 1 inch)

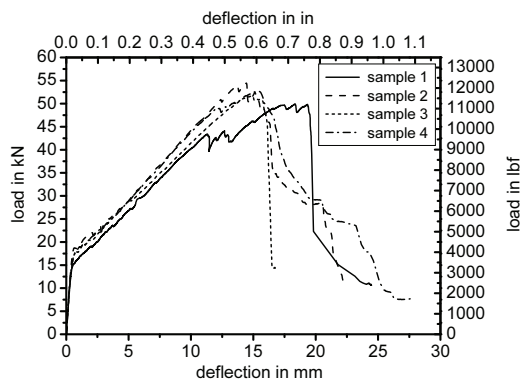


Figure 11 — Results of the bending tests carried out on composite beams



Figure 12 — Failure of the component due to flexural shear stresses

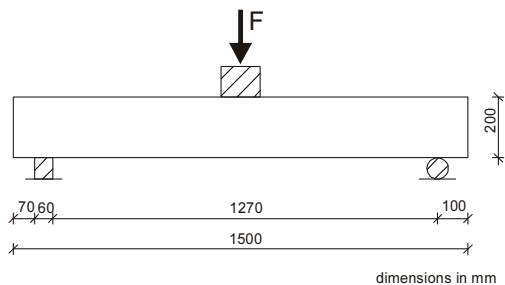


Figure 13 — Set-up of bending test on slab (25.4 mm = 1 inch)

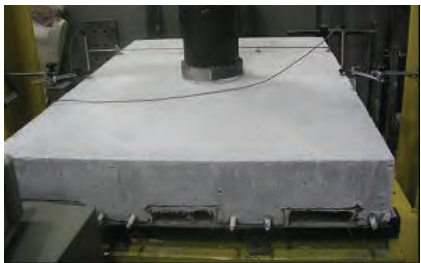


Figure 14 — Bending test carried out on a slab consisting of three formwork elements and reinforced top concrete

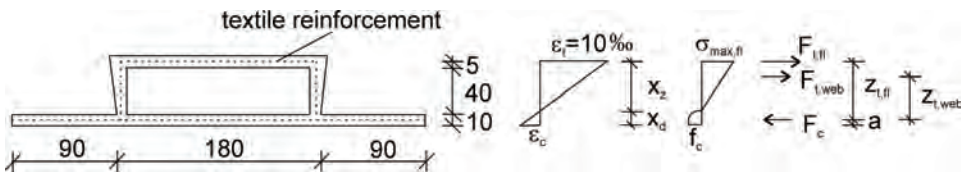


Figure 15 — Calculation of the flexural strength of the formwork (moment at support) (25.4 mm = 1 inch)

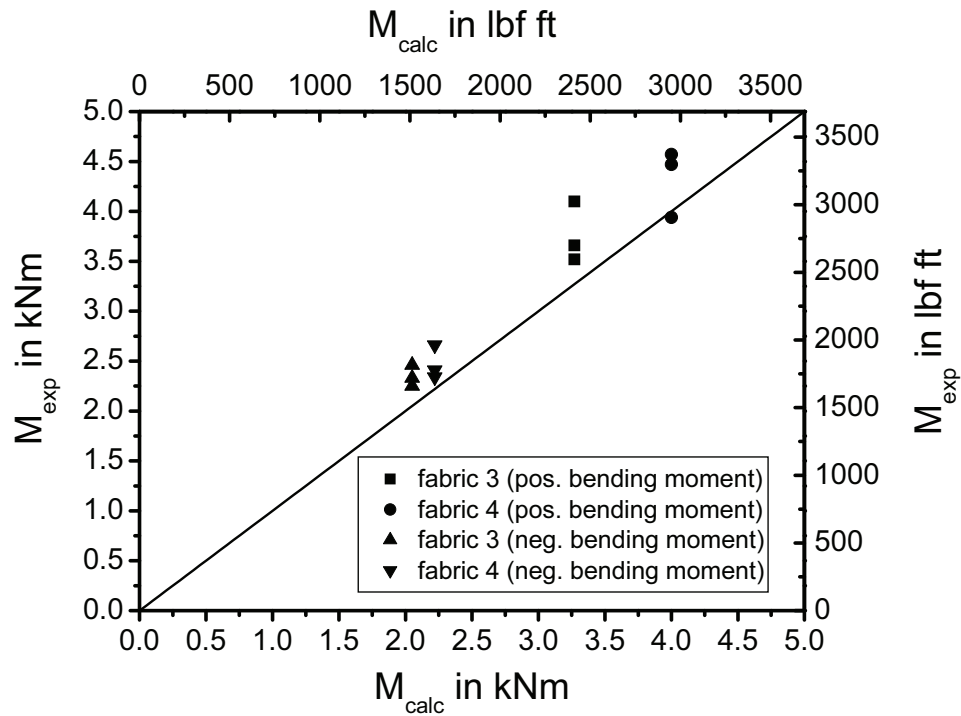
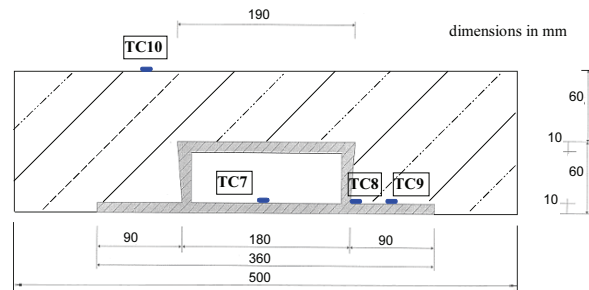


Figure 16 — Correlation between calculated and measured ultimate bending moments



Figure 17 — Test sample for the fire resistance test

Figure 18 — Arrangement of the thermocouples
(25.4 mm = 1 inch)

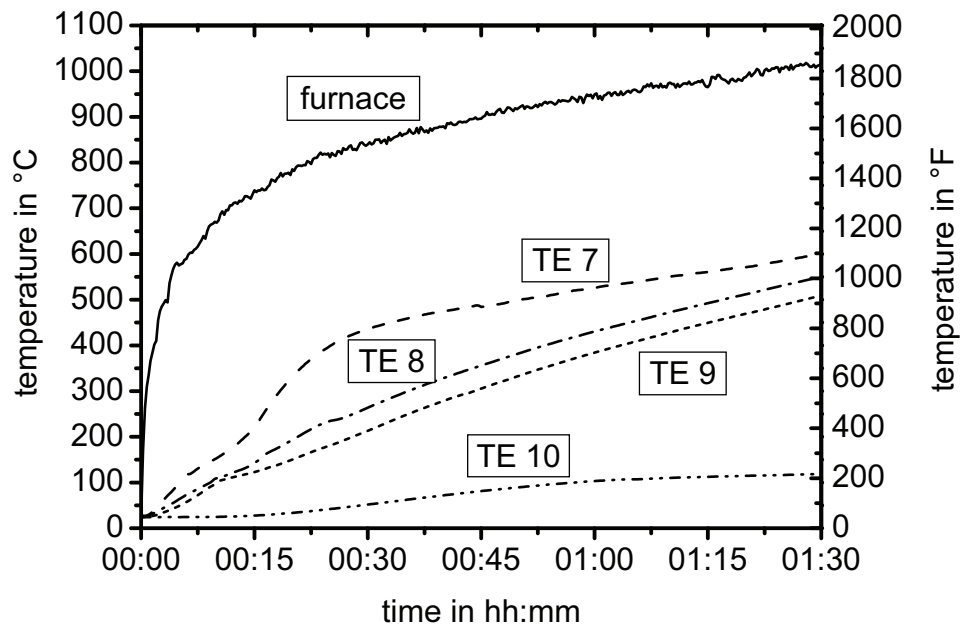


Figure 19 — Temperatures measured during the fire resistance tests

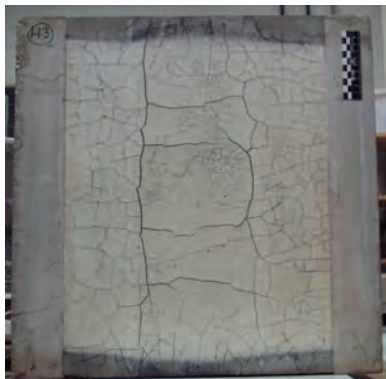


Figure 20 — Cracking of the bottom flange

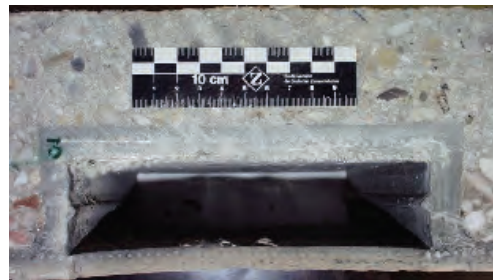


Figure 21 — Mid-section of the component after the fire resistance test

LIST OF NOTATIONS

a_{sw}	cross-sectional area per unit of shear reinforcement
$a_{t,fl}$	square area of textile reinforcement in 0°-direction
$a_{t,web}$	square area of textile reinforcement in 0°-direction in tensile zone
$F_{t,fl}$	tensile strength of the textile reinforcement in the flange
$F_{t,web}$	tensile strength of the textile reinforcement in the web
$f_{y,res}$	resulting load bearing capacity of the textile reinforcement
k_{fl}	reduction factor when the component is subjected to bending
M_{cal}	flexural strength of the formwork
z	inner lever arm
$z_{t,fl}$	lever arm
$z_{t,web}$	lever arm
β_r	angle of the shear crack
$\sigma_{max,t}$	tensile strength of the reinforcement investigated by tensile tests according to DIN 1045-1

Flexural Strengthening of RC Structures with Textile-Reinforced Concrete

by F. Jesse, S. Weiland, and M. Curbach

Synopsis: Textile-reinforced concrete (TRC) is a high-performance composite in which technical textiles made of high-performance fibers are embedded in a fine-grained concrete matrix. Textile-reinforced concrete extends concrete applications to completely new fields. Besides slender new concrete elements, strengthening of already-existing concrete structures by thin textile-reinforced concrete layers is possible. This type of strengthening noticeably increases both the ultimate load-bearing capacity and serviceability of reinforced concrete structures. This aspect is shown in the present paper using experimental results of TRC-strengthened slabs.

Keywords: AR glass; bond; carbon; delamination; fiber; flexural strengthening; strengthening; textile-reinforced concrete

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INTRODUCTION

Strengthening of reinforced concrete (RC) structures may be required for several reasons. Among these are: change of structural use; modification of static systems; and mitigation of structural damages (e.g., resulting from corrosion or extreme loading events). A variety of methods is available and has been used for several decades to increase the load capacity of RC structures. Primarily, these consist of the addition of reinforcement and concrete (i.e., shotcrete, in-situ concrete and injected concrete), as well as externally bonded or near-surface-mounted reinforcements such as steel lamellas or fiber-reinforced polymers (FRP). Strengthening with textile-reinforced concrete (TRC) is a new method of RC strengthening (figure 1).

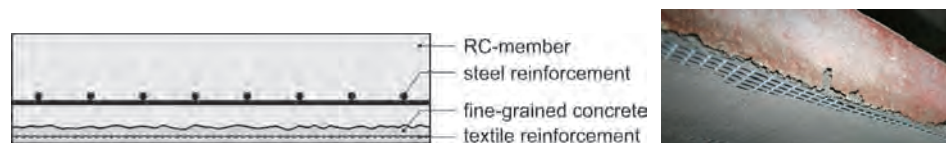


Figure 1 - Schematic TRC strengthening: steel reinforced concrete and Textile-reinforced fine grained concrete.

Textile-reinforced concrete is a relatively new, high performance composite. It consists basically of textile reinforcements that are embedded in thin layers of concrete. Textile reinforcements are produced from the processing of high performance fibers (i.e., fibers with high strength, ductility and durability) with flat or spatial reinforcing structures that utilize state-of-the-art textile technology. Compared to steel reinforcement, textile reinforcing elements are extremely filigree. As a result, a composite material with very remarkable properties, as outlined below, is developed:

- There is no concrete cover necessary for corrosion protection of the reinforcement since the reinforcing materials used do not exhibit corrosion under normal environmental conditions. Therefore, very thin strengthening layers can be produced due to this “waiver” absence of concrete cover.
- Textile reinforcements have a much larger surface area than ordinary steel-bar reinforcement. Thus, very high bond forces can be introduced into the concrete which, in practice, is evidenced by both the ability to use short anchoring lengths and the presence of very dense crack patterns.
- Fibers produced from either alkali resistant glass (AR-glass) or carbon, possess a distinctively higher strength than that exhibited by standard steel-bar reinforcement. Current third generation textile reinforcements have reached strengths of clearly over 1000 N/mm².

In addition to providing an increase in the ultimate loading capacity of reinforced concrete, TRC is also suitable for additional repair applications. TRC exhibits the following properties that appear to be suitable for the strengthening of RC structures:

- The use of additional TRC strengthening layers in RC structures is proven to have a positive influence on subsequent concrete cracking. The number of cracks increases while crack spacing decreases and crack widths are simultaneously reduced (figures 2 and 3).

- Members become stiffer. This effect is not only based on the application of additional material but also on the demonstrated fact that members remain longer in an un-cracked state I.
- It is possible to produce more advanced repairs with the use of a mineral-based matrix. In addition, pure re-profiling, re-passivation and the provision of a new or additional dense concrete cover are valuable options.
- Surface design of the strengthening layer can vary within a wide range. A large range of design options is available today for plasters that can also be utilized in TRC applications when suitable mixtures for matrices are used and the final layer is appropriately treated.



Figure 2 - Crack pattern of flexural TRC-strengthened RC-slab

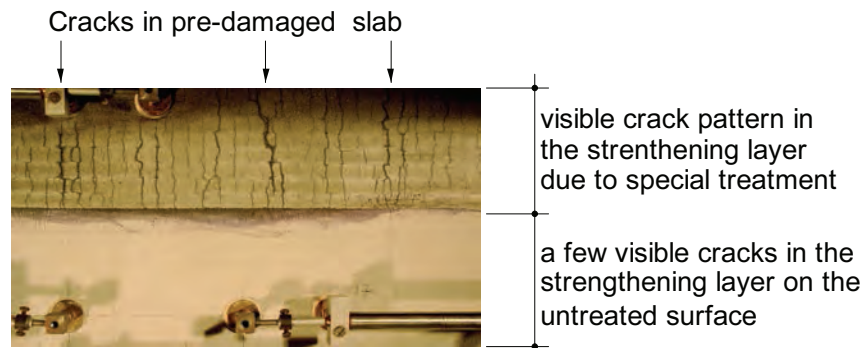


Figure 3 - Crack pattern of a pre-damaged RC-slab strengthened by TRC.

Given the newness of TRC, industry very often requires the development of suitable technology necessary for its proper processing. The authors maintain the conviction that procedures that are equally simple and tested (i.e., the “tried and true”) can be used as a basis rather than reliance on more complicated procedures. In the end, it is a matter of applying one layer of a fine-grained matrix at a time, with properties that are very similar to those of modern plasters with an embedded reinforcement, which again, at least from a handling perspective, have many similarities to standard plaster fabrics.

Compared to steel-bar reinforcement, textile reinforcements are much more easily shaped to fit any form necessary in contrast to steel rebars that require heavy machinery for such modifications. Therefore, it is also possible to utilize such strengthening means on profiled sections such as beams, T-beams or columns, and, in extreme cases, shell-like structures. Textile structures have the necessary deformability to adapt to such geometries.

LATEST DEVELOPMENTS

During the past 10 years, the development of textile reinforcements has shown considerable progress [1]. The first generation of textile reinforcements [2] had no properties that were adjusted to mineral matrices; however, the link between the construction of textile structures and load bearing behavior of the composites, has since been delineated and verified by several detailed studies [3], is very complex. The second generation of these reinforcements reflects these findings and possible benefits through a concerted effort to develop appropriate techniques for the application of textiles needed to attain specific property profiles [4]. While the potential is extremely high, the given properties of the fibers used could not be changed. Load bearing behavior, and in particular the ultimate load, could be in-

creased significantly when the bond strength between microscopic filaments was increased by impregnation with a suitable medium. This has been achieved in the development of third generation textile reinforcements [5]. However, all other properties of the reinforcement, besides strength, are changed by impregnation. On-going research has the goal of developing custom-made, textile structures whose property profiles are unique to the strengthening requirements of each particular case.

TRC-STRENGTHENING OF RC MEMBERS

If strengthening objectives are broken down according to cross-sectional form and loading, then the following variations are possible:

- Strengthening of slabs for bending;
- Strengthening of beams for bending and shear;
- Strengthening of T-beams for bending and shear and
- Strengthening of columns for axial loading, bending and shear.

Applications mentioned above have been extensively examined and reported on elsewhere [1], [6]-[11].

Reference [6] includes studies that examine situations in which textile reinforcements of the first and second generation have been used for flexural strengthening by a factor of two (where 8 layers of textile reinforcement have been needed). Meanwhile, textile reinforcements available from the third generation enable a higher load increase with the use of only two or three layers (figure 7). The focus of on-going research tends to be on open technological questions. Until now, experience relative to the application of fine-grained concrete with layer thickness of 1 to 2 mm (0.04 to 0.08 in) has only been available from laboratory results. Models exist for calculating the reinforcement for flexural strengthening and shear strengthening. These should be developed into easy-to-handle design aids – e.g., engineering software or dimensioning diagrams – in order to allow easy application in design practice.

The question always arises as to the manner in which the loads from an existing structure can be introduced into the strengthening layer. In the majority of cases, the use of custom anchoring methods require additional measures. Verification of proper anchoring frequently becomes the determining factor for dimensioning. When using TRC, no bond failure has been observed in any previous research cases in which the bending strength of slabs was increased. This is basically attributed to the plane structures of textile reinforcements which allow for a comparatively smooth load transfer.

The question of anchoring within the compression zone arises when providing shear strengthening of T-beams. Particular attention is paid to this question in all customary methods as cost is often non-negligible. To date, no studies have led to provisions for additional anchoring in load transference areas since no bond failure was observed. A bond failure was detected for the first time in tests of shear strengthening of T-beams with high strengthening ratios. It was observed that the failure inside the multi-layer strengthening material occurred within the first layer of textile reinforcement, adjacent to the existing layer of concrete [13]. Advanced tests have shown that the strengthening layer can be utilized to its fullest capacity by preventing displacement between the existing concrete and strengthening layer. Displacement is necessary for de-lamination to take place.

What conclusions can be drawn from this? Investigative results can be interpreted as proof that shear strengthening is possible. This even holds true when the strengthening terminates at the intersection of the web and slab and the compression zone cannot be enclosed by the strengthening layer.. This load bearing behavior can best be explained by strut and tie models which show a good correlation to the test results [9]. A topic for on-going research is the development of a model or criterion that excludes failure due to de-lamination with a well-founded explanation for all cases where the compression zone cannot be enclosed.

EXPERIMENTAL PROGRAM

Materials

A normal C25/35 concrete with a maximum aggregate size of 16 mm (0.63 in) was used for the base slab. The reinforcement consisted of 4 steel bars – BSt 500S – with an 8 mm (0.3 in) diameter. The strengthening layer was com-

prised of several layers of textile fabric and a fine-grained concrete matrix with maximum aggregate size of 1 mm (0.04 in).

Textile reinforcement as described in Table 1 and a fine grained concrete were used for the strengthening layer. The characteristics of the yarns used are listed in Table 2. Item NWM4-011-03 is a textile fabric from the second generation of textile meshes while NWM3-004-04-2b and NWM3-003-03-2b are from the more recent third generation of materials. The latter two received an application of a special coating as the final step in the production process. The purpose of the coating was to improve (i) the bond that exists between the filaments, (ii) the bond between the stitching fibers and reinforcing yarns, and (iii) the transferable forces at the crossovers/intersections between transverse threads and reinforcing yarns. While the improvement of the bond between the filaments affects the bearing capacity, in particular, the other factors ensure easy handling of the textile reinforcement fabric during application processes.

Table 1—Textile reinforcements

Name	Layer	Direction	Spacing, mm (in)	Fiber
NWM4-011-03	1	0° (warp thread)	10.8 (3/7)	VET-ARG2400-02
	2	90° (weft thread)	10.8 (3/7)	VET-ARG640-03
NWM4-011-04-2b	1	0° (warp thread)	10.8 (3/7)	VET-ARG2400-02
	2	90° (weft thread)	10.8 (3/7)	VET-ARG640-03
NWM3-003-04-2b	1	0° (warp thread)	7.2 (2/7)	TEN-CF800-01
	2	90° (weft thread)	10.8 (3/7)	VET-ARG620-05

Table 2—Fiber properties

Name	Material	Tex	Filament strength σ_{fu} N/mm ² (kips)	Filament diameter d_f μm / μ	Young's Modulus E_f N/mm ² (kips)
VET-ARG2400-02	AR-Glass	2400	1710 (248)	26.2	76 320 (11 070)
TEN-CF800-01	Carbon	800	2895 (420)	7.07	214 410 (31 000)

Manufacturing

The reinforced concrete slabs were manufactured within a horizontal formwork. At the age of at least 4 weeks the tensile zone was roughened by sandblasting. The roughness attained after Kaufmann [12] was approximately 0.7 ... 1 mm (0.025 ... 0.04 in). The slabs were then turned so that the tensile zone was on the top for the application of the strengthening layer. The concrete surface was wetted to avoid absorption of water from the fine concrete mix and provide a good bond between the new and the old concrete. First a layer of fine concrete was applied into which the textile reinforcement was inserted afterwards. Subsequently, an additional covering layer of fine concrete was applied. The latter two work procedures were repeated until the desired thickness and number of layers was reached. The average layer thickness was 2 ... 3 mm (0.08 ... 0.12 in). The total thickness of the strengthening layer was 15 mm (0.6 in) or less. The well-known curing process is necessary for strengthening layer after manufacturing. In this process, the strengthening layers were covered with wet cloths and foil for a period of up to 7 days. The specimens were stored under normal laboratory conditions without any additional special measures until testing.

Specimen, Test Setup and Instrumentation

The flexural properties of textile reinforcement of reinforced concrete slabs were investigated in a static four-point-bending-test to avoid shear force influences within the zone of the maximum bending moment. The dimensions and materials of the specimens were selected to be representative of a class of usual slabs of a multi-storey office building on a scale 1 : 2. The specimens had a length of 1800 mm (70.9 in), width of 600 mm (23.6 in) and a thickness of 100 mm (3.94 in). The effective span between the supports was up to 1600 mm (63 in). Each slab contained steel