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 looses 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 mm^2/m (0.033 in^2/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.

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 mm^2/m, 0.104 in^2/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 at 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 m^2 (10.76 to 21.52 ft^2) 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 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 mm^2/m (0.151 in^2/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 mm^2/m (0.099 in^2/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.

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Table 1 — Examples of textile reinforcements

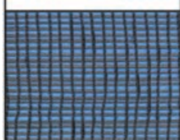
	Name	Material	Grid spacing [mm]/(in)		Areal wheight [g/m2]	Cross-sectional area [mm2/m]/(in2/ft)	
			0°	90°		0°	90°
	MAG_04_03	Carbon	8 (0.31 / 5/16)	8 (0.31 / 5/16)	400	105 (0.049)	105 (0.049)
	MAG_07_03	AR-Glass	8 (0.31 / 5/16)	8 (0.31 / 5/16)	400	105 (0.049)	105 (0.049)
	2D_02_06	AR-Glass	4,2/8,4 (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

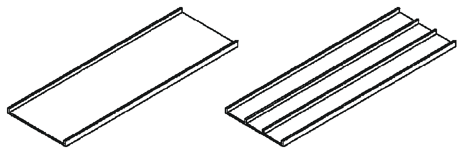
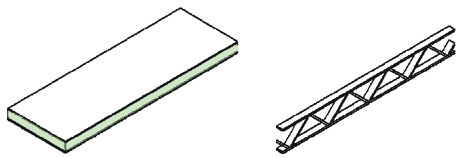
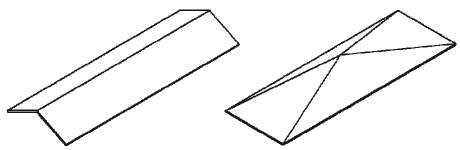
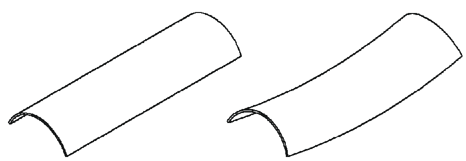
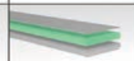
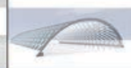
Component geometry	Category
	Profiling Left: simple Right: multiple
	Combining Left: composite Right: lattice structure
	Folding Left: simple Right: multiple
	Bending Left: simple Right: multiple

Table 3 — Examples of examined lightweight load-bearing structures

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

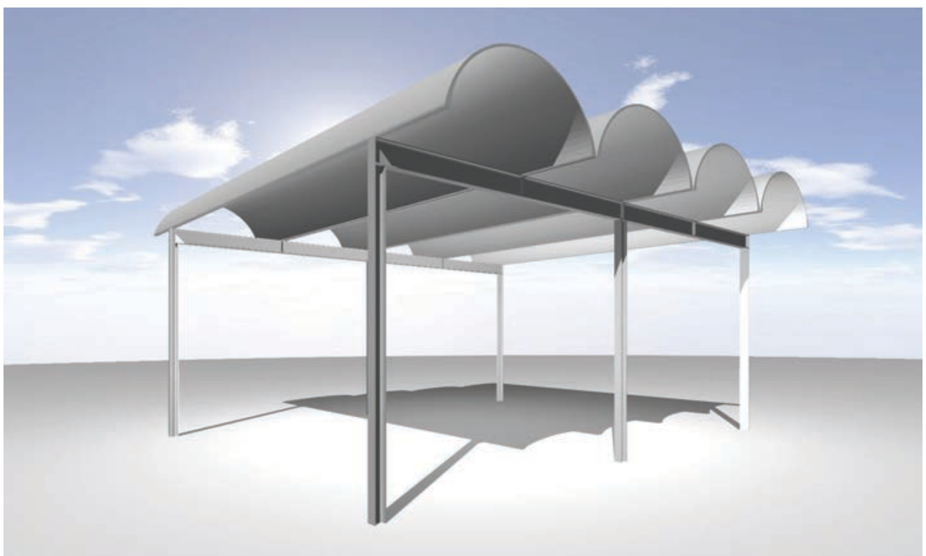


Fig. 1 — Semi-cylindrical barrel shell

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

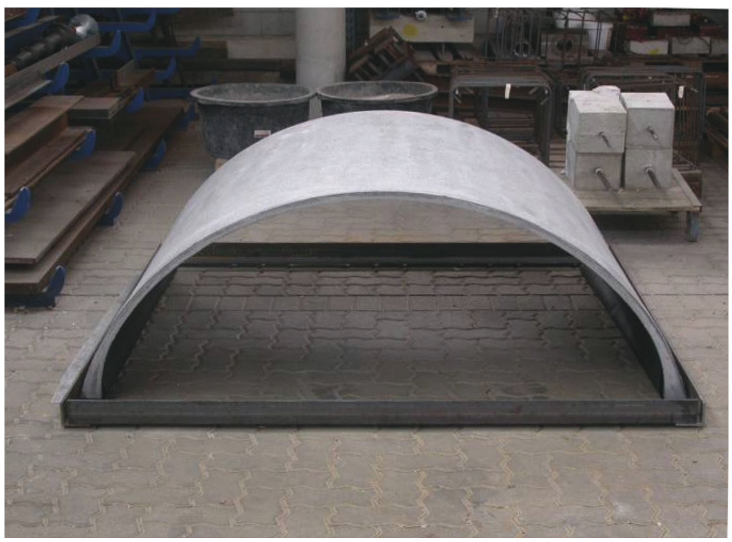


Fig. 3 — Prototype of the semi-cylindrical barrel shell

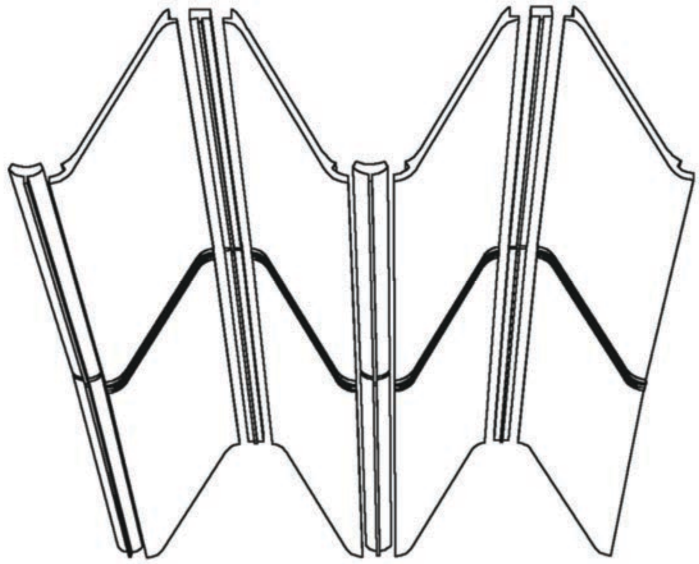


Fig. 4 — Exploded view of the grouted joints of the V-section shell-arch

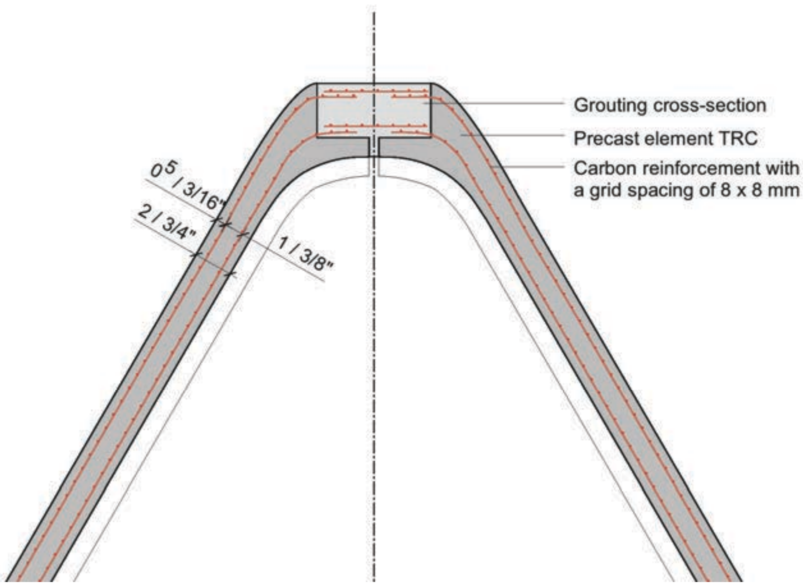


Fig. 5 — Detail of the grouted joints of the V-section shell-arch