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Shell Elements of Textile Reinforced Concrete Using Fabric Formwork: A Case Study

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Abstract: Innovations in formwork solutions create new possibilities for architectural concrete constructions. Flexible fabric replaces the stiff traditional formwork elements, and takes away a limiting factor for creative designs. Combined with textile reinforcement, the production of a new range of curved and organic shapes becomes possible without the intensive labour for formwork installation.

Besides a general introduction about the concepts of fabric formwork and textile reinforcement, this paper focuses on the production and structural evaluation of doubly curved shells. Creating a very interesting type of element from a structural point of view, the shape flexibility of both the fabric formwork and textile reinforcement make a perfect match to overcome practical production issues for thin shell elements.

The application of shotcrete and the integration of non-metallic reinforcement allowed first of all the production of very thin concrete shell elements based on the design approach of the textile architecture. Comparing a shell structure with traditional reinforcement and one with textile reinforcement, a case study evaluates furthermore both the design and the structural performance of such a shell structure.

Key words: formwork, fabric, textile reinforced concrete, glass fibre, shell element, manufacturing.

1. INTRODUCTION

There is an increasing demand for creative and organic shapes in modern architecture, it is however not always feasible to conceptualize the designs of the architects. Theoretically, concrete is the perfect material to realize this type of shapes, since fresh concrete can be poured into any shape. Architects acknowledge this interesting characteristic of concrete and seek to integrate organic concrete shapes in small and large designs. Some prestigious building designs are even completely based on the use of this “liquid stone”. The new Railway Station for Stuttgart (Ingenhoven Architects, Figure 1) or the design for the Ghent Music Theatre (Toyo Ito, Figure 2) illustrate perfectly how concrete can express movement by the use of curvature rather than box-shaped elements.

Traditional formwork however is very stiff and flat, shaping simple and rectangular elements, usually flat-surfaced. This is a limiting factor for the realization of more creative shapes. The same is true for traditional steel reinforcement: reinforcing strongly curved elements is difficult and labour intensive, which increases the total production cost of the structure.

The research presented in this paper combines two innovative techniques to overcome these problems: (1) fabric formwork and (2) textile reinforcement. The research focuses on one of the most interesting applications for the use of flexible fabric formwork: the production of thin, doubly curved shell elements, which are difficult to produce and reinforce with conventional means. These shell elements can be used as façade panels, self-bearing roofing structures, or permanent

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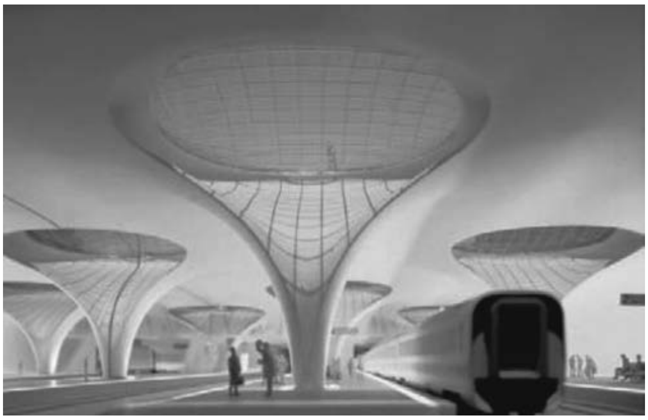

Figure 1. Railway station Stuttgart – ingenhoven architects

Figure 2. Ghent music theatre – Toyo Ito with Prof. Andrea Branzi

formwork elements. In the latter case, large spans can be realized, with very appealing design and a perfect surface finish.

When adding flexible and dense glass fibre textile reinforcement to a fine tuned mortar, a ductile cementitious composite with tensile capacity can be produced. Hence, the steel reinforcement can be omitted and the freedom of shape, inherent to fluid fresh concrete, can be fully exploited. Moreover, for glass fibre Textile Reinforced Concrete (TRC) shells the thickness is not governed by corrosion cover recommendations as is the case for steel-reinforced concrete. The combination of TRCs with a flexible fabric formwork thus makes it possible to produce strongly doubly curved shells without almost any limitations on radius of curvature or thickness.

The potential of TRC shell elements manufactured with a fabric formwork is examined in this paper by means of a comparative study with a steel-reinforced concrete shell. Firstly, a 2 m span TRC and a steel-reinforced concrete shell are designed according to the regulations of Eurocode 1-1.1 2002, Eurocode 1-1.3 2003, Eurocode 1-1.4 2005 and Eurocode 2.1.1 2004. In the second part of this paper, both shells, designed in the first part, are realized by using shotcrete on a fabric formwork, showing the feasibility of the proposed manufacturing process. Comparison of the manufacturing of the TRC shell with the steel-reinforced concrete shell highlights moreover the practical advantages of flexible textile reinforcement over stiff steel reinforcement. Finally, the load-bearing capacity of both shells is tested experimentally. While comparison of their structural behaviour demonstrates a comparable strength, the textile reinforced concrete shell however shows an improved ductility.

2. FABRIC FORMWORK

2.1. State-of-the-Art

The use of fabric formwork exists already for several decades, for very specific applications, often under-water concreting. Fabric envelopes or pile-jackets can prevent the wash-out of fresh concrete during casting and assure within certain tolerances the aimed shape for situations where applying normal formwork is difficult or even impossible. Figure 3 shows schematically the use of a concrete mattress as dike reinforcement. Figure 4 illustrates the idea of using fabric pile jackets, which is similar to the use of FRP-jackets. The fabric might be considered as a

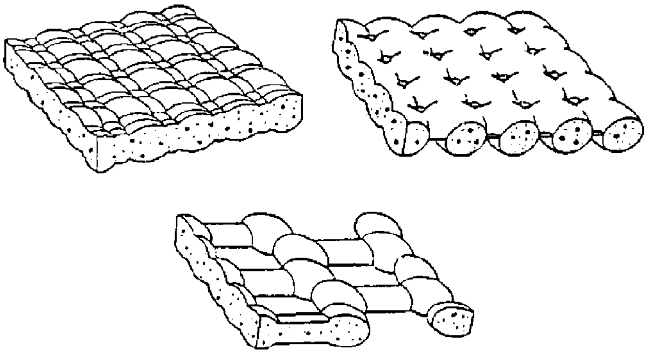

Figure 3. Fabric for under-water concreting of for instance dike reinforcement (Masuo 2000)

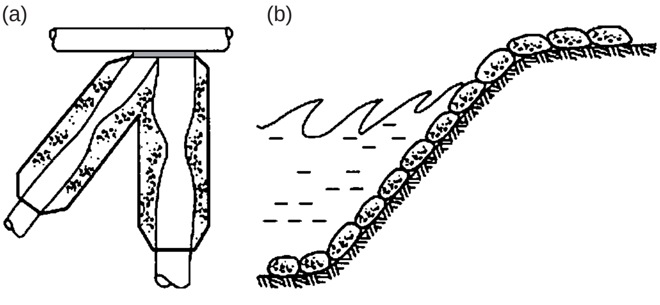

Figure 4. (a) Fabric for pile-jackets; and (b) erosion control (Al Awwadi Ghaib 2001)

stay-in-place formwork, and offers in certain conditions even a limited protection for the concrete.

A second technical step forward in the use of fabric for concrete formwork has been the introduction of formwork liners, which are used in combination with traditional formwork panels. This controlled permeable formwork (CPF) influences the concrete surface by allowing the excess mix water and air to be released from the face of the element (Cairns 1999). This results in a reduced water/cement (w/c) ratio near the concrete surface, and a reduction of the number and size of blowholes. These improvements might positively influence both durability and aesthetical appearance.

Recently, some researchers worldwide have explored the possibilities of fabric formwork for architectural purposes, exploiting the intrinsic flexibility of these materials. In Canada, pioneering professor West used fabric formwork to create architectonic panels, columns and beams (West 2006). His work highlights both the architectural and structural possibilities of concrete elements based on fabric formwork rather than on stiff steel or wooden plates. The truss design from Figure 5 focuses on optimal structural performance and minimal weight. The canopy with branch-like columns in Figure 6 illustrates the sculptural qualities.

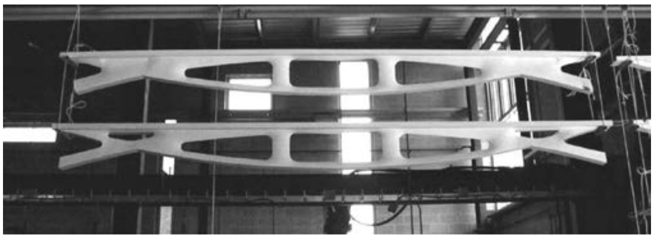

Figure 5. Plaster models of lightweight trusses made with fabric formwork (West 2006)

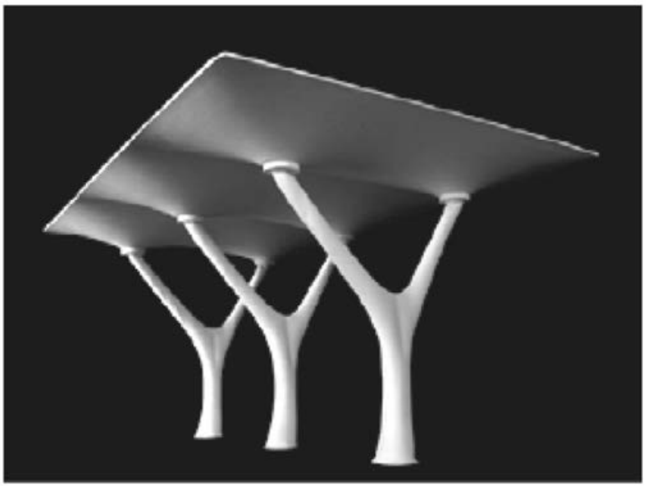

Figure 6. New architectural and sculptural possibilities with fabric formwork (West 2006)

Figure 7. Optimized beam shapes (Ibell 2009)

Figure 8. The construction of the Philips Pavilion (Pronk 2006)

Some case studies have been done in Edinburgh with columns and beams by Pedreschi (2005). Ibell (2009) used, among others, fabric formwork for optimizing beam shapes, based on the actual structural action (Figure 7). Pronk (2006) studied the use of a fabric for shaping shell elements, as a possible new technique for rebuilding the Philips pavilion as it has been build at the World Exposition ‘58 in Brussels (see Figure 8). Schmitz (2004) used form-finding software tools for the analytical modelling of fabric formwork, in order to predict accurately the resulting shapes after removal of the formwork.

2.2. Concept, Modelling and Shaping

The concept of using a flexible fabric as formwork for concrete elements has several advantages compared to traditional formwork solutions:

- Shape flexibility: changing column diameters, curved surfaces for panels or complex shell structures are nearly impossible to create with traditional formwork panels.
- Design optimization: the shape flexibility allows designers to correlate member design and

structural aspects. A beam formwork could for example take into account the actual moment curvature, as illustrated by Ibell (2009), and column heads could be designed to reduce problems with punching. In the search for lightweight structures, the formfinding of the shell could and should be included in the design process.

- The surface quality of the concrete: fabrics can modify the texture of the concrete, minimize the number of air bubbles or increase locally the water/cement-ratio by means of for instance a CPF ("controlled permeable formwork"). The effects largely depend on the type of fabric used.
- Transport: the weight and volume of the fabric formwork is very small compared to wood or steel, creating export opportunities. Additional falsework is however still needed.

When using fabric formwork, an important modelling stage precedes the actual formwork building. A number of choices have to be made with regards to: (1) the fabric characteristics, (2) the actual set-up including some kind of falsework, and (3) the allowable deformations during casting. These choices are based on an analysis of the stresses in the fabric with a formwork model.

In the framework of this project, the same approach as used for modelling textile architecture has been used, based on textile parameters (mainly bi-axial stiffness) and loading conditions (concrete self weight instead of wind or snow load). The modelling process, calculating an equilibrium state for the membrane, is based on the "force density" method, which starts the calculation from a pin-pointed or cable network (Schek 1973; Gründig 2006). Taking into account several boundary conditions, maximum stresses and deformations for the membrane and resulting forces on the borders are calculated. An iterative process results in an optimal material choice and final structural shape.

The modelling defines the formwork shape for fabric assembly, and calculates both formwork deformations during the application of the concrete, and the necessary pretension which needs to be applied to the fabric. This fabric pretension is an important issue to consider within each design since the deformation of the fabric after the application of the concrete can only be limited with sufficient pretension of the fabric.

Once the modelling step has been finalized, the software model might be used for making the cutting patterns that allow for the actual fabric formwork production.

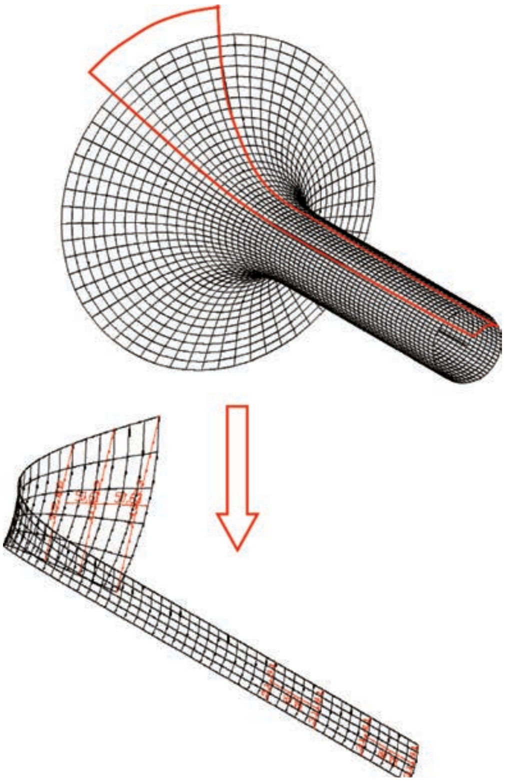

Figure 9. Simplified example of creating the cutting pattern (1/12th) for an axisymmetric column

Some simple shapes like straight-lined columns can be made out of one single piece of fabric. Most other elements however need a specific shaping of the fabric, for which the complete structure is subdivided in fabric pieces and recomposed afterwards. Several methods exist for creating these cutting patterns (Gründig 1996 and Figure 9).

2.3. Material Requirements and Formwork Production

Depending on the type of concrete elements to be cast, some minimum technical requirements for the fabric formwork can be listed:

- High elastic modulus, reducing deformations after concreting.
- A well-adapted surface quality, allowing for a good removal of the formwork of the concrete.

Because of these requirements, fabric types with rather high tensile strength (40–150 kN/m) at low deformations (18–30%) are selected. The elastic modulus ranges from 0.1 to 1 GPa and the tensile stiffness from 135 to 550 kN/m, based on bi-directional tests.

Both coated and non-coated woven PP, PE and PVC are used (Figure 10). The coated fabrics are impermeable and can give smooth or textured concrete surface finishes. The non-coated fabrics are slightly permeable which allows a limited drainage of excess water and air, similar to the CPFs.

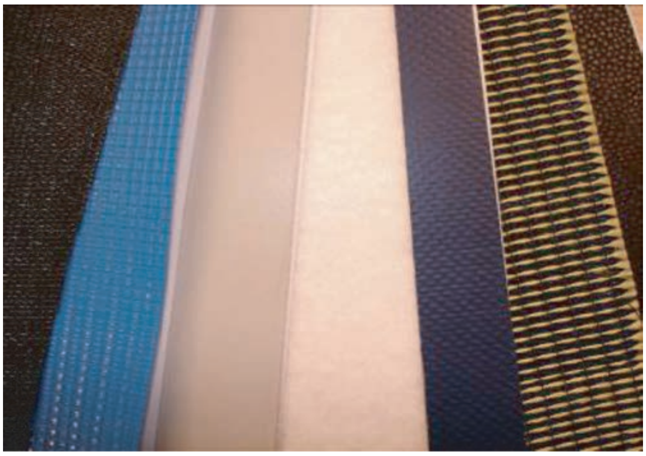

Figure 10. Range of fabric types

The formwork preparation usually includes an assembly step comprising the sewing or welding of the fabric pieces, starting from the cutting patterns. The falsework can be considered as a secondary construction. It allows furthermore for the fixation of the fabric and the application of the required pretension if any is needed.

3. GLASS FIBRE TEXTILE REINFORCED CONCRETE SHELL ELEMENTS: CONCEPT

Glass fibre Reinforced Concrete (GRC) mixes chopped glass fibres into a cement mortar or concrete before element production (with the premix method or the handspray method). GRC, containing no stiff and straight steel reinforcement, is nowadays often applied in small, curved, architectural elements. A functional example is the small span Sakan Shell emergency shelter by architect Kazuya Morita shown in Figure 11. As early as 1977, Schlaich used glass fibre reinforced concrete for a temporary shell for the Federal Garden Exhibition in Stuttgart, spanning 26 m with only 12 mm thickness (Holgate 1997). This structure, shown in Figure 12, designed to stand for six months, endured five years. During those five years it suffered damage to creep and brittleness and finally had to be demolished.

Figure 11. Sakan Shell Structure project, architect Kazuya Morita

Figure 12. GRC shell by Schlaich, for Federal Garden Exhibition in Stuttgart (Holgate 1997)

A disadvantage of reinforcing cement mortar or concrete solely with chopped strands is the resulting partially non homogeneous and disoriented distribution throughout the section and surface. This phenomenon reduces the fibre efficiency and the composite's tensile strength. Consequently, the function of the fibres in GRC is practically limited to reducing crack widths, improving durability and enhancing toughness of the composite. As a result, the design of curved GRC structural elements is restricted to shapes working mainly in compression.

The use of glass fibre textiles (shown in Figure 13) as reinforcement instead of chopped fibres eliminates these disadvantages of GRC: the fibre distribution is controlled, and, depending on the matrix particles size and textile geometry, larger amounts of fibres can be inserted into the matrix. These advantages result in a composite with a considerably higher and more reliable tensile strength, which can be taken into account in the design. Textile Reinforced Concrete (TRC) has already been successfully applied in numerous thin building elements experiencing both compressive and tensile stresses. Examples include flat sandwich panels for pedestrian bridges as shown in Figure 14 (De Roover 2002; Giannopoulos 2004), modular hyperbolic paraboloid sandwich roof panels (De Bolster 2009), large-size façade elements (Engberts 2006) and barrel vaults (Hegger 2008).

Whereas for GRC the glass fibres can easily be added to the fresh mixture with only limited adaptation of the manufacturing technique, glass fibre textiles need to be impregnated by the concrete layer by layer,

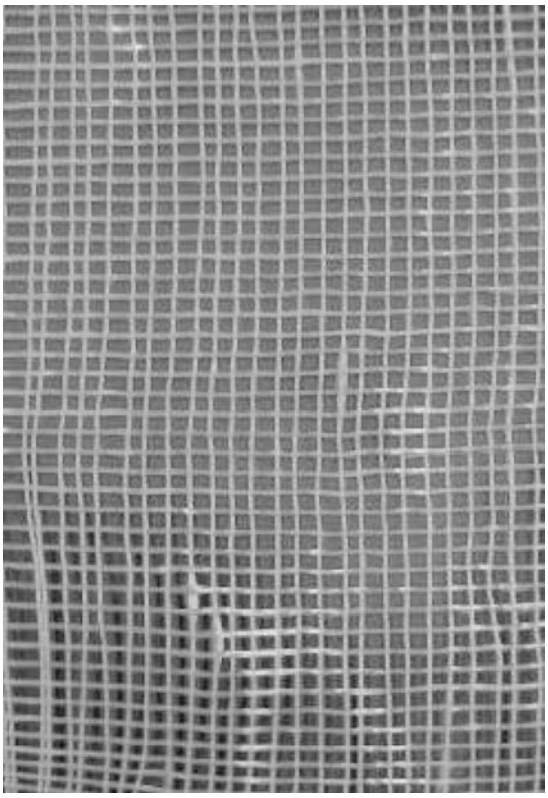

Figure 13. 2D AR glass fibre textile

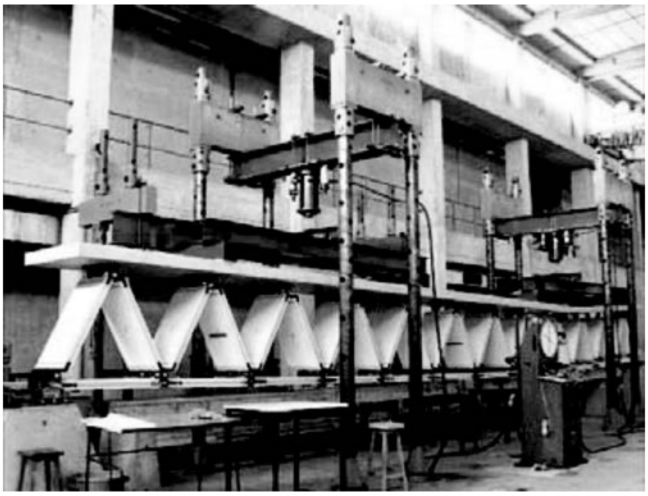

Figure 14. TRC sandwich panels applied in a pedestrian bridge

for example by hand lay-up or pultrusion. (Olivier 2008; Remy 2009). This paper proposes a total concept for the facilitated realization of strongly doubly curved shell elements, adapted to the practices of the construction industry. Wide 2D oriented alkali-resistant (AR) glass fibre textiles serve as reinforcement of Ordinary Portland Cement (OPC) shotcrete, sprayed on a fabric formwork. The open grid geometry of the 2D textile (Figure 13) and the AR-glass fibres permit the use of a fine grained (maximum aggregate diameter of 2 mm), commercially available OPC based mortar.

4. GLASS FIBRE TEXTILE REINFORCED CONCRETE SHELL ELEMENTS MADE ON A FABRIC FORMWORK: A COMPARATIVE NUMERICAL AND PHYSICAL CASE STUDY

4.1. Introduction

The potential of the proposed materials for the realization of doubly curved concrete shell elements, including flexible fabric formwork and textile reinforced shotcrete, is evaluated through the numerical and physical analysis of a laboratory scale shell element. The doubly curved shell, shown in Figure 15, spans 2 m × 2m and has a maximum height of 1 m. The proposed TRC is compared with the most widespread material used for shells - steel reinforced concrete - in terms of design, and structural behaviour.

Two shells having an identical geometry (shown in Figure 15) but made of steel-reinforced (SRC) and textile reinforced (TRC) concrete respectively, are analysed and designed for the same support conditions and load combinations defined in Eurocode 1 (Eurocode 1-1.1 2002). The fabrication of both shells will be used to prove the concept of doubly curved shells made of fabric formwork. The structural behaviour of both shell elements will be compared experimentally by a full scale test on both shells.

4.2. Design of Fabric Formwork

The fabric formwork has been designed according to the procedure defined earlier in this paper, starting with the CAD-drawing of the basic shape. The doubly curved shape is a minimal surface model calculated with Easy (Easy v.8), a software based on the force density

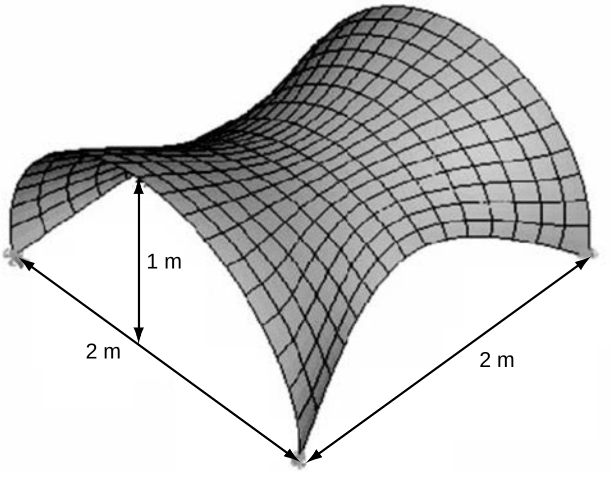

Figure 15. Geometry double curved shell element for case study

method. Different models of the tensioned textile were made for different fabrics, with force densities set between 0.5 kN/m and 2 kN/m. The formwork is fixed along two vertical arches and the two other boundaries are reinforced by a cable.

The calculation of the fabric stresses and deformations starts with an initial choice of fabric type and prestressing. The chosen fabric for these case studies is a PES textile, PVC coated, with an elastic modulus of 0.1 GPa and a tensile stiffness of 350 kN/m. The sole loading is the self weight of the concrete, with a thickness of 50 mm for the steel reinforced shell and 36 mm for the TRC shell. The necessary prestressing amounts to 1.5 kN/m. Based on the calculations, the resulting stresses in the textile can be verified.

The fabric for the formwork has been composed out of 3 pieces, a minimum to guarantee the specific shape (Figure 16). As mentioned earlier in this paper, several possibilities exist to create these cutting patterns. The more fabric pieces are used, the easier most (highly) curved shapes can be approached. An integrated rope and glass fibre bar ensures the good connection with the falsework. This approach is far different from the work of West (2006), where all elements are shaped by means of single flat sheets of fabric.

Figure 16. Fabric formwork after assembly of the fabric pieces

4.3. Design of Concrete Shells

The doubly curved shells are designed for their application in an enclosing roof, according to Eurocode 1 (Eurocode 1-1.1 2002; Eurocode 1-1.3 2003; Eurocode 1-1.4 2005). In serviceability limit state (SLS), the self weight load case was taken into account. In ultimate limit state (ULS), self weight, wind action and snow loads are taken into account. The wind load is approximated using the pressure coefficients for a cylindrical roof. This approach results in an asymmetrical wind load with varying pressure and suction areas on the transverse section of the shell. Different load cases are considered for snow: uniform, longitudinal linear accumulation towards the lowest sagging point and asymmetrical transverse distribution based on a cylindrical roof. The different load cases were combined - including safety factors and reduction factor for accompanying variable action - according to the described limit states. The most unfavourable ULS load combination for the design was determined to be the self weight with the asymmetrical wind load as main variable load, and the asymmetrical snow load as accompanying variable load.

Eurocode 1, part 1.4 (Eurocode 1-1.4 2003) states that the applied static approach for a dynamic wind load is only valid for structures exhibiting a first eigen frequency exceeding 5 Hz. This criterion is verified for both shells after the design.

To reduce stress concentrations in the shell corners, a bottom strip of 200 mm of the concrete shell corners was cut.

4.3.1. Steel-reinforced concrete shell

The steel reinforced concrete shell is linearly elastically analysed using the finite element programme FINELG (2004). The shell is mostly modelled by four node thin shell elements. At the pinned supports, some three node thin shell elements were used. Material parameters for concrete and steel are given in Table 1. The short term concrete Young modulus is applied for the wind and snow load cases, the reduced long term concrete Young modulus for the selfweight load case (long term concrete Young modulus = short term Young modulus

Table 1. Material parameters of concrete and steel reinforcement

	Compressive/Tensile strength f_{ck} (N/mm^2)	Safety factor γ_m	Elasticity modulus E (N/mm^2)	Dry density ρ (kg/m^2)
Concrete	35	1.5	35000 (short term) 11700 (long term)	2500 kg/m^2
Steel reinforcement	500	1.15	200000	

Table 2. Section forces and moments under ULS design load combination

	Max	Min
N_{xx} (kN/m)	27.3	–112.0
N_{yy} (kN/m)	16.9	–143.0
N_{xy} (kN/m)	98.9	–98.9
M_{xx} (kNm/m)	7.37E-2	–6.16E-2
M_{yy} (kNm/m)	0.16	–0.115
M_{xy} (kNm/m)	0.110	–0.110

divided by (1 + creep coefficient for the relevant time interval) according to §.7.4.3, EN 1992-1-1).

Due to the necessary concrete cover (Eurocode 2-1.1 2004) the 2 m span shell requires a minimum thickness of 50 mm (2*25 mm) which results in a self weight of 1.25 kN/m^2 shell surface. Due to the shell's large curvature and herewith associated large geometric stiffness, the vertical deflections under self weight are very low ($-6.9\ 10^{-5}$ m < span/250 = $8\ 10^{-3}$ m).

The maximum and minimum section forces and moments under the ULS load combination are given for both x and y directions in Table 2. Based on the positive and negative section moments of maximum 0.16 kNm/m, only 100 mm^2/m steel rebar (or a network of 6 mm diameter bars at 250 mm intervals) on the middle surface is necessary in both x and y directions. However, a higher steel percentage is preferable to improve the serviceability (crack control, creep, etc.) of the concrete shell (maximal distance between reinforcement bars equals 1.5 times concrete plate height according to Eurocode 2 ANB National Belgian Annex) (Eurocode 2-1.1 2004). Therefore, for the y-direction a 6 mm diameter rebar every 80 mm (1.5 times 50 mm height) is proposed. The resulting rebar distribution is shown in Figure 17. This results in a steel section of 350 mm^2/m in the shell centre and a reduced steel section at the boundaries of 135 mm^2/m. In the x-direction, 6 mm diameter rebars are placed every 150 mm (steel section equals 180 mm^2/m).

For this 50 mm thick shell, the first eigen frequency was verified to exceed 5 Hz, as required when using the static approach for dynamic loads prescribed in Eurocode 1-1.4 (2005).

This design confirms the assumption that steel-reinforced concrete is not the most efficient material for small span shell elements. First of all, the minimum 50 mm shell thickness is determined by corrosion cover requirements. Secondly, the steel reinforcement placed in the middle of the section, results in only half of the thickness being efficient to carry bending moments. Even so, due to the low section forces and moments in the small span shell, only a small reinforcement percentage is structurally required. However, due to the fact that a good distribution of the rebars is necessary to limit the crack width, an increased amount of reinforcement must be applied that is not efficient.

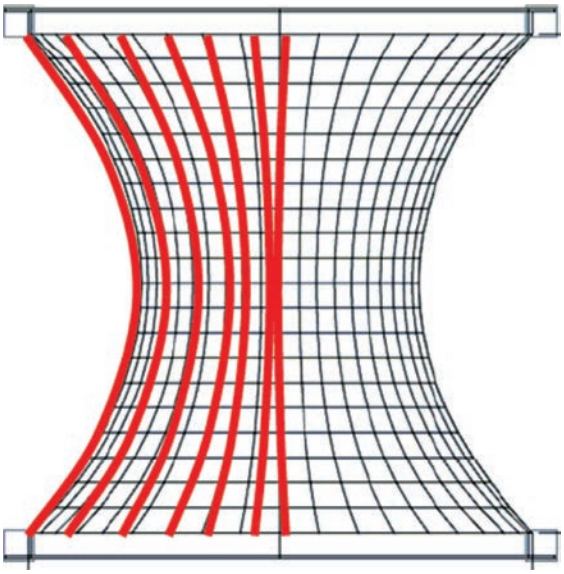

Figure 17. Reinforcement schedule in y-direction

With textile reinforcement, small diameter fibre bundles are homogeneously spread throughout the section and surface. Using textiles instead of steel rebars for small span shell elements could thus not only lead to a facilitated manufacturing process, but also to a structurally more efficient shell design.

4.3.2. Glass fibre textile reinforced concrete shell

The glass fibre textile reinforced concrete shell is designed using the finite element program Abaqus (2005). The shell is modelled with 15*21 thin shell elements with 5 degrees of freedom per node (three displacements and two in-surface rotations). The number of elements is selected to ensure computational convergence. The shell element is pin-supported at the four knotted edges.

The modelling of the TRC shell is approached differently because of the composite's different material behaviour. As the textile assures a homogeneous fibre distribution throughout the surface and section, the material can be considered isotropic on a macro scale. In practice, it is however hard to predict the fibre volume fraction and resulting tensile strength that will be achieved during the shell's manufacturing. Therefore, tensile tests were performed on 2 beam-shaped TRC specimen series with different fibre volume fractions

Table 3. Material parameters of glass fibre textile reinforced concrete (Tysmans *et al.* 2009)

Fibre volume	$f_{compression,k}$	γ_c	$f_{tension,k}$	γ_c	E_c	ρ
3%	35 N/mm^2	1.5	2 N/mm^2	2	20000 N/mm^2	1900 kg/m^3
7%	35 N/mm^2	1.5	10 N/mm^2	2	20000 N/mm^2	
13%	60 N/mm^2	1.5	40 N/mm^2	2	20000 N/mm^2	

(3% and 7%), and the shell design is carried out for both cases. The material parameters used for the analysis are shown in Table 3.

The minimum shell thickness is determined iteratively such that tensile and compressive stresses remain under their respective design values when the shell is loaded by the ULS load combination. This analysis results in a 36 mm thick shell design for 3 fibre volume percent TRC and a shell thickness of only 16 mm when a fibre volume of 7 % is achieved during manufacturing. Subsequently, the vertical deflections are checked under self weight. As in the case of the steel-reinforced concrete shell element, the deflections are well below the acceptable limit ($-7.51\ 10^{-5}$ m $< l/250 = 8\ 10^{-3}$ m for the 36 mm thick 3 fibre volume % shell and $-1.17\ 10^{-4}$ m $< l/250 = 8\ 10^{-3}$ m for the 16 mm thick 7 fibre volume % shell). Also, both shells have an eigen frequency exceeding 5 Hz. Finally, a linear perturbation buckling analysis performed in Abaqus (2005) showed that for this small span shells buckling was not the dimensioning design factor.

With no corrosion cover for AR-glass fibre reinforced concrete, TRC shells can be made only as thick as necessary to transfer the loads to the foundations. In other words, their thickness can be completely determined by the ULS. The discussed designs demonstrate that this fact is beneficiary for small span shell elements: the shell thickness is substantially reduced from 50 mm for the steel-reinforced shell to 36 or even 16 mm for the TRC shell. In the TRC shell all material is used in a structurally efficient way.

Tysmans *et al.* (2009) showed that the increase of the fibre volume fraction to 13 % results in the similar shaped shell with 8 mm thickness fulfilling both ULS and SLS requirements. This high fibre volume fraction was achieved by combining very dense randomly oriented glass fibre textiles with a fine grained Inorganic Phosphate Cement (maximum diameter of solids of 100 μm, elevated compressive strength of 60 MPa) with the labour intensive hand lay-up manufacturing technique. As TRC is a very versatile composite, different fibre volume fractions can be achieved with different production techniques, and very thin shells can thus be produced. Production costs are however quite high: the matrix cost increases significantly when adapted to a high fibre volume fraction, and more importantly the manufacturing becomes labour intensive and thus less economical. In this study, the open grid textile - shotcrete production technique is explored. This method can practically be integrated into the construction industry.

4.4. Manufacturing of Double Curved Concrete Shells

The practical manufacturing feasibility of the case study is evaluated by fabricating a steel-reinforced and a textile reinforced shotcrete shell on fabric formwork.

The actual fabric formwork design and production has been discussed in section 4.2. The falsework (for fabric formwork this will be the secondary structure onto which the fabric is fixed) consists out of two steel arches that support the fabric (arches A and B in Figure 18). A third arch allows the application of the prestressing in the membrane. A pretension of about 1.5 kN/m has been used. The fabric pretension has been monitored with a set of load cells installed between one of the main arches (arch B) and the third arch. These cells also monitor the additional load during the casting process. Figure 19 illustrates the final formwork configuration, ready for concreting.

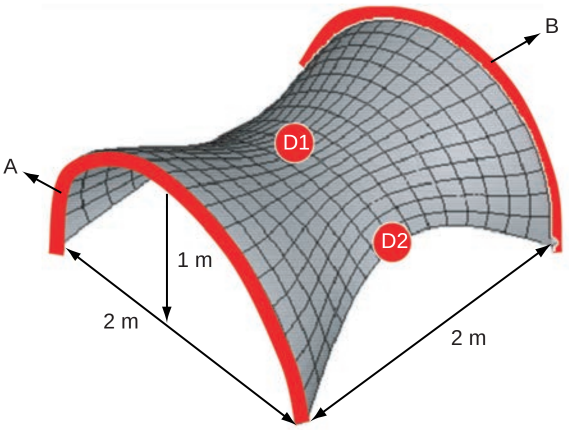

Figure 18. Arch design with indication of the fixation (steel arches A and B used as falsework) and displacement measuring points

Figure 19. Formwork setup before casting

Figure 21. Applying the textile reinforcement

Figure 20 shows how the steel reinforcement was first shaped and placed 25 mm above the fabric surface with spacers for the production of the steel-reinforced concrete shell. Then the shotcrete mortar was applied up to a slightly varying, but overall thickness of 50 mm.

The preparations for the TRC shell only implied the cutting of the fibre textiles to the correct dimensions. The textile roll being 1.20 m wide, an overlap between two strips of the textiles was foreseen to cover the surface of the entire 2 m span shell. In total four 2D fibre textiles (Figure 21) were laid on the curved shell surface, one after every shotcrete layer of about 7 mm. The impregnation of the fibre mats was improved manually by rolling the textile into the concrete. As the individual shotcrete layers were rather thick (7 mm), only the lowest fibre volume fraction (3%) was achieved. As a consequence, the shell thickness needed to be 36 mm. By refining this manufacturing method, a higher volume fraction and thus a thinner shell can be obtained.

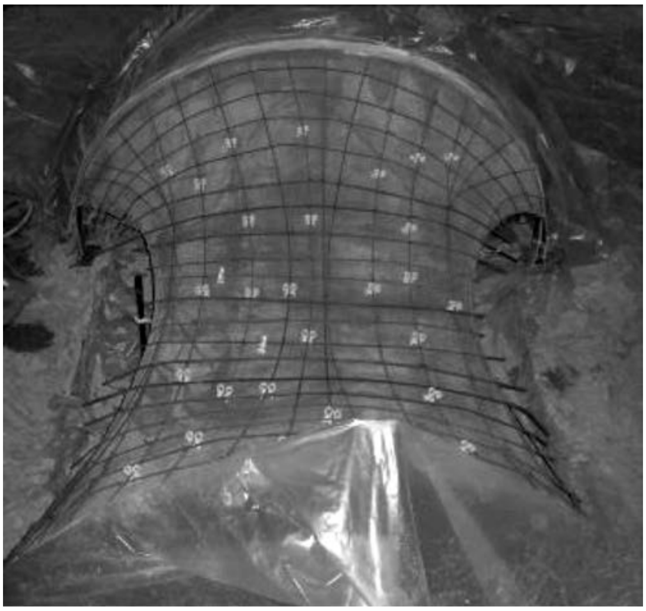

Figure 20. Placing of the steel reinforcement

Using shotcrete (see Figure 22), the actual concreting of the shell only took two hours. The facilitated manufacturing clearly demonstrates the advantage of the flexible reinforcement and its combination with shotcrete for highly curved shells.

Figure 23 shows the results of the monitoring during the casting of the steel-reinforced shell element. The measured force indicates the level of prestress and the additional load during the casting. The displacement measurements can be compared with the modelling. Displacement D1 has been measured in the centre of the shell, for which the model predicted a final value of 16 mm (14 mm measured). Displacement D2 has been

Figure 22. Concreting of the shell on fabric formwork with shotcrete

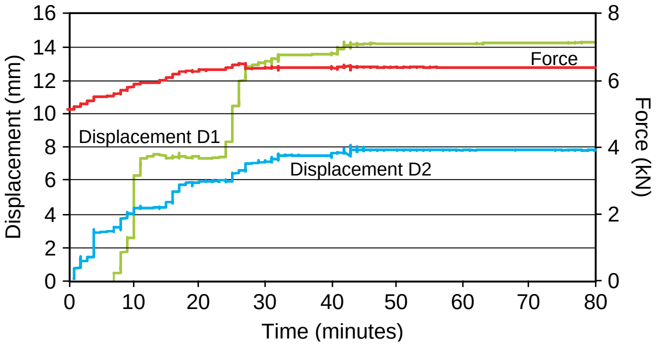

Figure 23. Force and displacement measurements during the casting

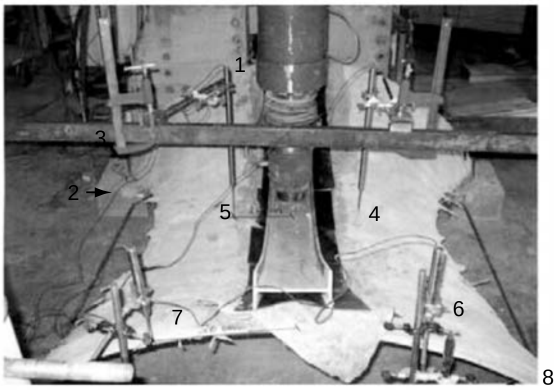

Figure 25. Displacement measuring locations on shell

measured on the border of the shell (both locations are indicated in Figure 18). This comparison between full-scale tests and the model clearly show the existing capacity to model and master the resulting shape.

4.5. Structural Testing of Concrete Shells

The structural capacities of the steel and glass fibre textile reinforced concrete shell elements are compared by means of a full scale test. Section 4.3 showed how both shells were designed for the same load combinations for roof application. As discussed before, the steel reinforced concrete shell has a slightly varying, but overall minimum thickness of 50 mm. One reinforcement layer with 6 mm diameter rebars is placed at the shell's neutral axis (80 mm spacing in the y-direction, 150 mm spacing in the x-direction, see Figure 20). The glass fibre textile reinforced concrete shell measures minimally 36 mm and contains 4 textile layers equally spaced throughout the thickness.

Both shells are loaded by a gradually increasing line load in the middle of the shell. Figure 24 illustrates the experimental set-up. A steel I-profile is curved to fit the shell's curvature and placed along the shell's longitudinal axis. A layer of mortar between the I-profile and the shell ensures full contact between the two. The steel profile is loaded in its centre by a servo-hydraulic testing equipment, at a speed of 0.5 mm per minute. The shell's supports are imbedded in concrete blocks, whose displacements are restrained by in plane bracing between the blocks. The shell's vertical displacement is measured by extension meters at several positions, i.e. (A) at the centre, at 250 mm distance of the loaded y-axis (locations 4 at side 1 and 5 at side 2 in Figure 25), (B) at the outside arch, on 300 mm distance of the loading axis (locations 6 at side 1 and 7 at side 2 in Figure 25) and (C) at the corner (locations 2 and 3 in Figure 25). Due to the load and shell symmetry, measuring the displacements of one fourth of the shell would suffice, however the vertical displacements were also monitored at the symmetric sides on the same relative location to measure any asymmetrical response.

Figure 24. Test set up for shell element under line load

Figure 26 compares the mechanical behaviour of the glass fibre textile reinforced concrete (TRC) shell with the steel-reinforced concrete (SRC) shell during the full-scale flexion tests. The figure plots the vertical displacement at location A (centre of the shell at

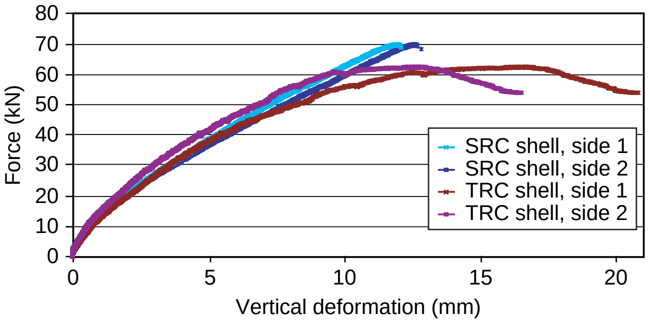

Figure 26. Vertical deformation at location A (centre of the shell) in function of the total applied load

250 mm of the y-axis on both sides) in function of the total applied load. The TRC shell reaches a maximum total load of 62 kN with a vertical displacement near the shell centre of 11 mm before failure at the corners. The steel-reinforced shell also failed at the corners, at a total load of 70 kN with a vertical displacement of 12 mm. This corner failure corresponds to the stress concentrations at the shell corners observed in the finite element model. The TRC shell shows a comparable strength and behaviour to the steel-reinforced shell. The low amount of fibres suffices to limit the crack width and resist the occurring tensile stresses in the TRC shell. Moreover, whereas the SRC shell loses its load-bearing capacity immediately after failure due to the non-optimal placing of the reinforcement (at mid-height), the TRC shell shows a strongly improved ductility. This ductility can be ascribed to a more closely spaced distribution of the thin fibre bundles over the surface as well as over the shell's thickness.

5. CONCLUSIONS

This paper proposes a total concept for the realization of small span strongly double curved concrete shells and validates the method by means of a case study on a laboratory scale shell element. Fabric formwork has proven its potential for application in shell manufacturing, by offering full shape flexibility for the design, resulting in a formwork that is easy to master during use.

This shape flexibility of the fabric formwork can be combined with the use of flexible textile reinforcement, removing another limitation for producing more creative, curved concrete elements. The Textile Reinforced Concrete (TRC) shell can be designed thinner and structurally more efficient. Moreover, the manufacturing process is significantly facilitated due to the flexible textile and the use of shotcrete. Finally, the mechanical testing of the TRC shell in flexion showed comparable strength and improved ductility with reference to the steel-reinforced concrete shell.

In conclusion, when combining the reusable fabric formwork with textile reinforced shotcrete, highly curved concrete shell elements become an economical alternative for traditional linear structures.

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