# SHELL ELEMENTS OF ARCHITECTURAL CONCRETE USING FABRIC FORMWORK – PART B: CASE STUDY

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## 1 INTRODUCTION

Modern architecture nowadays tends towards impressive shapes with three-dimensional curvature. Part A of this paper demonstrates that with the use of fabric formwork a considerable increase in architectural freedom is gained. Diameter-varying columns and doubly curved shells can be realised with fabric formwork. With this evolution, the demand for suitable materials for the free form shells themselves rises as well.

Concrete is the ideal choice for free form shells as it can be poured into any shape. The form freedom of steel-reinforced concrete shells is however limited due to the practical difficulties in positioning and shaping the steel reinforcement bars. The high cost associated with placing the reinforcement makes freeform steel-reinforced concrete shells often an uneconomical solution. Another disadvantage of using steel reinforcement is the necessity of a concrete cover, which causes increased dead weight and shell thickness (the minimal concrete cover on both sides amounts to approximately 2.5 - 3 centimetres, depending on the exposure coefficient [1]).

A promising alternative for the classical steel reinforcement for shell structures is the use of fibre reinforcement. As the reinforcement diameter is considerably reduced, the reinforcement becomes very flexible and the manufacturing of freeform shells is much easier. At the same time the reinforcement ratio and thus tensile strength can be retained by using dense fibre mats. Examples of these are depicted in Figures 1a and 1b. Moreover, when using a non corrodable reinforcement such as glass fibres, the concrete cover can be omitted and the shell self weight can be decreased. Especially for small span shells, this could lead to thinner shells than when using steel-reinforced concrete.

In this paper, a comparison between steel-reinforced and glass fibre textile reinforced concrete is performed by means of a case study. A small span doubly curved shell (Figure 2) is designed for both material types, and the resulting thickness is compared. Consequently, the shell is manufactured on a fabric formwork with respectively steel-reinforced and glass fibre textile reinforced shotcrete. With this, the first advantage of using a flexible reinforcement – the facilitated manufacturing - is highlighted. Both shells are then submitted to an increasing line load and loaded up to failure. The test results show promising results for the combination of the alternative fibre reinforcement with concrete.

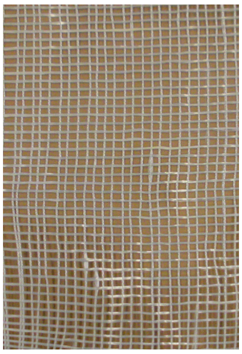

**Fig. 1a** 2D glass fibre textile

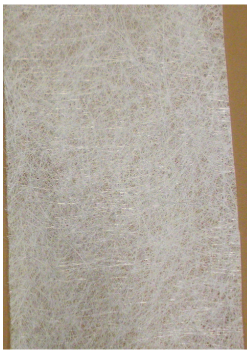

**Fig. 1b** Randomly oriented glass fibre textile

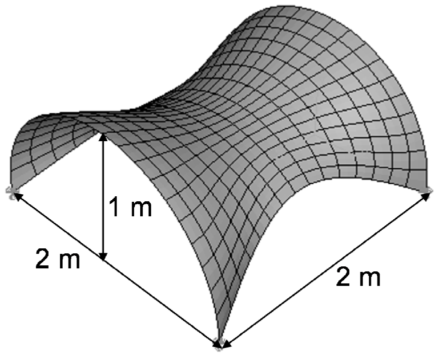


**Fig. 2** Studied doubly curved shell

## 2 DESIGN OF DOUBLY CURVED SHELL: STEEL REINFORCED VERSUS FIBRE TEXTILE REINFORCED CONCRETE

In order to demonstrate the advantages of using fibre textile reinforced concrete (TRC) for slender small span shells, the doubly curved shell depicted in figure 2 is dimensioned for different reinforcements. The comparison of the design is made for steel-reinforced concrete and AR-glass fibre textile reinforced concrete with different fibre volume fractions.

The doubly curved shell has a span of 2 m and a maximum height of 1 m. The relatively small span is chosen in order to enable the manufacturing on lab scale. The bottom 20 cm of the shell corners is cut to reduce the stress concentrations in the corners, which are hinged. The doubly curved shell is designed according to the Eurocode 1: Actions on structures [2]. Self weight, wind and snow loads are combined (including safety factors) according to the limit states described in Eurocode 1. Only a static analysis is performed in this preliminary design.

### 2.1 Steel-reinforced concrete shell

The material parameters of the used steel and concrete are given in table 1. A linear elastic analysis of the shell is performed in the finite element program FINELG. The shell is modelled by mainly 4 node thin shell elements. At the supports, some 3 node thin shell elements are used.

**Table 1** Material parameters of concrete and steel reinforcement.

| | $f_{ck}$ | $\gamma_c$ | $E_c$ | $\rho$ |
|---|---|---|---|---|
| **Concrete** | 35 N/mm² | 1.5 | 35000 N/mm² (short term)<br>11700 N/mm² (long term) | 2500 kg/m³ |
| | $f_{yk}$ | $\gamma_s$ | $E_s$ | |
| **Steel Reinforcement** | 500 N/mm² | 1.15 | 200000N/mm² | |

Due to the necessary concrete cover, the 2m span shell is minimally 5 cm thick (2*2.5 cm). Calculations show that a minimum orthogonal steel rebar grid of 6 mm diameter, placed at the shell's midplane, suffices for the shell to resist the considered load combinations (see Figure 3). It can be expected that for such a small span shell only a very low amount of steel reinforcement is needed. Even when this reinforcement is placed at the shell's midplane and can thus resist to smaller bending moments, the minimum reinforcement still suffices. It must be emphasized that, because the reinforcement can never be put close to the outside surfaces, it works inefficiently against bending. Moreover, the minimum shell thickness was 5 cm, which was not a structural but a corrosion resistance requirement. In conclusion, steel-reinforced concrete does not lead to slender designs for small span shells.

### 2.2 Glass fibre textile reinforced concrete shell

The design of the 2 m span shell in TRC is approached differently because of the composite's different tensile behaviour in comparison with steel-reinforced concrete. When fibre amounts larger than the critical fibre volume fraction are inserted in the cementitious matrix, multiple cracking occurs when the matrix tensile resistance is reached. In this case, cracks are not modelled individually but modelled as a general loss in stiffness and the material can be considered isotropic on macroscale. Material parameters such as stress-strain curve and tensile strength depend amongst other parameters (such as fibre-matrix interface) on this fibre volume fraction.

For the design of the 2 m span TRC shell different fibre volume fractions are considered; material properties are given in table 2. Obviously, the higher the fibre volume fraction is, the higher the tensile capacities of the matrix are. The lower fibre volume fraction was obtained by using the 2D glass fibre textile depicted in Figure 1a ([3]). To achieve 13 fibre volume %, dense randomly oriented glass fibre textiles (Figure 1b) were used. It must be mentioned however that the manufacturing technique (hand-layup) and the matrix (granulate size) needed to be adapted to this high textile density ([4]). This raises the price of the matrix and more in general the price of the composite structure. To manufacture the shell it was therefore chosen to apply the 2D textile with fine grain shotcrete.

**Table 2** Material parameters of glass fibre textile reinforced cementitious composites.

| Fibre volume % | $f_{compression,k}$ | $\gamma_c$ | $f_{tension,\ k}$ | $\gamma_c$ | $E_c$ | $\rho$ |
|---|---|---|---|---|---|---|
| **13 %** | 35 N/mm² | 1.5 | 40 N/mm² | 2 | 20000N/mm² | 1900 kg/m³ |
| **7 %** | 35 N/mm² | 1.5 | 10 N/mm² | 2 | 20000N/mm² | |
| **3 %** | 35 N/mm² | 1.5 | 2 N/mm² | 2 | 20000 N/mm² | |

The design rule for the doubly curved shell proposed by the author in [4] and which resulted from an analysis of the shell under Eurocode load combinations in the FE program Abaqus, is applied to determine the minimum thickness. The resulting thickness of the 2 m span doubly curved shell is only 8 mm for 13 % TRC. Due to their lower tensile capacity, the 7 % TRC shell should be 16 mm thick and the 3 % TRC shell should be 36 mm thick. A few things can be concluded from this. First of all, in general the use of glass textile reinforced concrete instead of steel reinforced concrete can lead to a considerable decrease of the thickness of small span shells. Moreover, as with TRC the reinforcement can be put very close to the outside surfaces, the reinforcement is more efficient to carry bending moments. More specifically when applying TRC, one can modify the composite depending on the structural requests. Lower fibre volume fractions are more economical as the matrix is cheaper and easier to apply (shotting). A higher fibre volume fraction leads however to an even more reduced thickness, which may be of importance when extreme slenderness is required.

## 3 MANUFACTURING AND MECHANICAL TESTING OF DOUBLY CURVED SHELLS

In this part of the paper, the practical feasibility of the case study is evaluated by fabricating a steel-reinforced and a textile reinforced shotcrete shell. The doubly curved shell (Figure 2) is manufactured on a fabric formwork. More details about the fabric formwork can be found in the first part of this paper; here focus is put on the manufacturing of the shell itself. The facilitated manufacturing clearly demonstrates the advantage of the flexible reinforcement. The shaping of the steel reinforcement and its placing alone took a full day (see Figure 3), while less than an hour preparation was necessary for the fibre textile reinforcement to be cut in the appropriate dimensions. With the use of shotcrete, the actual concreting of the shell only took about two hours in both cases. In the case of the flexible reinforcement, the 2D fibre textile (Figure 1a) was laid on the shell after every shotcrete layer. The impregnation of the fibre mats was improved manually by rolling the textile into the concrete.

The individual shotcrete layers were rather thick at manufacturing so that only the lowest fibre volume fraction (3 %) considered for design was achieved and the shell needed to be 36 mm thick. This however can be improved in the future. Due to the difficulties in controlling the thickness of the shotcrete layers, the thickness of the TRC shell varied locally between 3.5 cm (the designed minimum) and 5 cm. The manufactured steel-reinforced and glass fibre textile reinforced shotcrete shells have thus approximately the same thickness.

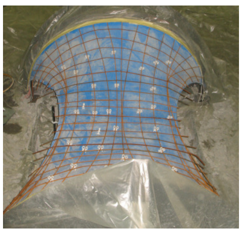

**Fig. 3** Steel reinforcement before concreting

**Fig. 4** Test setup: line load on doubly curved shell

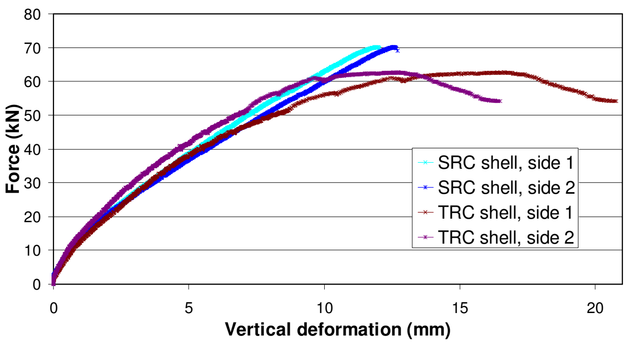


**Fig. 5** Vertical deformation at shell centre in function of total applied load

Both shells were loaded up to failure by a gradually increasing line load in the middle of the shell (Figure 4). The corners were imbedded in concrete blocks, attached to each other by steel bars. The vertical displacement was measured by extensionmeters in the middle of the shell, on both sides of the line load (at 25 cm of the load centre). This vertical displacement in function of the total applied load is given in Figure 5 for both the textile reinforced (TRC) and steel-reinforced (SRC) concrete shell. The TRC shell reached a maximum total load of 62 kN with a vertical displacement near the shell centre of 11 mm. The steel-reinforced shell failed at a total load of 70 kN, with a vertical displacement of 12 mm. Both shells failed in the corners, where large compressive stresses occur. The TRC shell shows a comparable behaviour to the steel-reinforced shell, and the low amount of fibres sufficed to limit the crack width and resist low tensile stresses.

A rough finite element model was made in Abaqus to simulate the behaviour of the TRC shell under the line load. The tensile strains measured with strain gauges (of 6 cm length) during the test as well as the failure load corresponded well to the rough model, considering the fact that a uniform thickness equal to the minimum shell thickness of 3.5 cm was used for the model, as well as approximations for material properties and the applied line load and supports.

## 4 CONCLUSIONS

In this paper, glass fibre textiles are shown to be a promising alternative for steel reinforcement in freeform concrete shells. Firstly, it has been proven that the use of this flexible reinforcement eases the manufacturing of freeform shapes. This advantage becomes even more pronounced when using shotcrete, for example on a fabric formwork. Mechanical testing of a doubly curved shell in glass fibre textile and steel reinforced concrete respectively, led moreover to comparable strength and vertical displacement of the shell under a line load.

By means of a case study, which designed a 2m span doubly curved shell according to the Eurocode, it was proven that the use of glass fibre textile reinforced concrete instead of steel-reinforced concrete leads to an important reduction of the necessary shell thickness. Slender small span shells can thus be designed and fast and easily manufactured with relatively open 2D glass fibre textiles and shotcrete. By optimising the structure to a shape that mainly works in compression and where only low tensile stresses need to be carried and crack widths need to be limited, the thickness of small span shells could be even more decreased. In the case-study it was also shown that higher fibre volume fractions can lead to even more slender shells, however matrix and production method then need to be adapted, which increases the price significantly.

## ACKNOWLEDGEMENTS

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