EXPERIMENTAL AND NUMERICAL ANALYSIS OF TEXTILE REINFORCED CEMENT COMPOSITES AS TENSILE REINFORCEMENT IN CONCRETE SHELLS.

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Abstract: Textile reinforced cement (TRC) composites are increasingly studied as a material for structural stay-in-place formwork for concrete structures, because elements with low thickness and relative high mechanical capacities can be produced. Current envisioned formwork applications - beams, slabs, columns - do not exploit another advantage of TRC’s, namely that the flexible textile reinforcement allows an exclusive freedom of form. With TRC, freeform moulds are easily prefabricated to serve as structural formwork for shells, facilitating the construction on site. This paper investigates the contribution of TRC formwork to the loadbearing behaviour of concrete shells. Tests are performed on a TRC reinforced spherical shell of 2m span and 200mm height, subjected to a distributed load. The experiment is compared to a numerical simulation performed in the finite element software Abaqus. The test shows promising results for TRC as reinforcement as the TRC layer contributes significantly to the concrete section. The finite element model shows similar behaviour as monitored during the test. This model allows to further develop the design methods for concrete shells with a stay-in-place TRC formwork and reinforcement. With the use of TRC composites, a more efficient and faster construction method for concrete shells is just around the corner.

INTRODUCTION

The construction of concrete shells is one of the challenges in civil engineering in western regions. Firstly, the current formwork methods for concrete shells, i.e. timber moulds [1] and foam blocks [2], are labour intensive and/or material wasting. Currently, research is performed on alternative formwork methods like flexible fabrics [3], [4] pneumatic formwork [5] or hybrid cable-net and fabric formwork [6]. These systems are flexible enough to easily realize curved surfaces, however they still experience relatively large deformations when casting concrete. Secondly, the placing of the rigid traditional steel reinforcement limits the curvature, is labour intensive and therefore increases the cost. Recently, alternative reinforcement methods based on fibre textiles are investigated in concrete shells, namely fibre and textile reinforced cements (FRC / TRC), like demonstrated in [7] and [8]. However, these alternative methods do not solve the formwork problems discussed before. Considering these issues, we developed an inventive formwork solution, which exploits the properties of textile reinforced cement (TRC) composites. These TRC composites are composed of a continuous fibre system, a textile, which is impregnated with a cementitious matrix. While this cementitious matrix is wet, the impregnated textile remains flexible (Figure 1a) and can be shaped onto any (reusable) mould, like e.g. a pneumatic formwork (Figure 1b). The low weight of the thin TRC layer compared to the concrete, which is normally directly cast onto these moulds, prevents large deformations and thus ensures a final shape closely approximating the initially designed shape.
Figure 1: While the cementitious matrix is wet, the textile remains flexible (a), and can be shaped on e.g. (reusable) pneumatic formwork (b).

After hardening of the cement, a thin composite is obtained which is rigid enough to withstand the casting of the concrete. When the concrete is hardened the stay-in-place formwork gets an additional structural function, i.e. as (partial) tensile reinforcement of the final concrete structure. The structural capacity of TRC stay-in-place formwork was already demonstrated for beam elements in [9] and [10]. This paper presents the experimental and numerical analysis of a TRC reinforced concrete dome. Firstly, the plain concrete dome, reinforced by the stay-in-place TRC formwork, is subjected to a point load. Secondly, the experiment is numerically simulated within the finite element software Abaqus. Finally, the experiment and the model are compared and conclusions are drawn.

EXPERIMENTAL ANALYSIS OF A TRC REINFORCED DOME

Materials and experimental setup

During the test, a TRC composite consisting of a textile mat of 300g/m² random E-glass fibres impregnated with Inorganic Phosphate Cement - IPC (18 % fibre volume fraction) - [11] is used in combination with concrete. Their mechanical properties are found in table 1.

<table>
<thead>
<tr>
<th>Properties concrete</th>
<th>Properties TRC</th>
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<tbody>
<tr>
<td>Compressive characteristic strength</td>
<td>50 MPa</td>
</tr>
<tr>
<td>Compressive characteristic strength</td>
<td>80 MPa</td>
</tr>
<tr>
<td>Tensile characteristic strength</td>
<td>4.1 MPa</td>
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<td>Tensile characteristic strength</td>
<td>40 MPa</td>
</tr>
<tr>
<td>Young modulus</td>
<td>35.7 GPa</td>
</tr>
<tr>
<td>Young modulus stage 1</td>
<td>18 GPa</td>
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<tr>
<td>Young modulus stage 2</td>
<td></td>
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<tr>
<td>Young modulus stage 3</td>
<td>4 GPa</td>
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</tbody>
</table>

The mechanical behaviour of glass fibre textile reinforced IPC (GFTR-IPC) differs significantly in compression and tension because of the brittle matrix. In compression, the composite is assumed to be linear elastic until failure [12], but in tension, it shows already a nonlinear behaviour at low tensile stresses - around 7 MPa - (Figure 2) due to the low tensile failure strain of the matrix relative to that of the fibres.
The geometry and experimental setup of the concrete dome are shown in Figure 3. The concrete dome has a span of 2 m, a height of 200 mm, a concrete thickness of 20 mm and it is reinforced with a 5 mm thick TRC. The shell is subjected to a point load ($\phi$100 mm) on the top. To restrict the horizontal displacement the edge is encircled with wooden panels.

Figure 4 shows the production process of the TRC reinforced concrete spherical dome. The glass fibre mat is placed in a foam mould (a) and impregnated with a cementitious matrix (IPC) (b). To obtain a TRC formwork of 5 mm, ten layers of mats are needed. After hardening, the composite is turned and a strong and stiff formwork is obtained (c). A rougher contact surface - by adding a layer of small stones - is created to assure the bond (d). Rubber rulers are placed on the formwork to control the concrete thickness during casting (e and f). The shell is tested after 31 days.
The experiment is monitored by strain gauges and Digital Image Correlation (DIC). For the DIC, two areas of approximately 400 x 400 mm (light blue squares in Figure 3) were monitored by two 3D camera systems. Strain gauges are placed on both the TRC layer (so in between the TRC formwork and concrete before, blue lines Figure 3) and on top of the concrete (red lines Figure 3), both in meridional and hoop direction. The nomenclature of the strain gauges is defined by three parameters:

1 M: meridional direction  
2 Position (see Figure 3)  
3 C: on concrete layer  
H: hoop direction  
R: on TRC layer  
S: 45° direction

**Results during testing of the TRC-concrete shell**

The vertical deformation of the top centre, measured by the load cell, of the TRC reinforced concrete dome is shown in Figure 5. The curve is linear up to 17.5 kN, where a first drop occurs. In an initial assumption this could indicate that the shell remains intact up to this drop, where after cracks initiate within the concrete material until the ultimate load of 18.7 kN. Finally, the load decreases to a constant value of 2 kN, where the test was stopped.

![Graph showing load progress](image)

**Figure 5:** Load progress shows two dropping points (at 17.5 kN and at 18.7 kN).

Figure 6 shows the shell after testing. During the experiment visible cracks initiated from the top along radial lines, exactly where the rubber rulers were placed while casting. Hereafter, a circular crack initiated around the point load. When the constant load of 2 kN is reached, no other visible cracks were formed. After the test, the concrete layer proved to be
completely debonded from the TRC shell, indicating the loss of composite action between both (Figure 6b).

![Images of debonding](image1.jpg) ![Images of debonding](image2.jpg)

Figure 6: Cracks formed along the radial lines were rubbers were placed (a) and debonding of TRC and concrete (b).

The strains monitored by the strain gauges are shown in Figure 7a, b, c and d.

![Graphs of strains](image3.jpg) ![Graphs of strains](image4.jpg)

Figure 7a shows the meridional strains on positions 2 and 4, on a quarter span of the dome. The strains on the TRC layer (M2R and M4R) are both in compression and have the same
curve up to 13 kN. From here on the axisymmetric behaviour clearly vanishes, indicating the initiation of damage, probably by concrete cracks. This phenomenon was however not observed in Figure 5, where the initial constant stiffness is retained until a load of 17.5 kN. A possible explanation for this phenomenon can be found in the crack bridging capacity of the TRC stay-in-place formwork, as is already observed for TRC external beam reinforcement [14] and [15]. Surprisingly, the strains on the concrete layer (M2C and M4C) do not exhibit a similar behaviour, not even before the initiation of the cracks. Considering the similar evolution of M2C to M2R and M4R, it can be assumed that a measurement error occurred for M4C.

The hoop strains on position 2 and 4 are shown in Figure 7b. Until the first crack, the strains on the TRC layer (H2R and H4R) are in tension and behave similar. The concrete layer also appears in tension (H2C), however it shows a breakpoint at 8 kN, which is again not noticed in load-deflection behaviour (Figure 5). The tension in the hoop direction explains the first concrete cracks, induced along the radial lines. Comparison of Figure 7a and b indicates the expected biaxial stress state of the shell, as the meridional strains are in compression and the hoop strains are in tension.

Figure 7c shows the strains on the centre top of the TRC layer. S3R and M3R behave opposite and H3R shows no similarities. However, a similar behaviour is expected on the top in an axisymmetric geometry. This discrepancy can be explained by imperfections: i.e. load not perfectly in the middle, strain gauges not perfectly placed at the centre, etc. However these strains remain limited in comparison with the ones obtained at a quarter span.

The meridional and hoop strains near the edge (position 5) are shown on Figure 7d. The meridional strains on both layers (M5C and M5R) are in tension until 10 kN, where after they switch to compression. For the hoop strains on both layers (H5C and H5R) the opposite phenomenon occurs. However up to 10 kN this observation is opposite to the expectations, which are similar to Figure 7a and b, namely meridional strains in compression and hoop strains in tension. This can possibly be explained by the lateral supports of the shell; the zone near the edge moves up due to the central loading. This effect leads to tension in the radial direction and compression in the hoop direction until the first concrete crack.

Up to concrete cracking the strains are as expected. Here after the axisymmetry is lost and the behaviour becomes unpredictable. The initiation of cracks is however well noticed in the strain curves by several breakpoints at 10 and 13 kN, indicating that the cracks are probably initiated at a lower load than 17.5 kN, which was initially assumed based on the constant stiffness in the load-deflection curve. The tensile strains in the TRC remain limited up to shell failure and do not exceed 400 με, which falls within the first linear part of the TRC stress-strain diagram (Figure 2). Thus, no stresses higher than 7 MPa are obtained, which is only 17.5 % of the tensile strength of the TRC (40 MPa). The DIC observations show qualitative results concerning the displacements over the surface of the shell. The vertical displacement of several points during loading is shown in Figure 8. All points follow the same trend, namely a downward displacement followed by a sudden upward displacement. The upward movement indicates the debonding of concrete and TRC, induced by the cracks in the concrete. These breakpoints approximately correspond to the two main drops in the load-deflection curve at 17.5 kN (400s) and 18.7 kN (800s) (Figure 5).
**Numerical analysis of a TRC reinforced dome**

The experiment is simulated using the finite element (FE) software Abaqus and the experimental results are compared with the numerical ones.

**Model build-up**

The numerical model of the dome is built up in two parts, which are placed on each other as two layers; the TRC layer is modelled as a shell part with a continuous shell section and the concrete layer is modelled as a solid part with continuous solid section.

For the TRC layer two types of linear elements are used, namely the 3-node S3 and the 4-node S4R elements, which are elements for doubly curved thin or thick shells with reduced integration. For the concrete layer, the 8-node C3D8R elements are used, which are linear bricks with reduced integration. Mesh convergence was checked for this geometry; in the end, elements with a seed of approximately 30 mm were used, chosen as a compromise between accuracy and calculation time.

The material behaviour for both the concrete and TRC layer are modelled with the Concrete Damaged Plasticity (CDP) model, which is inbuilt in Abaqus. Wozniak proved in [13] that the CDP model predicts the TRC material’s behaviour the best. As the concrete is cast on the TRC layer, the bond between the two material layers is not perfect and is therefore taken into account in the numerical model. The bond is modelled by the inbuilt cohesive behaviour in Abaqus, which has the possibility to include the damage of the bond. The parameters needed for modelling the bond are described in [16]. The dome’s edge is re-
stricted in three directions. The model is loaded by its self-weight and a point load, which gradually increases to 20 kN, at the centre top with a diameter of 100 mm.

**Numerical results**

The comparison of the measured strains during the experiment with the numerically calculated strains are shown in Figure 9 a and b. The numerical results are represented by a dotted line. The numerical model predicts general trend well, namely the biaxial behaviour of the shell, which means the meridional strains are in compression and the hoop strains in tension. Moreover, the order of magnitude is also well predicted. However, individually some differences are observed.

Figure 9: Comparison of the experimental and numerical results shows a similar trend and order of magnitude is well predicted.

Figure 9a shows the meridional and hoop strains on position 2, at a quarter span of the dome. For both strains the general trend and order of magnitude is well predicted, but the progress of the experimental and numerical curves are different. The hoop strains on the TRC layer are larger than those on the concrete layer, which proves opposite in the experiment.

Figure 9b compares the numerical and experimental meridional and hoop strains near the edge, on position 5. Up to the concrete cracking the numerical simulation fails to predict the strain distribution, as the inverted strains are observed in the experiment. This deviation can be attributed to local phenomena near the edges of the shell (as discussed above), which are not taken into account in the numerical simulation.

Due to the presence of nodes, in the numerical model near the load application zone, i.e. top centre, which encounter stress concentrations, these results are not represented. The comparison of the numerical and experimental vertical deformation of the top centre is shown in Figure 10. The numerical calculated deformation corresponds well to the first part of the load-deflection curve of the experiment, however after 17.5 kN the numerical curve linearly continues and shows no dropping point as was observed during the experiment.
Figure 10: Numerical calculated deformation of the top centre corresponds well to the first part of the load-deflection curve of the experiment.

The numerical model did not predict debonding of the two material layers, as the contact shear stress never exceeded the allowable shear stress of 2.8 MPa (Figure 11) [16]. However, note that the bond model is very complex and currently is intensively studied by Wozniak [16], this is possibly also the reason because of the discrepancy.

Figure 11: Contact shear stress on the contact surface is smaller than the allowable shear stress both in the x-direction (a) and y-direction (b).

CONCLUSIONS

This paper studied the experimental and numerical analysis of a TRC reinforced concrete dome. The dome - 2 m span, 0.2 m height and 20 mm thick - is reinforced with a 5 mm thick TRC and subjected to a point load on the top. The results of the experiment showed interesting results concerning both the production and the behaviour during loading. Firstly, visible cracks formed along radial lines during the test exactly where the rubber rulers were located while casting the concrete. Obviously, this phenomenon must be taken into account and every adjacent segment of concrete must be casted directly next to each other. In this way a good adhesion and a homogenous behaviour of the concrete shell is assured. Secondly, debonding between the concrete and TRC layer occurred sooner than expected. However, all measurements clearly indicate a composite action between the TRC and concrete before the crack initiation. As longs as debonding does not occur, the forces can be transferred through the contact surface and the TRC form work works as a tensile reinforcement.

The experiment was simulated with the finite element software Abaqus. In general the numerical model predicts the same trends and order of magnitude for the measured strains, except for those near the edge, where exactly the opposite phenomenon occurs. The vertical deformation of the top centre is also relatively well predicted up to debonding of both constituents. However, some notable differences are seen between the experimental and numerical analysis. These discrepancies can be explained by the experiment which failed
much faster than expected. The early debonding of the two layers was not foreseen and also not predicted by the numerical model. For this reason, it is difficult to validate the numerical model, thus the production and experiment must be improved. Simultaneously, the numerical model needs further development to exclude the stress concentrations near the load application zone and to make sure the model corresponds to the experiment.

These interesting and promising results encourage the further research on TRC reinforced concrete shells, where after a setup amelioration and model verification, other shell geometries can be examined.

REFERENCES