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DOUBLE-CURVED TEXTILE REINFORCED CONCRETE PANELS WITH TENSILE STRAIN-HARDENING CHARACTERISTICS

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Abstract

The construction of buildings with free-form surfaces can be accompanied with relatively high costs. An innovative method to produce free-form surfaces in concrete is the application of double-curved precast panels produced with a flexible re-usable mould technique. Traditional placing of reinforcing bars to strengthen such panels causes practical problems, since only thin rebars are able to follow the movement of the mould during the production process. The use of flexible textile reinforcement can overcome such production limitations and effectively strengthens the panels.

This paper discusses results of an experimental study on the behaviour of glass fibre textiles in concrete produced with a flexible re-usable mould. The movement of the mould during production might affect the position of the textiles and thus the flexural capacity of the panels. The accuracy of the production method related to the position of the textiles was determined by measurements and indicated that the textiles were able to follow the deformation of the mould. The friction of fibres inside a bundle not directly bonded with the mortar assured ductility of the panels. The proposed method to reinforce the panels proved feasible and a pronounced strain-hardening behaviour was obtained due to the action of the textiles.

1. INTRODUCTION

1.1 Flexible mould method

Building designs with free-form geometries are gaining popularity among architects due to the rapid developments in 3D CAD software. Currently research is ongoing at Delft University of Technology on an innovative production method "the flexible mould method" to realize such buildings in a cost-efficient way. The method allows producing highly accurate double-curved concrete elements in a re-usable flexible mould. This mould can be configured in a range of curved shapes to produce the uniquely shaped concrete elements, thus making the need to manufacture a mould per single element superfluous.

Earlier research [1-2] was executed on the casting procedure of concrete elements produced with the flexible mould method: a self-compacting concrete (SCC) mixture is cast when the mould is still in a horizontal position (Figure 1). After casting, the concrete remains some time in this position for initial stiffening, in order to counteract the flow of concrete out of the mould. 30-60 minutes after casting the mould is deformed into the desired curved shape. At this moment, the fresh concrete follows the deformation of the mould without flowing or cracking. The casting procedure of the flexible mould method was studied with an experimental program on the influence of the mould material, shaping mechanism, element thickness, mix design and rheological characteristics.

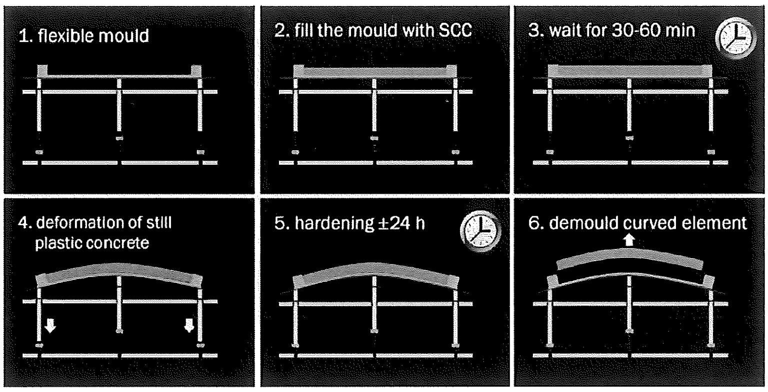

Figure 1: Casting procudure of the flexible mould method

1.2 Textile reinforced concrete

In the initial experimental program, no reinforcement was added for the production of elements. In order to use double-curved concrete elements in practice, for instance as façade cladding, reinforcement has to be added. Using traditional steel rebars to reinforce the elements produced with the flexible mould causes practical problems, since only rebars with a very small diameter are able to follow the deformation of the mould.

Research at RWTH Aachen [3-4] indicated the possibilities and mechanical properties of Textile Reinforced Concrete (TRC) as one of the alternatives to produce reinforced concrete elements with the flexible mould method. Textiles consist of bundles of fibres (yarns) which are structured in a mesh. Strain-hardening behaviour of TRC elements usually can be obtained by reinforcing a concrete element with multiple layers of textile, in which the yarns are orientated in the direction of the principal stress (Figure 2). From previous tests it was known that the behaviour of TRC elements has a lot of similarities with concrete reinforced with steel rebars. After exceeding the tensile strength of the concrete the element will crack at multiple positions. When the cracking pattern has stabilized the reinforcement strains up to failure. The main difference between these reinforcement types is the bonding between the reinforcement and the concrete: the yarns of the textiles are 'activated' by adhesion and friction. The outer part of the yarn of the textile is in contact with concrete: these fibres are directly anchored in the concrete by adhesion whereas the inner fibres are not impregnated with concrete and are activated by friction. Due to this bonding mechanism only a part of the tensile strength of the yarn can be utilized, since the outer fibres will already reach their maximum strength before the inner fibres are fully activated. Multiple aspects of a textile structure (e.g. fibre density of the yarn, binding type) and the concrete matrix (e.g. maximum aggregate size) affect the bonding mechanism and strength of the reinforcement.

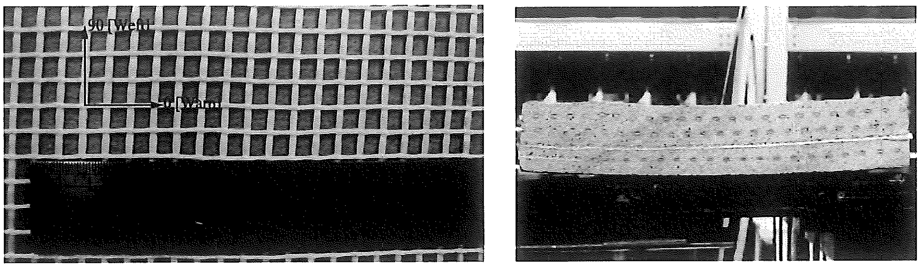

Figure 2: (left) Ar-glass fibre textile (right) Cross-section of TRC

The low bending stiffness of the textiles, the pronounced strain-hardening behaviour of the composite and the possibility to produce very thin concrete elements (since textiles only need a minimum concrete cover for bonding) made textiles worthwhile to consider as reinforcement option for elements produced with the flexible mould method. This paper discusses the experimental program [5] on the usability of textiles to reinforce double-curved concrete elements produced with the flexible mould method. To determine the realized (short-term) load bearing capacity of the specific textile and concrete mixture used for the specimens a series of four-point bending tests was carried out. In order to determine whether textiles are a feasible option, in technical sense, to be used as reinforcement for the flexible mould method a series of deformation tests was performed with a prototype of the flexible mould, simulating the described production process. Additional to the experimental program described in this paper, tensile tests on TRC were performed and the behaviour of TRC was modelled using finite element analysis. The results can be found in [5].

2. LOAD BEARING BEHAVIOR OF TEXTILE REINFORCED CONCRETE

2.1 Experimental set-up

Alkali-resistant glass fibre textiles (Table 1) were used for the experiments. The yarns of the textiles consisted of about 1600 alkali-resistant glass fibres with a diameter of 0.027 mm (cem-FIL 5325 manufactured by OCV Reinforcements). The yarns were stitched in a bi-axial mesh with 8.3 mm spacing between the yarns in both directions. The yarns had a tensile strength of 1700 MPa and a modulus of elasticity of 70000 MPa. A self-compacting concrete (Table 2) with a maximum aggregate size of 1 mm and high workability (slump flow of 850-900 mm directly after mixing) was used to produce the specimens. In the hardened state (at 28 days) the concrete had a mean compression strength (cube of 150x150x150 mm) of 91.8 MPa, a mean splitting tensile strength (cube of 150x150x150 mm) of 3.5 MPa and a mean flexural strength (prism of 40x40x160 mm) of 8.3 MPa.

All specimens were produced with a lamination procedure: a layer of self-compacting concrete was poured into the mould followed by the placement of one layer of textile at a time. This procedure was repeated until the required thickness of the element was reached. The high workability of the concrete (low plastic viscosity and low yield strength) made an even distribution of the concrete over the area of the mould possible.

The efficiency of a textile reflects the influence of the bonding mechanism on its effective tensile strength in concrete: it is the ratio of the maximum experimental tensile strength of a textile in concrete and the maximum tensile stress of the textile itself. To determine the load bearing behaviour and to define this efficiency factor for this specific textile and concrete mixture combination four-point bending tests were performed. Two series of 3 specimens with variable height were tested. The first series consisted of specimens with dimensions of 25x100x800 mm^3 (height x width x length) and 4 layers of textile reinforcement (ω_{tex} = 1,68%). The second series consisted of specimens with dimensions of 50x100x800 mm^3 and 8 layers of reinforcement (ω_{tex} = 1.68%). The textile layers were intended to be equally divided over the height of the specimen. Inaccuracies due to the production led to small deviations in position but were taken into account for modelling by measuring the actual position of each layer of textile reinforcement.

Table 1: Textile properties

Property	**Unit**	**Characteristic**
Material	[-]	Alkali-resistant glass fibres
Stitch length	[mm]	2.1
Stitch material	[-]	PES
Diameter fibre	[mm]	0.027
Number of fibres/yarn	[-]	1600
Cross-sectional area yarn	[mm^2]	0,916
Linear mass density yarn	[g/km]	2400
Mesh size (0° / 90°)	[mm]	8.3 / 8.3
Tensile strength	[MPa]	1700
Modulus of elasticity	[MPa]	70000

Table 2: Concrete mixture composition

Component	**Dosage [kg/m^3]**
CEM I 52,5R	570
Fly ash	100
Limestone powder	100
Superplasticizer Premia 196	4.95
Water	225
Sand 0,125 – 0,25 mm	233
Sand 0,25 – 0,5 mm	414
Sand 0,5 – 1 mm	647

2.2 Four-point bending tests

Four-point bending tests (Figure 3) were performed on a deformation-controlled testing machine in the Stevin 2 Laboratory at Delft University of Technology. The specimens were supported on two wooden strips (15 mm in width), with a span of 725 mm. The space between the two point loads was 295 mm. Two lasers-sensors registered the vertical displacement in the middle of the span. The curvature of the specimens was registered by measuring the strain at the top and the bottom of the specimen.

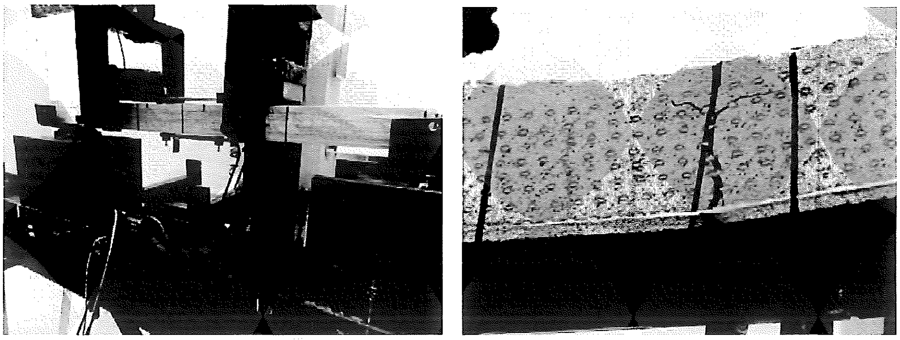

Figure 3: Four-point bending tests

Table 3 and Figure 4 show the results of the four-point bending tests. In Table 3 M_{max} is the bending moment at failure of the specimen, σ_{fl} is the flexural strength of the uncracked cross-section (M_{max} / $W_{specimen}$), f_{tex} is the maximum tensile stress of the textile and $\sigma_{tex,max}$ the equivalent maximum tensile stress in the bottom textile layer of the specimen, which was estimated by iterating the maximum stress in the bottom textile layer until the ultimate moment with the related deformation from the bending tests was obtained [5]. The results show that for both series about 35% of the tensile strength of the textiles can be utilized when used as reinforcement in concrete.

Table 3: Results of the four-point bending tests

Specimen	M_{max} [kNm]	σ_{fl} [MPa]	f_{tex} [MPa]	$\sigma_{tex,max}$ [MPa]	**Efficiency** [%]
1.1 (25 mm)	0.19	18.58	1700	565	33
1.2 (25 mm)	0.22	20.64	1700	656	38
1.3 (25 mm)	0.20	19.50	1700	546	32
2.1 (50 mm)	0.88	21.00	1700	599	35
2.2 (50 mm)	0.94	22.60	1700	598	35
2.3 (50 mm)	0.85	20.46	1700	578	34

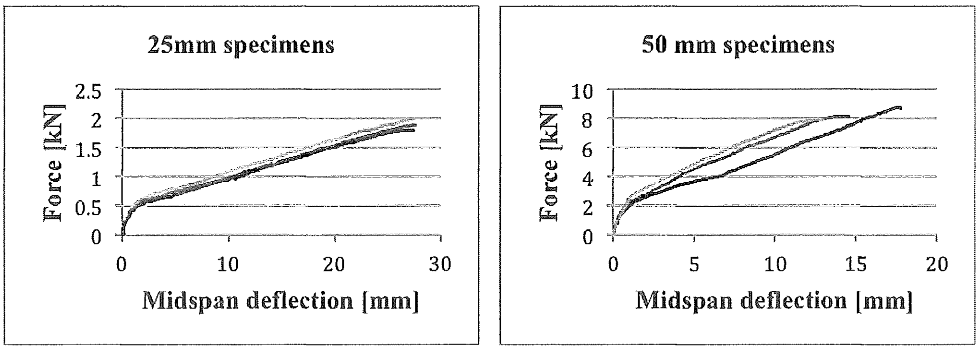

Figure 4: Force-displacement graphs for four-point bending tests

In Figure 5 the typical behaviour of the specimens observed during the experiments is shown. After the linear elastic stage of concrete, a specimen cracks at multiple places, 'activating' the textile reinforcement. At the maximum load, after a long strain hardening trajectory, the width of one of the cracks increases rapidly. The outer fibres of the yarn, which are directly anchored in the concrete, fail in a brittle manner on tensile strength. The inner fibres of the yarn are pulled out with increasing deformation and provided residual strength due to friction of the fibres with each other. As a result a certain ductility of the specimens was obtained after reaching the maximum load.

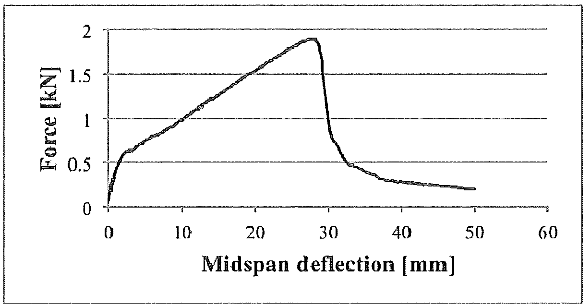

Figure 5: Force-displacement graph for Specimen 1.3

3. DEFORMATION EXPERIMENTS IN A FLEXIBLE MOULD

3.1 Experimental set-up

The flexible mould method (Figure 6) requires a reinforcement type that is able to deform together with the concrete during the deformation process. Due to the lamination procedure and the movement of the mould the position of the textile reinforcement might deviate from the intended position. Such deviations have influence on the flexural strength of TRC elements and they were studied through a series of deformation experiments simulating the flexible mould method. Four TRC elements with variable curvature were produced with the prototype of the flexible mould. The produced TRC elements had the dimensions of 25x400x800 mm^3 and consisted of 4 textile layers with an intended vertical spacing of 5 mm and a 5 mm concrete cover.

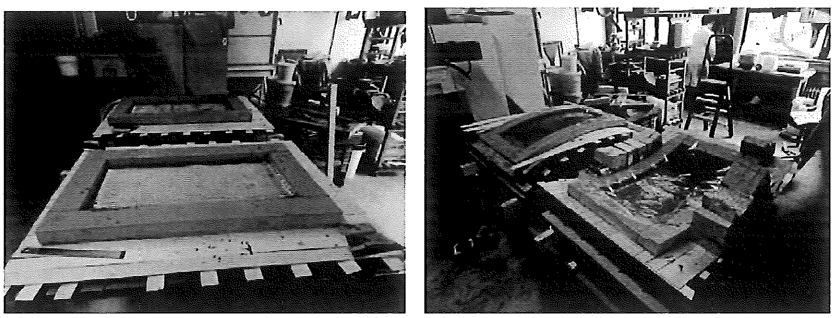

Figure 6: Deformation tests with the flexible mould

The prototype of the flexible mould consisted of a polyether foam mould covered with a silicone layer to protect the foam from the cement paste. This mould was supported by a flexible system of thin wooden planks, which were supported by a subsystem; the height and the curvature of the subsystem were pre-set by adjusting nuts on a thread.

3.2 Deformation tests

Two elements with a positive and negative single curvature (radius = 1500 mm) and two elements with a bowl- and saddle-shaped double curvature (radius = 2500 mm) in both directions) were produced during the deformation experiments. The elements were cast with the earlier described lamination procedure, while the mould was still in a horizontally levelled position. All elements were deformed into the desired curvature 45-50 minutes after mixing of the concrete. After demoulding, the elements were cut in eight equal segments: it was observed that the textile layers neatly followed the curvature of the edges, indicating that the reinforcement deformed together with the concrete. In order to compare the actual position of the textiles with the intended positions the thicknesses of the layers were measured on 10 positions of the element. The production process caused small deviations: most layers were cast within 1 mm accuracy; the maximum deviation of the layer thickness was 2,5 mm. Figure 7 shows an overview of the measurements on layer thicknesses of the double-curved concrete elements; Figure 8 shows the positions of the layers and concrete surface at the centre of the double-curved elements.

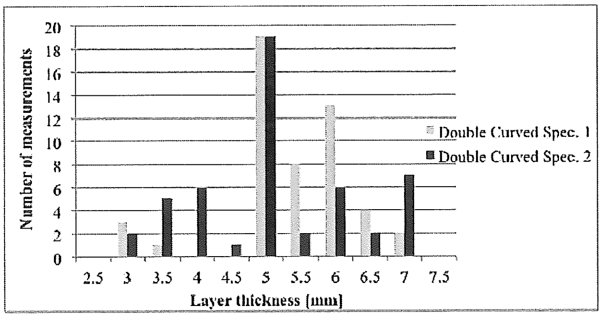

Figure 7: Overview of the layer thicknesses of the double-curved specimens

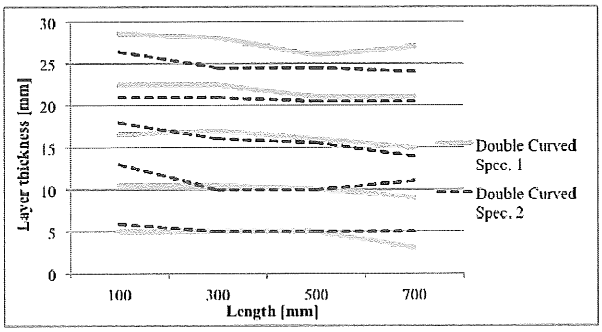

Figure 8: Position of the textile layers in the center of the double-curved specimens (the heighest line being the concrete surface of the panels)

Taking into account the deviation in textile positions, the flexural capacity of the produced elements deviate at a maximum of 22% from the intended flexural capacity.

4. CONCLUSIONS

This paper discussed an experimental study on the application of textile reinforced concrete to produce double-curved concrete elements with a flexible mould. Based on the experimental results the following conclusions can be drawn:

- The results of the four-point bending tests show that strain-hardening behaviour can be obtained by adding multiple layers of glass fibre textile to the specimens.
- Although glass is a brittle material, glass fibre textile reinforced concrete elements showed a ductile behaviour after reaching the maximal load. Beyond this stage, outer fibres will fail on tensile strength and inner fibres will be pulled out, ensuring the ductile behaviour.
- During the production of textile reinforced concrete elements deviations can occur in the position of the textile layers. These deviations affect the flexural capacity of the elements. By measuring a series of specimens the accuracy of the production process can be determined and thus the influence of the production process on the flexural capacity of the specimens can be taken into account.
- The deformation tests proof that textiles are a suitable option as reinforcement for concrete elements produced with the flexible mould method.

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