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TAILORING STRUCTURES WITH TEXTILE-REINFORCED CONCRETE TO REDUCE WEIGHT

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ABSTRACT

By carefully removing material in structures with limited plasticity, such as reinforced concrete (RC), the bearing capacity can be increased. This, however, comes at the cost of a lower stiffness. Here we investigate the tailoring of RC-structures, where the thickness of the structure at certain locations is reduced to 30 mm by inserting novel textile reinforcement. Subsequently, such a tailored beam was cast and tested. The results indicate that this tailoring concept not only saved 10% of the material, but also retained a high stiffness. The concept therefore shows great potential towards a more resource-efficient use of materials.

KEYWORDS

Tailored structure; Functional grading; textile reinforcement; textile-reinforced concrete; TRC

INTRODUCTION

Concrete is by far the most widely used building material and except of water even the most consumed material in the world (Monteiro et al., 2017). It comes with great advantages, such as the ability to cast it in almost any shape. Due to its cheap price, however, it is often used inefficiently, with designers and construction firms aiming for easy to build formworks rather than to utilise the material properties fully. Given global resource shortages (Miller et al., 2018; Torres et al., 2017) and most importantly the climate crisis, which is fueled considerably by high carbon emissions from cement production (Barcelo et al., 2014), a necessary shift in the way we build with concrete becomes evident. As there is not one specific solution to this challenge, many different approaches are pursued by researchers and policy to foster a more sustainable concrete construction (Shanks et al., 2019).

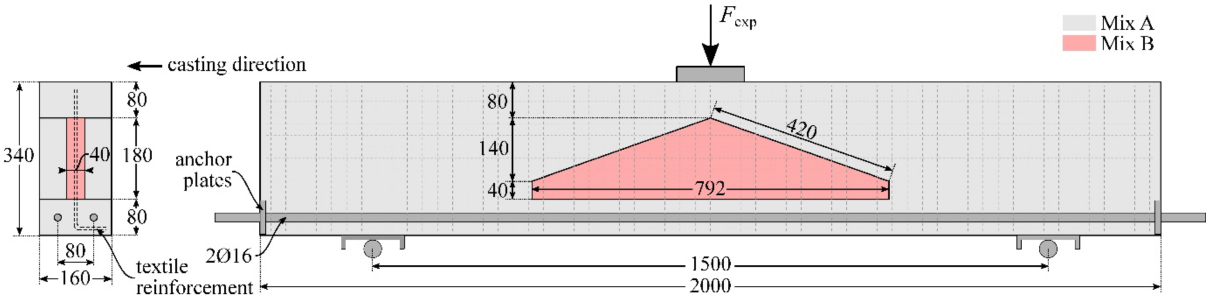
If the concrete is used in a more efficient way, for example, there is great potential for reducing carbon emissions. The use of novel materials, such as high-performance textile reinforcement, offer new design perspectives. Due to the outstanding mechanical properties and high durability of the fabrics, the concrete cover can be reduced, and lightweight structures can be created where the material consumption is reduced to a minimum. Also, the concrete is typically chosen according to the most stringent requirement within a structure, resulting in higher-performance concrete being used in areas that would not be necessary to fulfil local requirements (Preinstorfer & Lees, 2022). Functionally grading the concrete in a structure to account for these irregular conditions can reduce the environmental footprint without adversely affecting the performance of a structure (Forsdyke & Lees, 2023; Torelli et al., 2020). Moreover, researchers have shown that by carefully tailoring the concrete grade or even removing material and creating voids in structures with limited plasticity, such as reinforced concrete (RC), the bearing capacity can be increased as the load is transferred along favourable load-paths (Mak & Lees, 2023a, 2023b). This, however, comes at the cost of a reduced stiffness and hence increased deformation.

In this paper, we investigate through the incorporation of thin-walled panels made of textile-reinforced concrete (TRC) into the design of concrete beams, whether the results of Mak and Lees (Mak & Lees, 2023b) on the higher bearing capacity of voided beams can still be achieved while simultaneously limiting the deflections. Therefore, a functionally graded TRC beam was cast and tested and compared to the results reported in literature.

METHODS

Specimen layout

The specimen layout is based on the voided beams reported in Mak and Lees (Mak & Lees, 2023b), with a total length of the beam of 2000. The cross-sectional dimensions are 160 × 340 mm^2 (length × height). In Mak and Lees, a central void with 180 mm in height, positioned 40 mm above the bottom surface, is created. This void has a length of 792 mm at the bottom 40 mm and then tapers to a single apex at the top, which also is the symmetry point in longitudinal direction. Instead of the central void, however, a 40 mm panel was designed in this study. This panel is made of low-strength concrete while the rest of the beam is made of high-strength concrete. Two reinforcement bars Ø16 at the bottom, which are anchored by means of anchor plates, serve as bending reinforcement. The panel itself is reinforced with two planar textile grids that bridge the interface, thereby connecting the areas made of low- and high-strength concrete. In fact, the textile reinforcement was placed over the entire length of the beam for the sake of simplicity. To achieve the necessary anchorage length, it is bend at the bottom.



(a) (b)

Figure 1: Layout of the functionally graded TRC-beams: (a) cross-section at midspan. The central part is narrowed to 40 mm in thickness. (b) Front view of the specimen. The high strength concrete is shown in grey while low strength concrete is shaded light red. [all dimensions in mm]

Materials

Two reinforcement bars of mild steel B500 were used as flexural reinforcement. The textile reinforcement was a hybrid reinforcement sourced from the company solidian in Germany, with carbon fibre strands in one direction and glass fibre strands in the other (solidian FLEX GRID CAR-420-CCS-14x18-MS). The reinforcement details, including the material properties stated by the manufacturer are listed in Table 1.

Table 1: Details and material properties of the textile reinforcement used for the prototype. The textile was sourced from the company solidian (FLEX GRID CAR-420-CCS-14x18-MS). It is impregnated with styrene butadiene, which makes it a flexible reinforcement.

	Fibre Material	Mesh width [mm]	Tensile strength [kN/m]
Weft direction	Glass	18.2	54
Warp direction	Carbon	22.2	159

Two concrete mixes were introduced, aiming for a wide spread of concrete strength. The mix designs of concrete Mix A and B are listed in Table 2. While the low-strength mix (Mix A) was only used for central textile reinforced panel, the high-strength mix (Mix B) was used in the other parts of the specimen. To distinguish between the two concretes in the hardened state 15 kg/m^3 red dye was added in Mix A.

Table 2. Mix design of concrete Mix A and B

	CEM I [kg/m³]	CEM II [kg/m³]	Water [kg/m³]	Fine agg. [kg/m³]	Coarse agg. [kg/m³]
Type	52.5 N	32,5 R		0-4 mm	4-10 mm
Mix A	-	297	226	1078	718
Mix B	550	-	220	700	855

The compressive strength of these mixes was tested on cubes with dimensions 150 × 150 × 150 mm^3 according to BS EN 12390-3 ('British Standards Institution', 2019). Moreover, splitting tensile tests were conducted according to the specifications in BS EN 12390-6. The results are listed in Table 3.

Table 3. Material properties of the concrete ($\mu \pm \sigma$ after 25 days of hardening)

	$f_{\text{cm,cube}}$ [MPa]	$f_{\text{ctm,sp}}$ [MPa]
Mix A – Low strength	21.50 (±0.9)	1.86 (±0.3)
Mix B – High strength	63.90 (±6.4)	3.82 (±0.6)

EXPERIMENTAL TESTING

Casting process

The casting was done sideways and the reinforcement placement is aligned with the sequence of the manufacturing process, see Figure 2a. In the first instance a 65 mm layer of high-strength concrete is placed in the formwork. The central triangle was recessed by a void former. Subsequently, a 15 mm layer of concrete is placed on top, where an additional grading in horizontal direction is applied. The horizontal grading of the concrete, which is made visible by adding red dye to the lower-strength mix, was achieved by a panel, that was lifted once the concrete was filled to the desired height. When the desired concrete depth is reached, the textile shear reinforcement was placed, with the carbon fibre strands orientated in longitudinal direction, on the top of the concrete layer. Subsequently the next layer of 15 mm graded and the final layer of 65 mm of high-strength concrete was cast. To achieve symmetry a void former was once again used in the final layer to create a recess in the central triangle of the high-strength layer. To protect the specimen from drying, the top surface was covered in foil after the casting process. The specimen was demoulded after one day and stored under ambient conditions for 25 days. The samples for the material testing were cast and cured under the same conditions.


(a) (b)

Figure 2: Manufacturing of test specimen (a) Inserting the reinforcement in stages after a layer of the functionally graded concrete was already cast (specimen is cast sideways) and (b) tailored specimen after demoulding.

Test setup

The load bearing behaviour was tested by means of a three-point bending test (see Figure 1b). Therefore, the specimen was placed on two bearing plates connected to rollers for rotational freedom. The effective length between the rollers was 1500 mm. The load was introduced through an actuator using displacement control with a velocity of 0.1 mm/min that was connected to a stiff steel rig. To measure displacements a light emitting diode (LED) optical measurement system was used. With this measurement system an accurate displacement field can be created with a greater resolution relative to what can be achieved using singular measurements obtained from Linear Variable Differential Transformers (LVDTs). LED reflectors are glued to the specimen at points of interest which are then monitored during testing (see Figure 3a). As an output, the 3D coordinates of the LED reflectors are obtained in high frequency. For the testing of the prototype the reflectors were glued onto the front side of the specimen in a regular pattern of 150 by 150 mm. Additionally, reflectors were glued along the diagonal struts above the textile shear panel with a distance of 175 mm and on the loading and bearing plates to measure any deformation of the test setup itself.

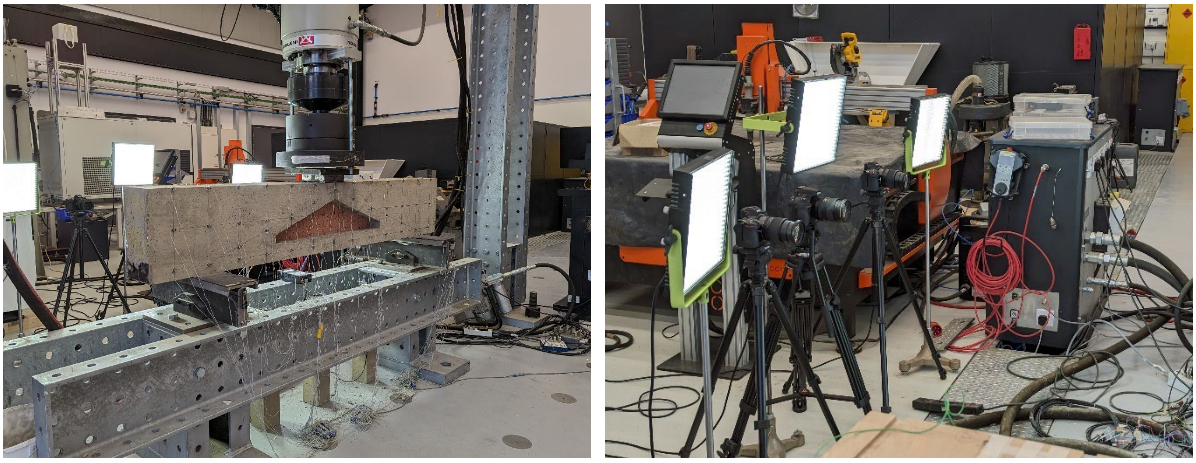

(a) (b)

Figure 3: Test setup of the bending test on a functionally graded TRC beam: (a) LED measurement system to create a displacement field. Reflectors were glued in a regular distance of 150 by 150 mm on the front surface of the specimen. (b) Three Single-lens reflex cameras that created images every five seconds for the purpose of digital image correlation.

Additionally, digital image correlation (DIC) measurements were conducted on the back surface of the specimens. Therefore, the specimen was painted black and sprinkled with black dots so that a stochastic pattern is created. Three Single-lens reflex cameras (east, middle and west) were then used to monitor the beam along its entire length (see Figure 3b). Photos were taken during testing with a frequency of 0.2 Hertz. DIC evaluation was conducted after testing in GOM correlate (*Gom Correlate*, 2019).

RESULTS

Failure Mode

The specimen failed in a brittle manner by crushing of the concrete below the load introduction. Large deformations and wide cracks in the bottom tie suggest a yielding of the reinforcement. The crushing of the concrete only occurred on the back side, with the front side seemingly being intact besides some visible cracks especially in the bottom tie. Moreover, a larger shear crack originating from the support inclined in direction of the centre panel, see Figure 4a. The crushed part of the concrete on the back side reached to the centre of the beam where the textile reinforcement is located. The fabrics became visible after failure, as can be seen in Figure 4b.

(a) (b)

Figure 4: Failure mode of the functionally graded TRC beam: (a) Visible bending cracks at the bottom tie and shear crack originating from the support inclined in direction of the centre void (b) Concrete compression failure at the top visible at the back side of the specimen.

The shape of the crushed concrete and the cracks in the adjacent areas indicate the presence of a fan like compression strut towards the narrow central TRC panel, which caused splitting tensile stresses and eventually triggered the concrete crushing. This suggests that a tapering of the central panel would allow for a better transfer of load. It is noteworthy, however, that the failure load, as will be seen in the next section, was at maximum capacity with the bottom reinforcement already yielding.

Load-deflection behaviour

To process the data of the LED measurements, a script that performs a coordinate transformation to the desired coordinate system and displays the deflection field during testing (see Figure 5 for a load stage of 120 kN) was created. The measured data indicates a good symmetry in loading.

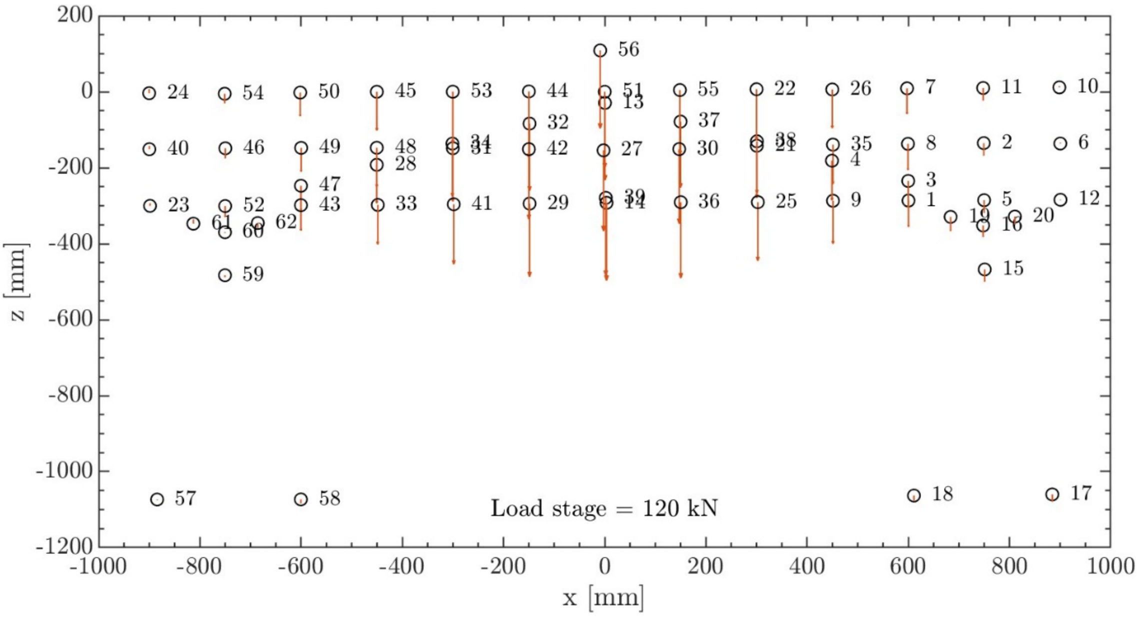
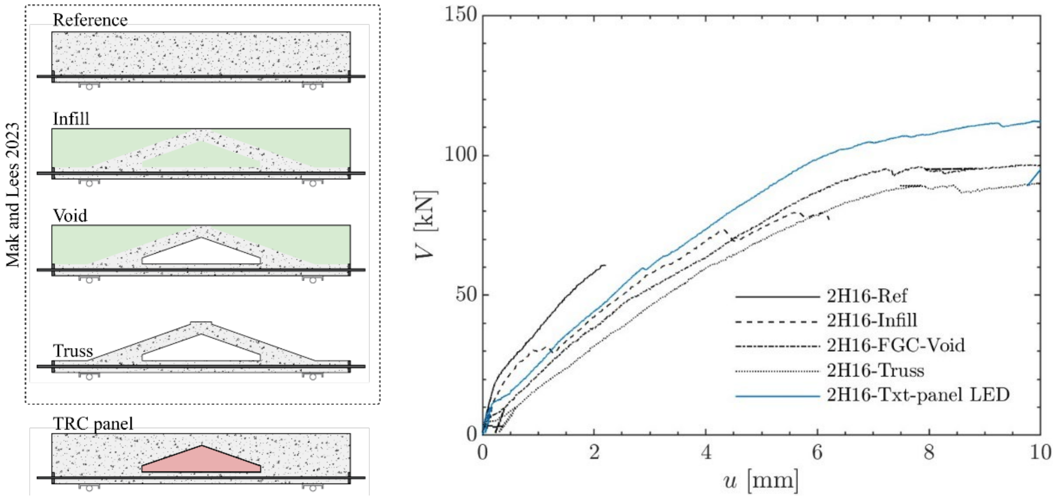


Figure 5: Vertical Deformation field at a load stage of 120 kN, measured with the LED system.

In addition, load-deflection curves for the monitored points of interest can be displayed, as shown in Figure 6b, where the deflection at midpoint of the specimen is shown during loading (blue line; any vertical deformation at the supports is subtracted). When comparing the novel TRC panel behaviour with the results from Mak and Lees (Mak & Lees, 2023b) for a solid reference beam, an uplift in load capacity is evident. While this was also reported in Mak and Lees for the infilled beam the effect is amplified by the TRC panel where the uplift in bearing capacity is roughly twofold compared to the reference beam. While a higher initial stiffness was observed for the infilled beam of Mak and Lees, this behaviour changed at a loading of about 60 kN (shear force of 30 kN), where the deflections in the functionally graded TRC beam became smaller than for the infilled beam. This suggests a better structural integrity of the beam due to the TRC panel. Moreover, the ultimate load was even higher than of the voided and truss beams in Mak and Lees. This is because the longitudinal fibre strands of the textile reinforcement also act as additional flexural reinforcement.

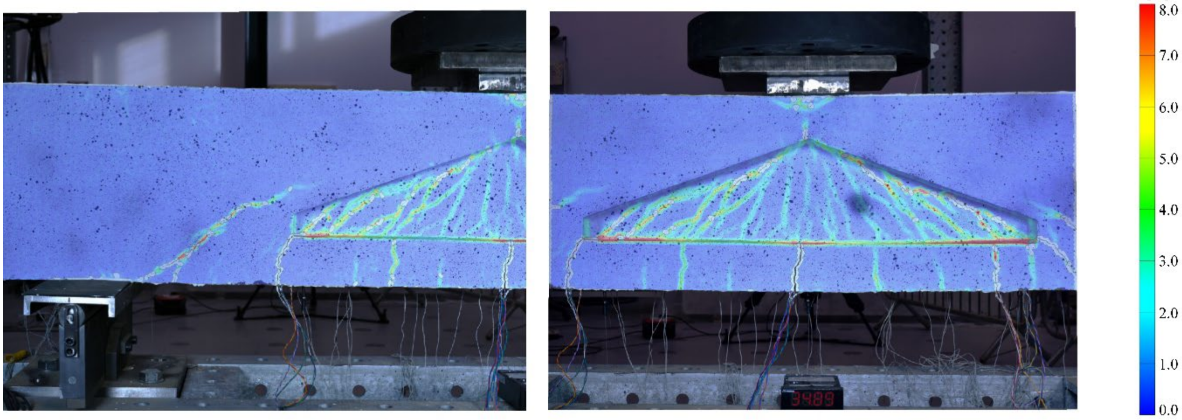


(a) (b)

Figure 6: (a) Design of voided and functionally graded beams according to Mak and Lees (Mak & Lees, 2023a) and the functionally graded TRC beam presented in this study (a, bottom beam). Therefore, the centre void was cast as a thin-walled textile-reinforces panel made of low-strength concrete. (b) Load-deflection behaviour of the different variants.

Cracking behaviour

In Figure 7 the crack pattern at the final load stage before failure is displayed for the area including the left support (Figure 7a) and the central panel (Figure 7b). Larger flexural cracks are visible in the bottom tie. These cracks disperse in the panel creating a pattern of fine cracks in small distances.



(a) (b)

Figure 7: Crack pattern observed trough DIC: (a) Area of east support of the beam. An inclined shear crack is visible that propagated from the support towards the central panel. (b) fine cracks in narrow distances in the central TRC panel

All these cracks are oriented towards the apex of the central panel and in general do not extend into the high-strength concrete above. Hence, a potential direct strutting of the load towards the support is not disturbed, and a potential shear failure, as it was the case in the reference beam of Mak and Lees (Mak & Lees, 2023b) is supressed. Only in the apex a vertical crack becomes visible from bending stresses due to the abrupt change in beam thickness at that location. Moreover, the upcoming concrete crushing is already indicated by arcuate cracks below the load introduction.

CONCLUSIONS

In this paper a functionally graded TRC beam was studied by means of experimental testing. The specimen layout is based on the voided and functionally graded beams reported by Mak and Lees (Mak & Lees, 2023a, 2023b). In contrast to their study, here we introduced a thin TRC panel in the central part of the beam. Following conclusions can be drawn from this investigation:

- The manufacturing of such beams poses challenges. In this study the beam was cast sideways in several steps to achieve the desired grading and tapering of the structure. This requires logistical efforts and manual input. It was, however, possible to cast the beam in the desired design with high accuracy. Future research should also focus on the automation of the fabrication process of such complex designs.
- By incorporating the TRC panel into the design of the beam, a higher stiffness was achieved compared to the trussed and voided beams of Mak and Lees. In comparison to the infilled beams, the structural integrity was retained throughout the tests. While the stiffness was lower in the beginning compared to the infilled beams, the improved structural integrity led to lower deflections at higher load stages.
- The flexural cracks in the bottom tie dispersed into fine cracks in the TRC panel. These cracks were all oriented towards the apex of the panel and did not extend into the high-strength concrete above. Hence, a potential concrete strut between the load introduction and the support is not disturbed by such cracks.
- Similar to the voided beams of Mak and Lees an uplift in load was therefore observed for the functionally graded TRC beam. This is because shear failure is supressed. As the longitudinal fibre strands of the textile also act as additional flexural reinforcement the highest capacity of all beams could be achieved. Failure was eventually caused by a crushing of the concrete below the load introduction. The steel reinforcement at this stage, however, was already yielding, indicating a good material utilisation.

The experiment described in this paper is the result of a preliminary study on the potential optimisation of beams by combination of two design approaches, namely functional grading of concrete and textile-reinforced concrete. By incorporation of a thin TRC panel into the design of a functionally graded concrete beam 10% of the material could be saved, therefore achieving a lighter structure, while simultaneously the load capacity was twofold compared to a solid beam. This suggests great potential for further research.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest associated with the work presented in this paper.

DATA AVAILABILITY

Data on which this paper is based is available from the authors upon reasonable request.

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