TAILORED STRUCTURES WITH TEXTILE-REINFORCED CONCRETE

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ABSTRACT
By careful removal of material in concrete structures with limited plasticity such as shear critical beams leads to an increase in the bearing capacity. This uplift, however, can come at the cost of a lower stiffness. Here we investigate the tailoring of RC-structures where the concrete is functionally graded, the width of the structure is locally reduced and novel textile reinforcement is included. To demonstrate the proof of concept, such a tailored concrete beam was cast and tested in three-point bending. The results indicate that this tailoring concept does not only offer material savings but also demonstrates a high stiffness and load capacity. The concept therefore shows great potential for the more resource-efficient use of materials.

KEYWORDS
Tailored structures; functional grading; textile reinforcement; textile-reinforced concrete; TRC

INTRODUCTION
Concrete is widely used as a building material and, with the exception of water, is the most consumed material in the world (Monteiro et al., 2017). Concrete offers certain advantages such as the ability to cast a concrete element in almost any shape. However, its historically low price has meant that concrete material properties are often utilised inefficiently due to over-specification and design and construction preferences for standard formwork shapes. Given emerging global resource shortages (Miller et al., 2018; Torres et al., 2017) and most importantly the climate crisis, which has been exacerbated by high carbon emissions from cement production (Barcelo et al., 2014), the need for 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 being pursued by researchers and policy makers to foster more sustainable concrete construction (Shanks et al., 2019).

If concrete is used more efficiently there is great potential for the reduction of 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 textiles, the concrete cover can be reduced, and lightweight structures with minimised material consumption can be created. Also, the concrete mix is typically chosen according to the most stringent requirements 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 such that different concrete mixes are tailored to meet those spatially varying requirements can reduce the environmental footprint without adversely affecting the performance (Forsdyke & Lees, 2023; Torelli et al., 2020).

In shear critical beams with limited plasticity, researchers have shown that by carefully tailoring the concrete grade in conjunction with the removal of material to create voids, the load 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 introduce thin-walled panels made of textile-reinforced concrete (TRC) into the design of functionally graded voided concrete beams to determine whether an uplift in bearing capacity 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 beam length of 2000. The cross-sectional dimensions are 160 × 340 mm² (width × height). In Mak and Lees, a central void with 180 mm in height, positioned 40 mm above the bottom surface, was created. This void had a length of 792 mm at the bottom, for a height of 40 mm and then tapered to a single apex at mid-span, which was also a point of symmetry in the longitudinal direction. Instead of a central void, however, a 40 mm thick panel was designed in this study. This panel (see Figure 1) is made of low-strength concrete (indicated using a light red colour) while the rest of the beam is made of high-strength concrete (shown as grey). Two reinforcement bars Ø16 in the tensile zone are anchored by means of anchor plates and serve as bending reinforcement. The central panel itself is re-inforced 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 simplicity of fabrication. To achieve the necessary anchorage length, the textile is bent out of plane in the lower chord with a horizontal length of 40 mm as shown in Figure 1a.

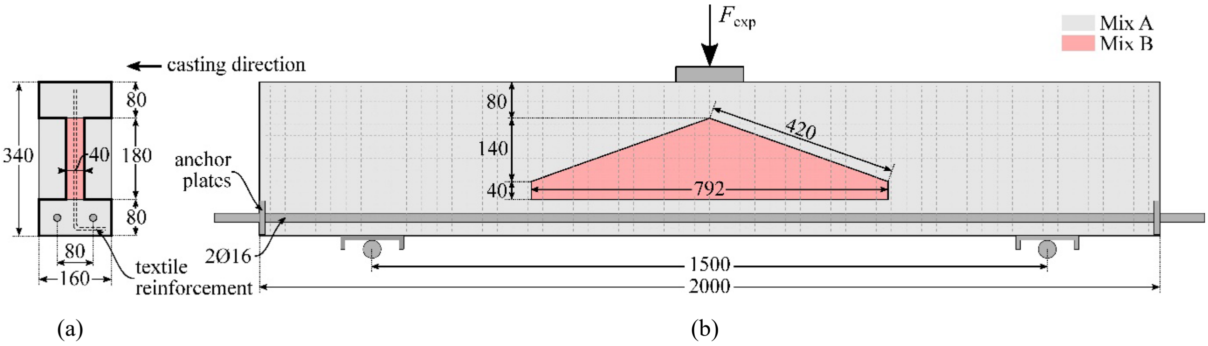


Figure 1: Layout of the functionally graded TRC-beams: (a) Cross-section at midspan with the central 40 mm thick panel. (b) Front view of the specimen. The high strength concrete is shown in grey while low strength concrete is shaded light red. [all dimensions in mm]

Materials

Two reinforcement bars of mild steel grade B500 were used as the flexural tensile 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 (solidian GmbH, 2023)). The reinforcement details, including the material properties stated by the manufacturer are listed in Table 1.

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

	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, with the objective to achieve a significant difference between the two concrete strengths. The mix designs of concrete Mix A and B are listed in Table 2. The low-strength mix (Mix A) was only used in the zone of the central textile reinforced panel whereas the high-strength mix (Mix B) was used everywhere else. To distinguish between the two concretes a small proportion (15 kg/m³) of red dye was added to 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 $f_{cm,cube}$ was determined using cubes with dimensions 150 × 150 × 150 mm^3 according to BS EN 12390-3 ('British Standards Institution', 2019). Moreover, splitting tensile tests were conducted to find $f_{ctm,sp}$ in accordance with the specifications noted in BS EN 12390-6. The results are listed in Table 3.

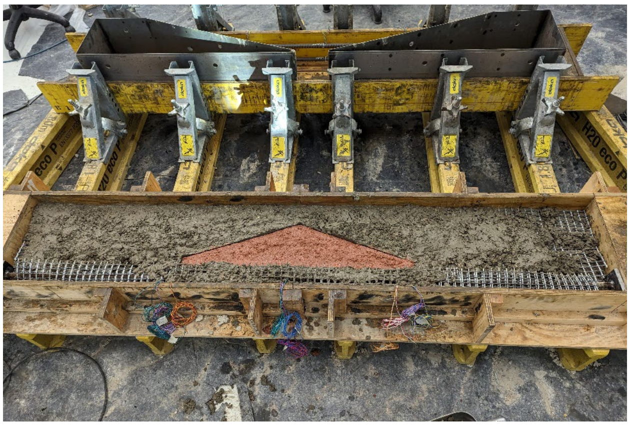
Table 3. Material properties of the concretes ($\mu \pm \sigma$ after 25 days of hardening)

	$f_{cm,cube}$ [MPa]	$f_{ctm,sp}$ [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)

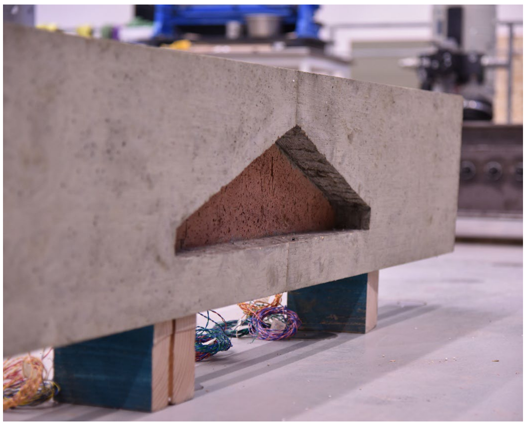
EXPERIMENTAL CASTING AND TESTING

Casting process

The beam was cast sideways and the reinforcement placement was aligned with the sequence of the manufacturing process, see Figure 2a. In the first instance a 60 mm layer of the Mix B high-strength concrete was placed in the formwork. The central triangle was recessed using a 60 mm thick void former. Subsequently, a 20 mm layer of graded concrete was cast. The horizontal grading of the concrete was achieved by lifting an upright metal panel in the shape of the central void, that initially served as a barrier between the two mixes. When the desired concrete depth was reached, the textile shear reinforcement was placed, with the carbon fibre strands orientated in the longitudinal direction, on the top of the concrete layer. Subsequently the next layer of 20 mm graded concrete and the final layer of 60 mm of high-strength concrete was cast. To achieve symmetry another void former was 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 plastic sheets after the casting process. The specimen was demoulded after one day and stored under ambient lab conditions for 25 days. The samples for the material testing were cast and cured under the same conditions.



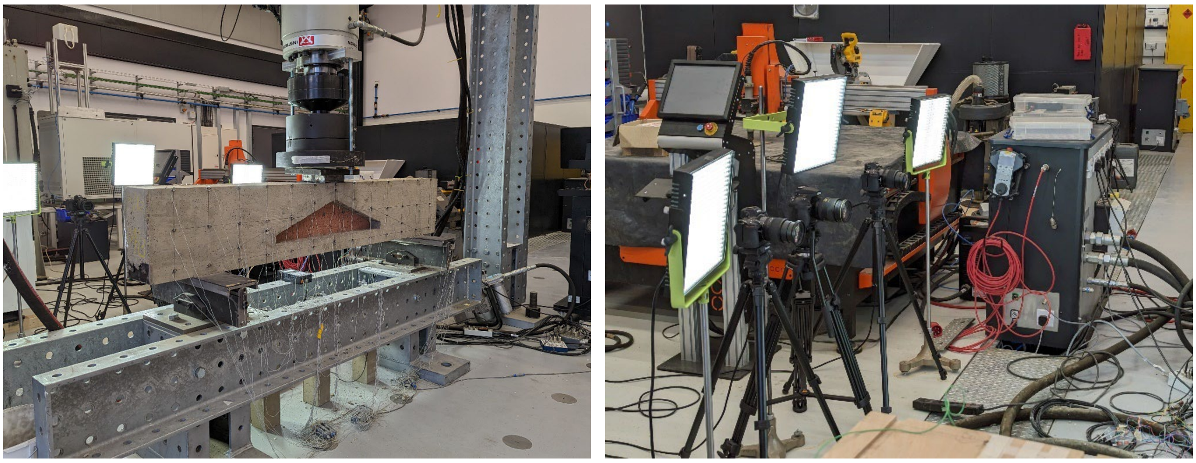
(a)



(b)

Figure 2: Manufacturing of test specimen (a) Inserting the reinforcement in stages after a layer of the functionally graded concrete had already been cast (specimen was 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 and Figure 3). 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 loading rate of 0.1 mm/min that was connected to a 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 could be achieved using singular measurements obtained from Linear Variable Differential Transformers. LED reflectors were glued to the specimen at points of interest which were then monitored during testing (see Figure 3a). As an output, the 3D coordinates of the LED reflectors are obtained with a high frequency. For the testing of the prototype beam the LED reflectors were glued onto the front side of the specimen in a regular grid pattern of 150 mm by 150 mm. Additionally, reflectors were glued along the diagonal struts between the supports and the load introduction at 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 grid of 150 mm by 150 mm on the front surface of the specimen. (b) Three single-lens reflex cameras that captured images at five seconds intervals for the purpose of Digital Image Correlation analysis.

Additionally, Digital Image Correlation (DIC) analysis was conducted on the back surface of the specimens. Therefore, the specimen was painted black and sprinkled with black dots so that a stochastic pattern was 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. The DIC analysis was conducted after testing in GOM correlate (*Gom Correlate*, 2019).

RESULTS

Failure Mode
The specimen failed in a brittle manner due to the crushing of the concrete below the point of central load introduction. Large deformations and wide cracks in the bottom tie suggested yielding of the reinforcement. The crushing of the concrete only occurred on the back side, with the front side seemingly being intact except for visible cracks located primarily in the bottom tie. Moreover, a large shear crack inclined in direction of the centre panel originated from one of the supports, see Figure 4a. The crushed region of the concrete on the back side extended through the beam width to the depth where the textile reinforcement was located. The internal textile fabric was exposed 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 in the bottom tie and shear crack originating from the support inclined in direction of the centre void (b) Concrete compression failure at the top of the beam and visible from the back side of the specimen.

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

Load-deflection behaviour

To process the data of the LED measurements, a script that performed a coordinate transformation to the desired coordinate system and displayed the deflection field during testing was developed (see Figure 5 for an example of the deformation field at a load stage of 120 kN). The measured data indicates a good symmetry in load bearing behaviour.

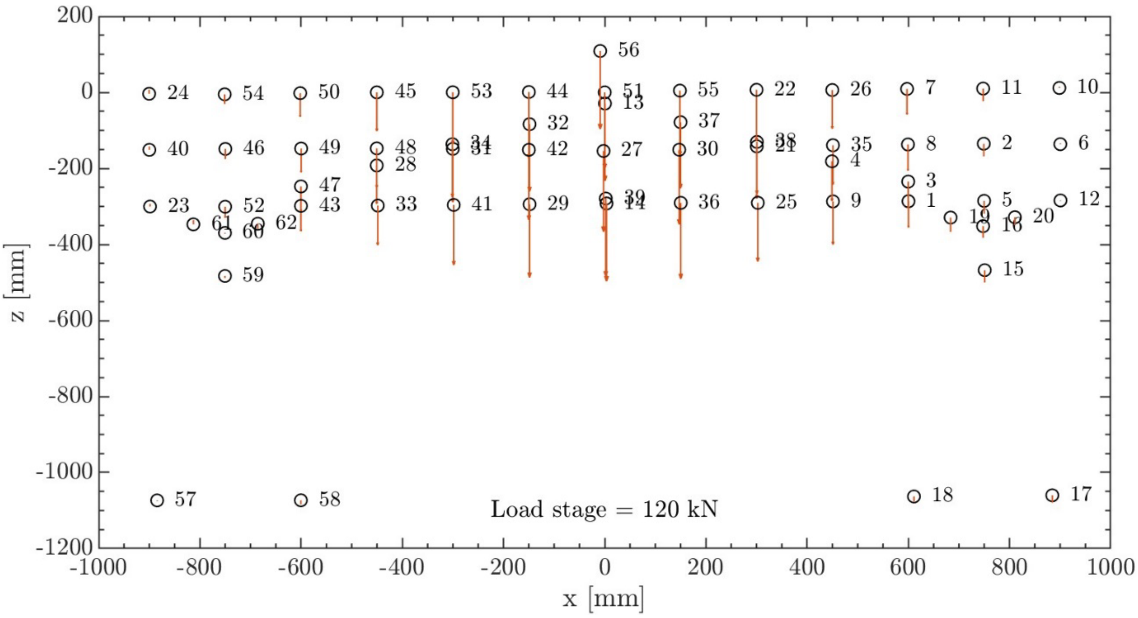
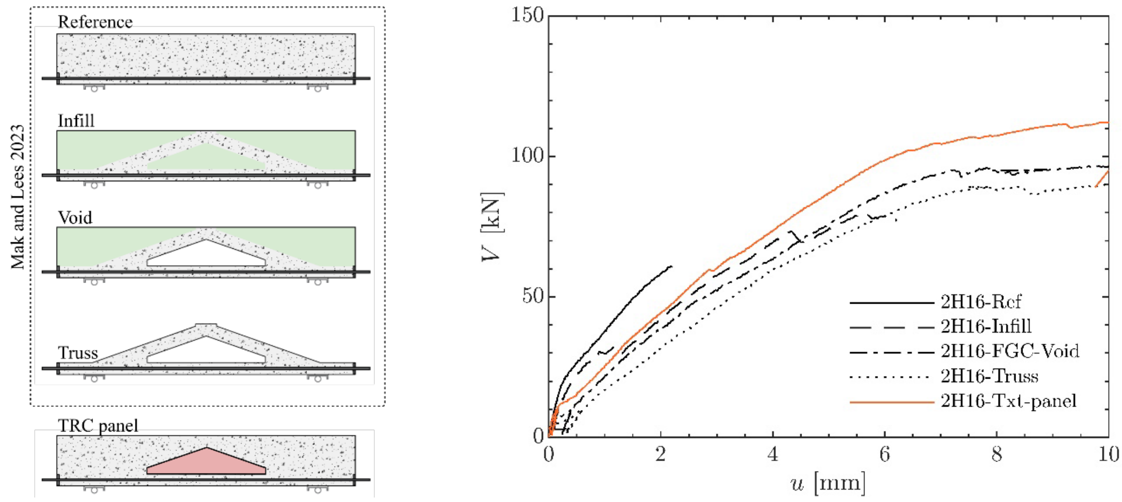


Figure 5: Vertical Deformation field at a load stage of 120 kN, measured with the LED system.

In addition, load-deflection curves can be extracted based on selected points of interest, as shown in Figure 6b, where the top face deflection at the midpoint of the specimen is shown during loading (indicated with a blue line; any vertical deformation at the supports was subtracted). When comparing the novel TRC panel behaviour (denoted at 2H16-Txt-panel) with the results from Mak and Lees (Mak & Lees, 2023b) for a solid reference beam denoted as 2H16-Ref, an uplift in load capacity is evident. While an increase in capacity relative to a reference beam was also reported in Mak and Lees for a full width infilled functionally graded beam (2H16-Infill), this effect was amplified in the current work through the inclusion of the TRC panel where the bearing capacity was roughly twofold compared to the reference beam. And although a higher initial stiffness was observed in the infilled beam of Mak and Lees relative to the functionally graded TRC beam, the behaviour changed at a loading of about 60 kN (shear force of 30 kN), and thereafter the TRC beam deflections in became smaller. This suggests a better structural integrity of the beam due to the TRC panel. Moreover, the ultimate load was found to be even higher than of the Voided (2H16-FGC-Void) and Truss (2H16-Truss) beams in Mak & Lees, 2023b. This is because the longitudinal fibre strands of the textile reinforcement also act as additional flexural reinforcement.

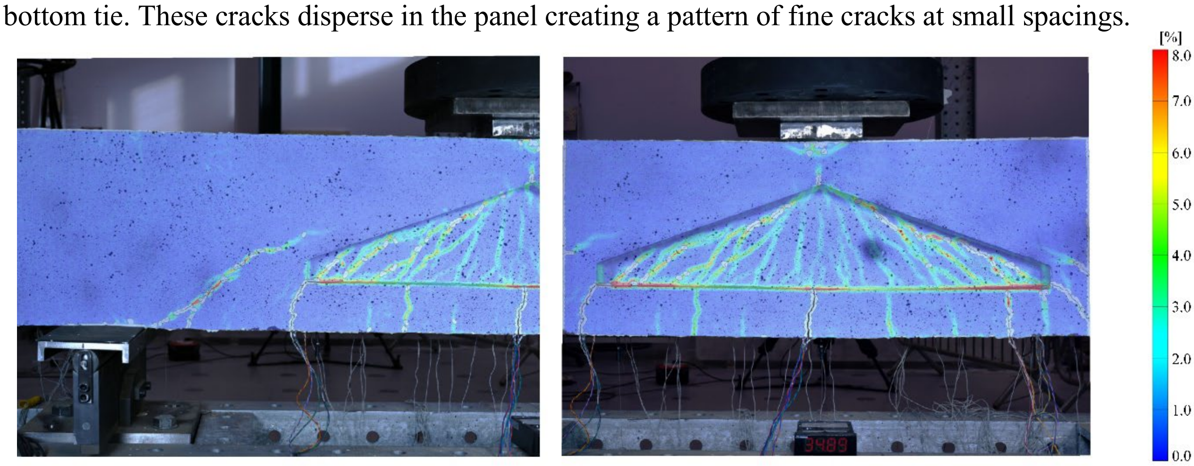


(a) (b)

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

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 at small spacings.



(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 at small distances in the central TRC panel

All these cracks are oriented towards the apex of the central panel and in general did not extend into the high-strength concrete above. Hence, a potential direct strutting of the load towards the support was not disturbed, and a shear failure, as was the case in the reference beam of Mak & Lees, 2023b was prevented. It is only in the region of the apex that a vertical crack became visible due to local bending stresses as a result of the abrupt change in beam thickness at that location. Moreover, the cracks below the central point of load introduction are indicative of impending concrete crushing.

CONCLUSIONS

The experiment described in this paper is the result of a preliminary study on the potential optimisation of beams through a combination of two design approaches, namely functional grading of concrete and textile-reinforced concrete. The specimen layout was based on the voided and functionally graded beams reported by Mak and Lees (Mak & Lees, 2023a, 2023b) except that a thin TRC panel was included in the central part of the beam where the width of the beam was also locally reduced. 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 functional grading and tapering of the structure. This requires logistical effort and manual input. It was, however, possible to cast the beam in the desired configuration to a high degree 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. Although the TRC panel beam stiffness was lower than that of an infilled functionally graded beam at early loading stages, an improved structural integrity and lower deflections were observed at higher load stages.
- The flexural cracks in the bottom tie of the TRC panel beam were dispersed and associated with fine cracks. 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 central load point and the support was not disturbed by such cracks.
- Similar to the voided beams of Mak and Lees, the functionally graded TRC beam exhibited an uplift in load relative to a homogeneous concrete prismatic reference beam. This was because a shear failure was prevented. As the longitudinal fibre strands of the textile also acted as additional flexural reinforcement a high ultimate load capacity was achieved. Failure was eventually caused by the crushing of the concrete below the central load point. The steel reinforcement at this stage, however, was already yielding indicating good material utilisation.
- The incorporation of a thin TRC panel into the design of a functionally graded concrete beam meant that a further 10% of material could be saved, therefore achieving a lighter structure, while simultaneously realising a load capacity that 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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