STUDIES ON THE SUSTAINABILITY POTENTIAL OF TAILORED TEXTILE-REINFORCED CONCRETE STRUCTURES

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Abstract

The geometric shapes and materials commonly used in conventional steel-reinforced concrete can result in a high wastage of cement that in many cases is not necessary to deliver the required load-bearing capacity. Textile-reinforced concrete (TRC) allows for a reduction in the material mass through the optimization of the cross-sectional geometry according to the stress state under flexural conditions. Hence TRC enables the realisation of more efficient shapes such as an unequal flange I-beam. However, even within this optimized geometry, there are well-defined areas with different performance requirements. This paper explores the economic and environmental advantages that can additionally be achieved if the concrete is functionally graded within a textile-reinforced structure to better match the environmental and mechanical requirements. For this purpose, concrete mixes with different compressive strengths and CO_2 footprints are identified. To help minimise environmental impact, the mix designs take advantage of the inert chemical characteristics of the textile reinforcement. As such, the need for high cement contents that would otherwise be required to ensure high alkalinity to passivate internal steel reinforcement is mitigated. The synergy of innovative TRC and functional concrete grading leads to significant reductions in the embodied CO_2 of up to 75% relative to a representative conventional concrete beam.

Keywords: *textile reinforcement; CFRP-reinforcement, eco-efficiency, environmental impact; functional graded concrete*

1. INTRODUCTION

The concrete industry is facing major challenges due to the climate crisis. 5-7% of global carbon emissions can be traced back to cement production [1]. New strategies have to be deployed to reduce the carbon footprint of concrete. As such, tailored textile-reinforced concrete (TRC) structures offer a promising avenue for material and weight savings. Textile reinforcement is a novel composite material that consists of bundles of high-performance fibres (e.g. carbon, glass or basalt) that are processed to form a mesh. The fibres are characterised by their high strength and are chemically inert making them a viable alternative to ordinary steel as reinforcement in concrete structures [2]. Since the reinforcement is not susceptible to corrosion, the concrete cover can be reduced and more lightweight structures can be designed.

In recent years, several such filigree structures have been presented in the literature [3-6]. In all cases a shift in design philosophy is evident, aiming to fully utilize the cost- and resource-intensive reinforcement. In general, the aim is to place material where it is needed according to the prevailing exposure or loading conditions. In the case of a simply-supported beam, this leads to cross-sectional shapes that are common in steel construction. Under flexural conditions, the highest stresses occur in the outermost fibres of the cross-section, which typically results in a wide flange to carry these stresses. Shear on the other hand is carried by thin webs. The translation of these design features into concrete structures enables a crucial reduction of the required material mass while maintaining almost the same ultimate bearing capacity to that of a comparable rectangular reinforced concrete (RC) beam. But even within an optimized geometry, there are well-defined areas with different performance requirements.

The concrete class is usually selected according to the most stringent requirements. For example, in a flanged fibre-reinforced polymer (FRP) reinforced I-beam under flexural conditions, the compressive stress is highest at midspan in the upper section of the top flange. In other regions, such a high concrete compressive resistance is generally not required. A gradual change in concrete class - subsequently referred to as functional grading - throughout the structure can therefore better meet different environmental and mechanical conditions [7]. This paper explores the economic and environmental advantages that can additionally be achieved by incorporating functional grading of the concrete in a TRC structure. In the first step, the cross-section of a simply-supported beam is optimized under flexural conditions. Three different concrete mixes were then identified that differ significantly in their performance. In the design and selection of the concrete mixes, special attention was paid to the inert characteristics of the textile reinforcement with the aim of reducing the overall amount of cement clinker used. The feasibility of functional grading with the selected mixes was demonstrated in a trial test. A theoretical study of functional grading as applied to a TRC beam with the previously described optimized cross-sectional shape is then conducted. It is shown that this synergy of innovative materials and production techniques leads to significant reductions in the embodied CO_2 relative to a representative concrete beam of up to 75%.

2. CROSS-SECTIONAL OPTIMIZATION

The starting point for the optimization process described in this paper is a carbon-reinforced beam that was introduced by Kromoser et.al in 2019 [3]. The beam has a height of 260 mm and unequal lower and upper flanges. The upper flange has a width of 300 mm whereas the bottom flange has a width of 100 mm, mainly to provide space for two internal carbon fibre-reinforced polymer (CFRP) reinforcement rods to enhance the bearing capacity. The web thickness is reduced to 30 mm, which is only possible due to the use of textile shear reinforcement [8]. The feasibility of producing such thin-walled structures with and without prestressing the CFRP-bars was demonstrated elsewhere [3, 9]; see Figure 1. It was subsequently intended to place several beams adjacent to each other and add a topping slab.

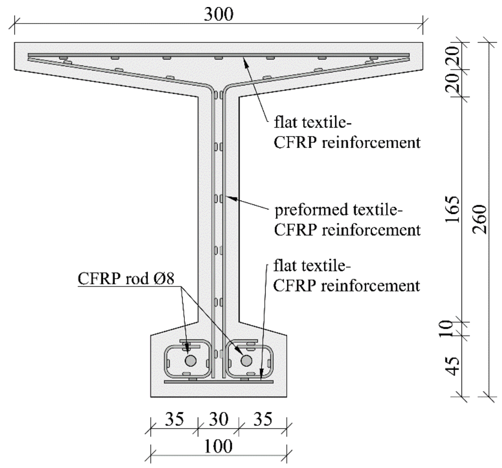

Figure 1: Cross-section of carbon-reinforced I-beam introduced by Kromoser et.al ([3]; left) and prototypes thereof as a proof of concept (right); Figures taken from [3]

The concrete used in this study was classified as Ultra-high-performance concrete (UHPC) with a compressive strength of 170.6 MPa (tested on cubes with dimensions 100×100×100 mm³). The design strength of the concrete is given as 103.3 MPa with a corresponding failure strain of 2 mm/m. The material behaviour is described as linear elastic up to failure. In terms of the carbon rod and the textile reinforcement, a design tensile strength and a corresponding breaking strain of 1.400 MPa - 8.7 mm/m and 1917 MPa - 8.3 mm/m respectively, are given.

The flexural capacity of the beam with the given geometry and the defined material behaviour is governed by a failure of both the carbon rods and the textile reinforcement. On the other hand, the concrete is not fully utilized as can be seen in Figure 2 (left). The peak concrete compressive stresses in the upper flange (-77 MPa) are 25 % below the UHPC design compressive strength, which was given by 103.3 MPa. UHPC usually contains a large amount of cement to achieve such high compressive strength. If the material properties are not fully exploited this means that cement, which is accountable for a large proportion of the carbon emissions in UHPC, is wasted. This in turn has a negative impact on the environmental performance of such beams.

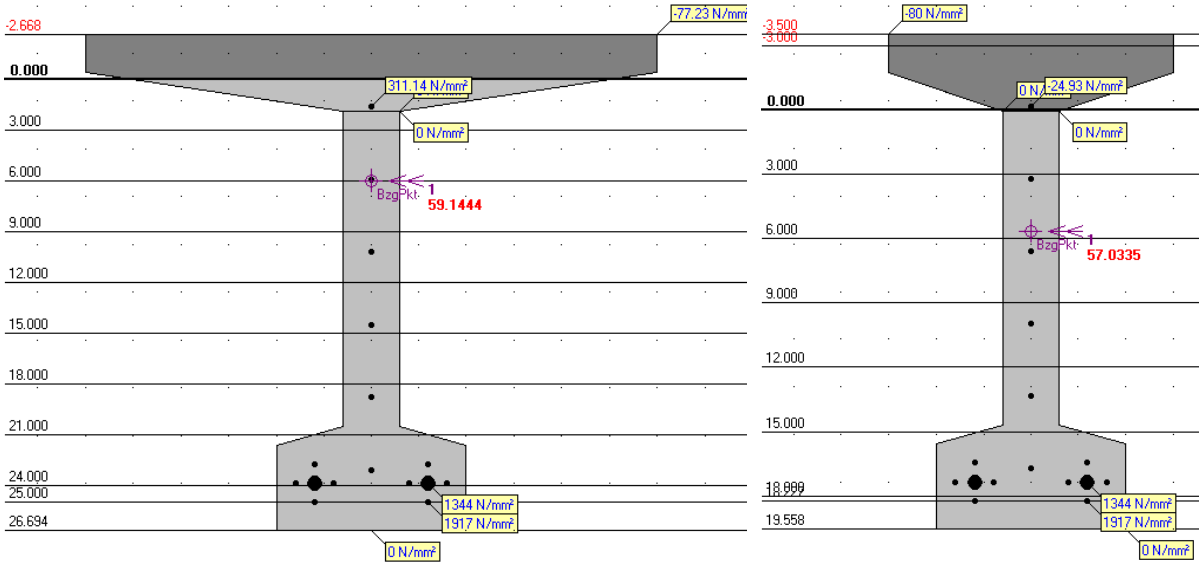

Figure 2: Strains and stresses at design failure load for original beam taken from Kromoser et.al ([3]; left) and optimized cross-section in this study to fully utilize material properties (right); note that the concrete is not active in tension (displayed as 0 MPa for example at the bottom).

In the following, an attempt is made to improve the effectiveness of the cross-sectional shape of such a beam under flexural conditions. While the properties of the textile reinforcement and CFRP rods stay the same, the target value of the concrete design strength is reduced from 103.3 MPa to 80 MPa (see also section 3.1). In addition, the properties of the upper flange are optimized so that both the concrete and the carbon reinforcement can be more utilized. This results in a slightly thicker flange (45 mm instead of 40 mm) but with a significantly reduced width of 160 mm compared to 300 mm for the original beam. By calculating the design bending resistance, which is of the same magnitude as the initial beam, it can be seen in the strains and stresses that all materials are now fully utilized. Through the simple measures described in this section, the cross-sectional area in the new design could be reduced by 34.5 cm² based on a total of 194.5 cm² for the original cross-section. This means that even in isolation the reduction of the concrete mass would reduce the required amount of cement by 17.7 %. In addition, if the provided concrete compressive strength more closely matches the required strength, this is also likely to lead to a further reduction in the cement required. This aspect will be addressed in more detail in the following sections. It should be noted here that possible effects on the serviceability limit state were not taken into account when optimizing the cross-sectional shape.

3. FUNCTIONAL GRADING OF I-SHAPED BEAM

Functional grading describes a tailored material variation throughout a structure to meet local requirements. Functional grading is well known in nature where the efficient usage of materials is of utmost importance. Since then, it has found its way into aerospace engineering, automotive engineering and many other disciplines. In civil engineering, functional grading is still not widely established except for certain specialised products such as semi-precast elements. However, this technique is capable of significantly enhancing the material efficiency in structural concrete and reducing carbon emissions [7]. This is especially the case for structures made of high-performance materials, as these materials usually have a higher energy demand in production. To assess the sustainability potential of this technique for TRC-structures a functional grading is applied to the I-shaped beam which was described in the previous section. In a first step, three concrete mixes are designed. These mixes are then graded within the structure both vertically and horizontally to meet the mechanical requirements due to the acting shear and bending stresses.

3.1. Concrete mix design

The three concrete mixes, were designed to take advantage of the inert characteristics of the FRP reinforcement. Since an alkaline environment is not required to protect the FRP reinforcement from corrosion, larger quantities of cement can be substituted with other materials such as limestone powder or fly ash [10]. The main objective of the design was to obtain three mixes with a wide spectrum of concrete compressive strengths ranging from a relatively low to medium to high strength. Efforts were also made to use essentially the same raw materials for all three mixes, varying only the quantities of each ingredient to allow for a simple adjustment from one mix to another. The final mix designs can be seen in Table 1. The increments between the concrete compressive strength after 28 days are about 35 MPa ranging from 44 MPa for the "Low" to 112 MPa for the "High" mix. Compared to the initial UHPC concrete mix design in Kromoser et.al [3] with a cement content of 750 kg/m³, it can be seen that the amount of cement clinker could be significantly reduced in all three mixes.

Table 1: Concrete mix designs used in this study - "Low", "Medium" and "High"

Component	Low	Medium	High
Cement (CEM I) [kg/m³]	157	383.4	624.3
Microsilica [kg/m³]			62.4
Limestone Powder [kg/m³]	314	187.9	62.4
Fly ash [kg/m³]	39		
quartz-sand 0.1-0.5 mm [kg/m³]	292.8	279.3	256.8
Sand 1-4 mm [kg/m³]	704.6	672.1	617.9
Sand 4-8 mm [kg/m³]	757.4	722.5	664.2
Water [kg/m³]	144.5	161	149.8
Superplasticizer [kg/m³]	4.7	5.4	21.9
Slump keeper [kg/m³]	2.4	3.5	12.5
Compressive strength [MPa]	44	77.8	112.2

Subsequently, the stability of the interface was tested when grading the different concrete mixes using the wet-on-wet technique [11]. For this purpose, two different concretes separated by a panel were filled into cubes. This panel was removed after the cube was filled to the top and vibrated afterwards. When the mould was removed after 48h of hardening, it was found that no significant geometric inaccuracies occurred along the vertical interface with any combination of two of the three mixes (see Figure 3). Further work is required to scale the results and refine the practicalities but this initial study suggests that using combinations of these concrete mixes for functional grading of TRC could be feasible.

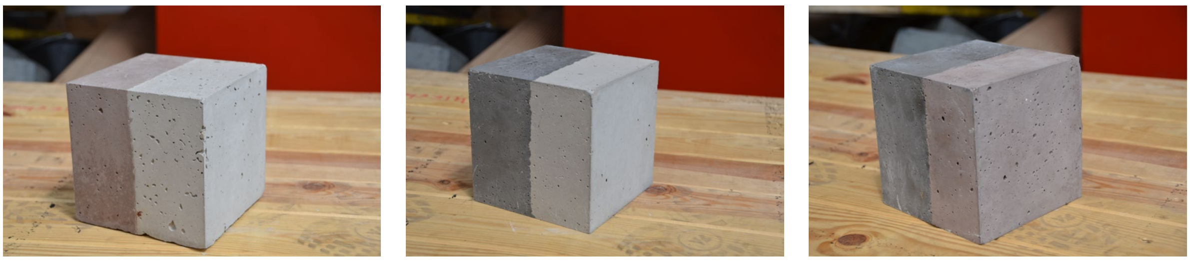

Figure 3: Functional grading of the concretes used in this study; combination of "Low and Medium" (left), "Medium and High" (middle) and "Low and High" (right); note: the red colour is due to a dye added during mixing to make the concrete mixes more distinguishable.

3.2. Determination of concrete types by area

The I beam cross-section (see Figure 1) was originally designed such that the concrete compressive zone at ultimate load is within the upper flange. However, while a high concrete resistance is then needed in the upper flange, the concrete in the web and in the bottom flange have lower mechanical requirements. To account for this in a functionally graded design, the concrete material is graded through the depth of the beam (Figure 4a) where in top flange region is denoted as area A_1 and the lower region as A_2. Concrete of type “High” is placed in the upper flange regions where the highest bending moments occur. In less highly stressed areas of the cross-section (A_2) concrete of type “Low” is placed (Figure 4b). As discussed previously, the section is almost balanced since failure is both governed by concrete failure and reinforcement failure at the same time, although the material behaviour(s) are brittle. A grading along the length of the beam can also be applied i.e. when the acting bending moment decreases and a high compressive resistance is no longer needed concrete of medium strength (Figure 4c) or even low strength (Figure 4d) can now be used in the top flange. In this case, the neutral axis moves towards the centre of gravity and failure is governed by a concrete compression failure (Figure 4c-d). The bending resistances (M_{Rd}) for the material combinations shown in Figures 4a, b and c are 57.0, 42.6 and 22.5 kNm respectively.

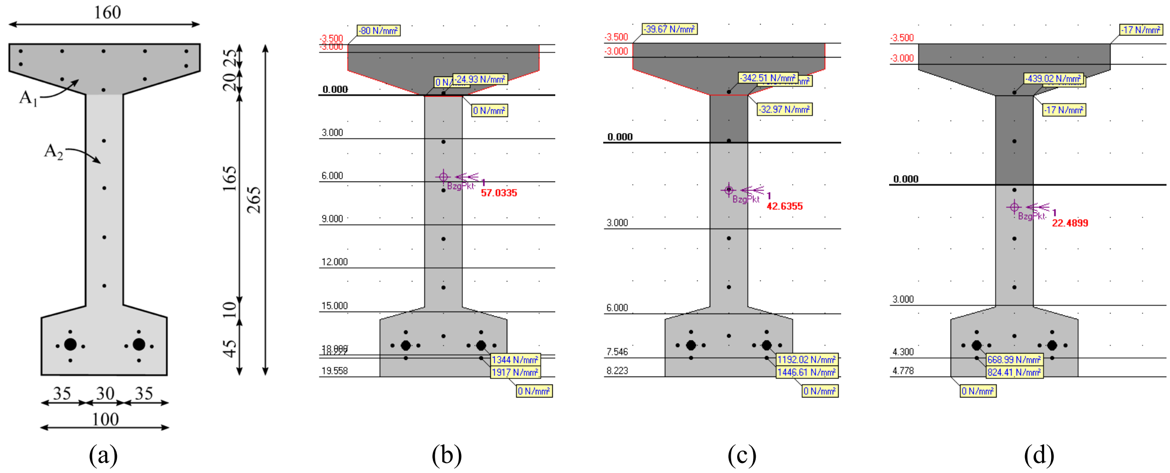

Figure 4: Functional grading in vertical direction applied to the I-shaped CFRP beam; geometry and dimensions (left), stresses and strains at ultimate bending moment for a combination of concrete type “High and Low” (b), “Medium and Low” (c) and “Low and Low” (d); note that the dark grey area in (b)-(c) displays the concrete compression zone

In the following, a simply-supported beam with a uniformly distributed load is investigated. The design load is calculated in such a way that the peak bending moment corresponds to the one in the studies by Kromoser et.al ([3] where a single point load was applied). This results in a distributed load of q_d = 11.62 kN/m. The resulting design bending moment and shear force distributions are depicted in Figure 5. Their respective magnitudes at intervals of 0.5 m are given in Table 2.

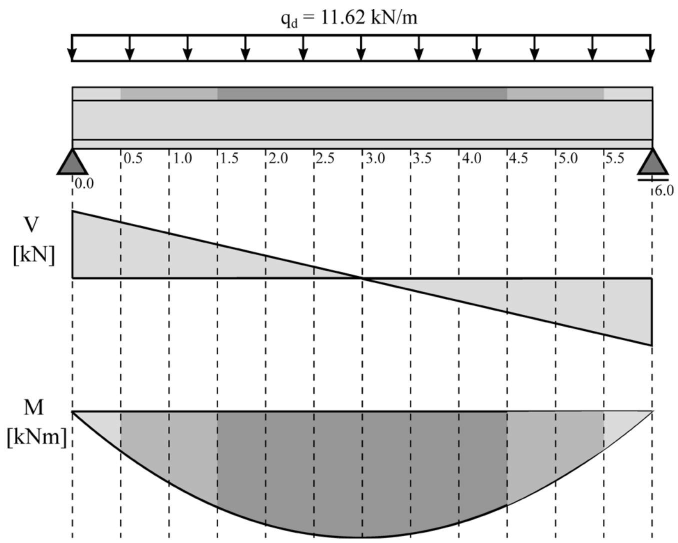

Figure 5: Application of a functional grading as a function of bending moment and shear force distribution.

The acting bending moment (M_{Ed}) at the individual intervals can be compared with the bending moment resistances (M_{Rd}) for the combinations considered in Figure 4. As such, the high strength concrete in the flange is needed only within ± 1.5 of the midspan. Further towards the supports, the medium strength concrete in the flange provides sufficient bending resistance from this point upwards ($M_{Rd,ms}$ = 42.6 kNm > $M_{Ed,1.5}$ = 39.2 kNm). The last half metre of the top flange can even be made with the low strength concrete as the bending resistance of 22.5 kNm exceeds the acting bending moment at 0.5 (5.5) m which is 16.0 kNm.

Since the shear force increases towards the supports, the applicability of the proposed functional grading also needs to be investigated in the context of the shear capacity of the web. However, in this case the shear resistance of the web is V_{Rd} = 34.9 kN [12] when using the concrete type "Low" throughout the section. This is already slightly higher than the acting shear force at the support (see Table 2). This means that the entire web could in principle be concreted with the low strength concrete and sustain the required shear force. This is a promising result although the shear resistance of functionally graded sections requires further investigation.

Table 2: Acting and resisting bending moment and shear force at intervals of 0.5 m with their respective degree of utilization when a functional grading is applied

x **[m]**	M_{Ed} **[kNm]**	V_{Ed} **[kN]**	M_{Rd} **[kNm]**	μ **[-]**	V_{Rd} **[kN]**	μ **[-]**
0	0.0	34.9	22.5	0.00	34.9	1.00
0.5	16.0	29.1	22.5	0.71	34.9	0.83
1.0	29.1	23.2	42.6	0.68	34.9	0.66
1.5	39.2	17.4	42.6	0.92	34.9	0.50
2.0	46.5	11.6	57.0	0.82	34.9	0.33
2.5	50.8	5.8	57.0	0.89	34.9	0.17
3.0	52.3	0.0	57.0	0.92	34.9	0.00

3.3. Concluding remarks on functional grading

The fabrication process for functionally layered specimens is still a key issue when translating this technique into building practice. However, it is likely to be easier if only a grading of the compression flange is done, as shown in this study. The formwork can be filled with concrete of type "Low" up to the bottom of the top flange. A functional grading of the top flange is then made by pouring the quantities of the different types of concrete in the intended location. It is not necessary to have an "exact" interface where the different concretes meet but rather an approximate transition between the different mixes [13]. As far as the setting time is concerned, it has been shown that a relatively strong interface can be achieved if the different concretes are chosen to be compatible and processed within one hour.

Another aspect that must be considered when applying a vertical grading to such structures is, that if the interface is within the concrete compression zone, interface shear forces occur due to the different mechanical performance of the materials. This has to be taken into account when designing the structure and may slightly increase the required web reinforcement. For this particular beam this would be the case when the web is cast with low strength concrete and the flange with the medium strength concrete (see Figure 4c). It is of note that the study on the functional grading of a filigree carbon-reinforced concrete beam was carried out with regard to the mechanical requirements due to bending and shear. Other aspects such as the bond performance, which is also governed by the concrete mix design require further consideration. Those aspects will be investigated in future work.

4. ENVIRONMENTAL EVALUATION

In the following, the environmental impact of the original structure is estimated and the sustainability potential of the functionally graded optimized design is assessed. Since most of the environmental impact of concrete is attributed to the cement [14], this is done by calculating the cement mass needed for the original beam design and comparing it with the cement mass needed for the optimized design. The impact can be quantified by linking the cement masses to the respective values per impact category. Table 3 lists the environmental impact of cement in different impact categories during stages A1 to A3 (Product Stage [15]) according to [16].

Table 3: Environmental impact of cement in phase A1-A3 (1000 kg CEM I from Germany); [16]

	GWP[1] [kg CO_2-aq.]	ODP[2] [kg CFC11-aq]	AP[3] [kg SO2-aq]	EP[4] [kg Po_4^{3}-aq]	ADPE[5] [kg Sb-aq]	ADPF[6] [MJ]	PERT[7] [MJ]	PENRT[8] [MJ]
CEM I	805	5.16E-06	0.964	0.268	0.378	2030	313	1950

[1]Global Warming Potential (GWP); [2]Ozon Depletion Potential (ODP); [3]Acid Potential (AP); [4]Nutrification Potential (EP); [5]Abiotic Depletion Potential for Elements (ADPE); [6]Abiotic Depletion Potential of fossil fuels (ADPF); [7] total use of renewable primary energy resources (PERT); [8]total use of non-renewable primary energy resources (PENRT)

To assess the carbon emissions, the global warming potential is of particular interest. In the original beam design, the total concrete volume in the beam is 0.1167 m³. If the concrete mix is the UHPC discussed previously, 750 kg Cement per m³ is used. This means a total amount of 87.5 kg cement for the whole beam or, when linked to the GWP, 70.46 kg CO_2-aq (see Table 4). In the case of the geometrically and functionally optimized beam presented in this study, the required cement mass is determined for each concrete type and then multiplied by the volume of that mix (see Table 4) used in the beam. The volume of low strength concrete is relatively large (V=0.0654 m^3) in relation to the total volume of the beam (0.096 m^3). However, the CEM I quantity of the low strength concrete is low (157 kg/ m^3) when compared to the high strength concrete (624.3 kg/m^3). Hence, it transpires that the small volume fraction of the high strength concrete is responsible for about half of the required cement mass and thus the GWP. Overall, the optimized beam results in a cement mass and associated GWP of 22.9 kg and 18.47 kg CO_2-aq, respectively. This means an overall reduction in CO_2-aq of 74 % compared to the original design. This impressively shows how a large amount of cement clinker can be saved using simple measures. It is, however, important to note that only the cement mass has been compared in this chapter. The environmental impact of the reinforcement is not considered here but will be in further studies.

Table 4: Required cement mass and associated GWP for the optimized beam design compared to the original design.

	Low	Medium	High	Σ Opt. beam	UHPC beam
CEM I [kg/m³]	157	383.4	624.3	-	750
***V* [m³]**	0.0654	0.096	0.0144	**0.096 (82.2 %)**	0.1167 (100 %)
CEM I total [kg]	10.3	3.7	9.0	**22.9**	87.5
GWP [kg CO_2-Äq]	8.27	2.96	7.24	**18.47 (26.2 %)**	**70.46 (100 %)**

5. CONCLUSIONS

Designing with textile reinforcement enables lightweight structures that make optimal use of the high strength and durability of FRP materials. In such structures, there are clearly defined regions where the concrete is exposed to different mechanical and environmental conditions. Functional grading of the concrete to meet those requirements enables the creation of more sustainable structures since mixes with larger quantities of cement are used only where needed. In this study, the overall sustainability potential of an I-shaped carbon-reinforced concrete beam is assessed by applying concrete functional grading. The following conclusions can be drawn:

- The cross-sectional design is important when aiming for the efficient utilization of structural materials. By narrowing the compressive flange of an I-shaped beam and reducing the compressive strength of the concrete, a balanced cross-section under ultimate load was achieved, where failure is governed both by a failure of the reinforcement and the concrete. This allowed for a reduction of the concrete mass by about 18 % compared to the original design with a wider flange.
- In the course of this study three different concrete mix designs were developed, ranging from a low strength concrete (f_{cm} ~ 44 MPa) to a medium (f_{cm} ~ 78 MPa) to a high strength concrete (f_{cm} ~ 112 MPa). The inert characteristics of the textile reinforcement mitigated the need for higher cement contents as would otherwise be required to provide an alkaline environment to avoid steel corrosion. Therefore, a significant portion of the cement could be replaced by other raw materials such as limestone powder. The workability and stability of those mixes when applying a functional grading was demonstrated in preliminary casting tests, where different combinations of the selected concretes were cast in two layers.
- A functional grading of the concrete material through the depth and span of a TRC I-beam can significantly reduce the amount of cement needed. Although the concrete for a structure is usually selected according to the most stressed or higher exposed regions, most of the structure has lower performance requirements. For the I-shaped beam presented in this study, the high strength concrete was only needed in the top flange within ±1.5 m (for a beam of six metres in length). The vast majority of the beam could be cast with a low strength concrete (except for a small region where medium strength was also used in the upper flange).
- With these relatively straightforward measures it was possible to reduce the total amount of cement used in the structure by 74 %. Since the carbon emissions of the concrete structure are largely determined by the cement mass used, this means a corresponding reduction of the GWP. This should be considered against the background, that the original I-shaped beam design already exhibited a lower GWP than a rectangular beam with the same flexural capacity but using ordinary reinforced concrete.

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DATA AVAILABILITY

The data supporting the findings of this study are available on request from the corresponding authors.

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