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Downsizing weight while upsizing efficiency: An experimental approach to develop optimized ultra-light UHPC hybrid beams

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Abstract

A three-phase topology optimization is applied to a conventional reinforced concrete (RC) beam loaded in four-point bending. The aim is to reduce material amounts to a minimum while preserving load bearing capacity and stiffness. The optimization result is converted into two alternative designs, namely a RC truss structure and a hybrid concrete-steel (HCS) truss structure. The RC truss structure is constructed in conventional reinforced concrete. By contrast, the HCS truss structure is designed using ultra-high performance fiber-reinforced concrete (UHPFRC) and S355 structural steel. Experimental studies demonstrate a 53% reduction in weight of the RC truss structure compared to the reference beam, while achieving a similar load bearing capacity and a significantly higher stiffness, albeit by increasing the structure's height. For the HCS truss structure, the weight saving is considerably higher, namely 83%, whereas the load bearing capacity can be increased by 10%. The stiffness remains comparable to that of the RC truss structure by increasing the structure's height likewise, while a more ductile type of failure is achieved.

KEYWORDS

CO₂, hybrid concrete-steel truss structure, lightweight design, micro fibers, micro-reinforcement, resource efficiency, topology optimization, UHPFRC, ultra-high performance fiber-reinforced concrete

1 | **INTRODUCTION**

Approximately 25% of CO_2 emissions worldwide are caused by the building sector. Its contribution to the global energy consumption is even higher, reaching 40%.¹ High demands for housing and infrastructure lead to a significant global warning potential (GWP).

Concrete is the most common construction material exhibiting the ability of free shaping, worldwide availability and low costs. However, cement production alone accounts for 5-8% of the global CO₂ emissions.^{2,3} According to

forecasts, this portion could rise up to about 10% by the year 2050 due to the increase of living standards and the growth of population.⁴

Various efforts have been made in recent years to mitigate this tendency. For example, on the material level, alternative binders for low carbon concrete have been investigated in order to replace Portland cement.⁵ On the structural level, the development of ultra-high performance concrete (UHPC) with compressive strengths >150 N/mm² provides the feasibility for designing slender and more lightweight reinforced concrete (RC) structures.⁶ First exemplary applications are hybrid UHPC-steel bridges,⁷ slim columns made of plain UHPC⁸ and slender concrete members of micro reinforced UHPC.⁹ Recently, new materials such as

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carbon reinforced concrete have been employed, for instance to design and build slender parking decks¹⁰ or bridges.¹¹

However, apart from a few exceptions, for instance,¹² most attempts generally have in common that conventional design principles of cross-sections and structures are adopted and that they are merely built more slender due to the properties offered by the new materials, that is, a higher strength and lower sensitivity to corrosion.

An alternative approach is to apply optimization methods and thus adapt either the reinforcement^{13–16} or the overall structural design.^{17–19} Doing so, the structures are shaped and designed according to the internal flow of stresses and consistent with the principle of "form follows force." In the paper, a similar strategy is employed. A suited topology optimization approach considering the specific material properties of UHPC and steel is applied to a conventional RC beam to yield a weight-optimized structure which is oriented towards principal stress trajectories. Load bearing capacity and overall stiffness are preserved. The latter is tackled through an increase of the structure's height. The design proposal from the optimization is then translated into two alternative structural designs that are validated experimentally.

The paper is organized as follows. Section 2 briefly describes the optimization strategy used and applies it to a conventional RC beam with rectangular cross-section that serves as a reference. Section 3 describes the transformation of the obtained optimization result into two alternative structures, namely a RC truss and a UHPC-steel truss structure. Design and fabrication of both alternatives are discussed in detail. Section 4 presents the experiments and the results obtained. Finally, Section 5 draws conclusions.

2 | OPTIMIZATION APPROACH

The optimization starts from a standard RC beam made of normal strength concrete with a rectangular cross-section (Figure 1a). The RC beam is loaded in four-point bending and designed in such a way that crushing of the compression zone and yielding of the lower bending reinforcement (2Ø25) occur simultaneously. The total weight amounts to 305 kg and serves as a reference for the subsequent optimization steps. The aim is to eliminate redundant material from the beam by designing it affine to the internal load transmission. Moreover, and in accordance with the beneficial properties of the materials involved, the design should be assembled from compression-only regions made from standard concrete or UHPC as well as tension-only regions made from rebars or raw structural steel. Load bearing capacity and stiffness should be preserved while the weight is minimized.



FIGURE 1 (a) Reference beam and reinforcement, (b) FE model of the initial design space, and (c) topology optimization result with structural steel (blue) and concrete (gray)

A three-phase (concrete, structural steel, and void) approach for topology optimization is adopted, namely the Material Replacement Method (MRM). It is able to take into account the compression and tension affinity of materials within a linear finite element (FE) context.²⁰ The advantage of this strategy is a much shorter computation time compared to direct physically nonlinear analyses with FEs. Two design variables are assigned to each FE. The first one controls whether material is assigned to the element or not. The second one determines the material composition of either compression affine concrete or tension affine structural steel. Naturally, the aim is to clearly assign just one material to each element. Separation of the materials is tackled by first calculating the principal strains and stresses in each element by assuming linear-elastic material properties. Next, the sensitivities, that is, the derivatives of the objective and constraint functions with respect to the design variables, are modified according to the corresponding element stress-state and depending on the material to which the respective element is assigned. Subsequently, the modified sensitivities are utilized to update the design variables. The objective is to minimize the mean compliance (=reciprocal of stiffness). The constraint function restricts the total amount of material that is available for this purpose to a predefined portion β of the initial design space, $\beta \in [0,1]$. Thus, a fully utilized structure is sought where no part is oversized. The optimization procedure for the reference beam using this method can be summarized as follows:

- 1. Define and discretize the initial design domain with FE and determine all boundary conditions, that is, loads and supports (Figure 1b).
- 2. Restrict the amount of available material using the parameter β .



FIGURE 2 Axial forces and bending moments (exemplarily for the RC truss structure), conceptual design with concrete (C) and steel (S) struts, respectively, node declaration: C, compression, T, tension,²⁴ and resulting structures

- 3. Link the analysis model (FE) to the optimization model using the three-phase SIMP approach.²¹
- 4. Minimize the objective function in multiple iterations using a nonlinear algorithm, for example, method of moving asymptotes,²² by rearranging the available material within the design space. Consider the compression and tension affinity of materials in linear FE analysis using MRM.²⁰

For a thorough description of the method the reader is referred to Reference 20. In order to prevent the design from a loss of stiffness due to the reduced amount of material, the design space's height is initially enlarged by 50% compared to that of the reference beam. Thus, structures of increased height may arise. This value is estimated under the condition of an equivalent elastic bending stiffness between the reference beam's rectangular cross-section made of normalstrength concrete ($E_0 = 33,000$ MPa) and a cross-section made of UHPC ($E_c = 48,000$ MPa) that is reduced to a compression and tension zone of equal size,²³ compare Figure 10. The reduction in cross-sectional area is chosen to 90%-so just 10% remains-what leads to an adjustment in height of about 50%. In addition, the supports are defined at half the height to allow for a better adaption to the bending (cf. Figure 1b).

The optimization result is depicted in Figure 1c. It is composed of longitudinally stressed compressive and tensile struts that consist of the corresponding compression affine (concrete) or tension affine material (structural steel). Figure 2 illustrates the dominance of axial forces N in the load transfer since only negligible small bending moments M are present. The struts, which are fully assigned to either concrete (C) or steel (S), are predominantly subjected to

TABLE 1 Mixture proportions and projected material parameters to design the test specimens

Reference beam—C30/3	37 (ready-mixed concrete)							
CEM III 32.5 N		Sand 0/2		Gravel 2/8	Gravel 8/16	Water	$f_{\rm cm, prj}$	$f_{\rm y, prj}$
(kg/m ³)							(N/mm ²	²)
279.4		797.1		391.4	768.6	102.6	38	500
RC truss structure—C40)/50							
CEM I 42.5 N		Sand 0/2		Gravel 2/8	Water	PCE SP	$f_{\rm cm, prj}$	$f_{\rm y, prj}$
(kg/m^3)							(N/mm ²	²)
500.0		669.7		1004.6	190.0	2.0	48	500
HCS truss structure—U	HPFRC							
Nanodur [®] compound							$f_{\rm cm, prj}$	$f_{\rm y, prj}$
CEM II 52.5 R (59%)	Quartz fine sand (41%)	Quartz sand 0/0.5	Water	PCE SP	SRA	Steel Fibers 13/0.19		
(kg/m ³)							(N/mm ²	²)
832.0	578.2	652.5	213.0	16.6	7.0	150.0	110	355

compressive or tensile stresses that merge in nodes. Obviously, load transfer is similar to a truss, whereby the region at midspan has to be designed as a frame with rigid upper corners to provide a static determination and thus robustness.



FIGURE 3 Visualization, cross-section dimensions, and reinforcement of the RC truss structure

It should be emphasized that the optimized structure is only valid for the considered load case. The robustness can therefore only be related to moderate load variations. Any other, significantly deviating load cases must already be included in the optimization procedure, for example, by minimizing the sum of all objective functions resulting from all considered load cases. Taking these structural characteristics into account, two different designs are derived: a RC truss structure and a hybrid concrete-steel (HCS) truss structure.

3 | **DESIGN AND FABRICATION**

3.1 | Materials

The more the material amount is reduced in optimization, the more the concrete strength must be increased, compare Table 1. The reference beam is designed based on a concrete strength class C30/37 according to EC2,²⁵ thus with a projected mean compressive strength of $f_{cm,prj} = 38 \text{ N/mm}^2$ and conventional reinforcement with a projected yield strength of $f_{y,prj} = 500 \text{ N/mm}^2$. The concrete class used for the RC truss structure is C40/50 and a flowable consistency is sought using a polycarboxylate ether-based super-plasticizer (PCE SP). For the HCS truss structure, a self-compacting, fine-grained (0.5 mm) ultra-high performance fiber reinforced concrete (UHPFRC) based on Nanodur[®] Compound 5941 is used. The compound is a premixed binder consisting of 59% CEM II cement and 41% quartz fine sand.



FIGURE 4 Formwork and nodal reinforcement details of the RC truss structure





FIGURE 5 Visualization, cross-sections, micro mat (MM) reinforcement, and node details of the hybrid concrete-steel (HCS) truss structure

Shrinkage reducing admixture (SRA) is added to tackle the increased shrinkage tendency of UHPC. The projected strength used for the design is conservatively assumed to be 110 N/mm². The tensile struts are designed of structural steel S355 with a projected yield strength of 355 N/mm².

3.2 | RC truss structure

3.2.1 | Design

Design and reinforcement of the RC truss structure are shown in Figure 3. The main tensile strut at midspan consists of $2\emptyset14$ and $2\emptyset12$. The $2\emptyset14$ are anchored behind the CTTT node, whereby the remaining $2\emptyset12$ are anchored in a compact loop-like manner not before the supports. The diagonal tensile struts connect the tension chord with the compression flange through 2 stirrups, $\emptyset8$ each. The upper flange is reinforced nonstructurally with a rebar $\emptyset6$ and welded transverse bars having the same diameter (Q188 mat). At midspan, two additional longitudinal rebars $\emptyset6$ welded at both ends of the transverse reinforcement bars ensure anchoring. These transverse bars are intended to carry the tensile stresses from the compressive stress expansion in the flange. The area at midspan is designed as a frame. A concrete cover of 2 cm is provided for all elements within the structure. It corresponds to a minimum value that applies for minor expositions by carbonation, for example, for components under dry conditions. Of course, higher values usually have to be chosen for exterior building elements. As a result, the total weight of the RC truss structure results to 143 kg, which corresponds to a weight decrease of 53% compared to that of the reference beam.

3.2.2 | Fabrication

Concreting is carried out in a horizontal formwork. The different strut thicknesses are realized by a three step casting procedure. When the concrete level reaches the formwork's top edge of the lower, smaller struts a cover of timber is mounted before concreting continues. Figure 4 shows formwork and reinforcement layouts at the nodes. Detailing is performed corresponding to classical RC design rules with a specific focus on well-designed nodes with anchorage of the tensile struts. Obviously, compacting with internal vibrators is practically unfeasible. Therefore sufficient flowability of the wet concrete must be ensured in preliminary tests. Due



FIGURE 6 Formwork, assembly, and details of the hybrid concrete-steel (HCS) truss structure

to a flow class 4/5, concrete can be compacted by slight rubber hammer blows on the outer framework.

The RC truss structure design reveals that a greater material reduction is possible, since some concrete remains that covers the reinforcement of the tensile struts. Furthermore, structural boundary conditions such as minimum concrete cover and spacing demands between reinforcement bars prohibit to reduce the cross-sections further. In order to exploit the potential for additional material savings, the design is elaborated to a hybrid truss structure.

3.3 | HCS truss structure

3.3.1 | Design

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Concrete and steel are now consistently segregated and assigned purely to the single struts in terms of compression and tension affinity, respectively (Figure 5). No concrete cover is provided at the steel struts. Thus, the design of the HCS truss structure approaches a "fully stressed design" to a greater extent than the RC truss structure. As indicated above, UHPFRC is used to slim the compressive struts down

IADLE 2 Material parameters of the test specimens (N/mm	Т	Γ.	ŀ	4]	B	I	L	ŀ	C	2	2		N	12	te	er	ia	1	pa	ra	m	le	teı	S	of	t	he	te	est	S	pe	ciı	ne	ns	$(\mathbb{N}$	V/	mı	'n)
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	$f_{\rm cm}$	E _{cm}	$f_{\rm ctm,sp}$	$f_{\rm ctm}~f_{\rm ctm,sp}$
Reference beam	28.9	24,182	1.9	1.9
RC truss	58.3	33,042	3.5	3.5
HCS truss	144.9	43,450	5.0	5.0

to merely 20 mm. The microfibers employed aim at preventing brittle, potentially explosive failure in compression. To withstand local tensile stresses and provide robustness and ductility, a micro-reinforcement mat (MM) consisting of stainless steel (material number 1.4301^{26}) with a bar diameter of 2 mm and a mesh width of 20 mm is used as reinforcement. The main tensile strut consists of structural steel S355 with a rectangular cross-section of $40 \times 20 \text{ mm}^2$. Locally curved at the CTTT node and bound to the supports it is anchored by perforated and welded steel plates. The secondary tensile struts consist of two round steel bars Ø14 made from S355 structural steel, which have a rolled thread on each side. They are screwed with steel elements using nuts.



FIGURE 7 Test setup and positioning of linear variable displacement transducers (LVDT)

Additionally, a thin layer of mortar is applied between the concrete and the steel elements at the compressive flange to ensure unimpaired contact in between. At the tensile flange (CTTT node), load transfer is ensured via welded connections between steel elements and tensile strut. At the same node, the loads of the diagonal concrete strut are transmitted to the steel chord via a jagged steel element welded onto it.²⁷ Doing so, the teeth like pattern aims in the direction of the axial stresses of the diagonal strut. So, intentionally almost no lateral drift occurs.

Similar to the RC truss structure, the section at midspan is designed as a frame to provide robustness against moderate load variations. Due to the high slenderness of the concrete struts, sudden buckling failure has to be prevented. Regarding an almost linear-elastic behavior of plain UHPC below the compressive strength,⁶ a simplified but conservative approach using derived failure diagrams based on second order theory⁸ is utilized. When dimensioning the HCS truss structure's struts, a simple supported column (Euler mode III) with a constant eccentricity of L/400 was assumed. Provided that the real imperfection can be kept to a minimum, further downscaling of the cross-sections seems feasible. However, the HCS truss structure's overall weight amounts to merely 51 kg, which corresponds to a reduction of 83% compared to the reference beam.



FIGURE 8 Load-deflection curves of the test specimens

3.3.2 | Fabrication

The concreting process is performed similar to that used for the RC truss structure, that is, employing horizontal formwork (Figure 6) and casting sections stepwise before covering them. Owing to the dense microstructure of UHPC, concrete cover can be reduced to 5 mm. Compaction is not required since the concrete is self-compacting. The small dimensions of down to 20 mm, in conjunction with microreinforcement, demand a sufficiently small aggregate grain size. Here, a size of maximum 0.5 mm is used, compare Table 1. As indicated in Figure 6, the steel rods Ø14 that form the secondary tensile struts are assembled in a subsequent step just after stripping the formwork. The latter was done the day after concreting.

4 | EXPERIMENTS

4.1 | Material parameters

Material parameters are determined for each of the test specimens as the mean value of three cylinders with 150 mm diameter each and 300 mm height. These parameters are the compressive strength $f_{\rm cm}$, Young's modulus $E_{\rm cm}$, and splitting tensile strength $f_{\rm ctm,sp}$ (Table 2). The axial tensile strength, $f_{\rm ctm}$, was estimated to be about $1.0 \times f_{\rm ctm,sp}$.²⁸ Despite the admixture of fibers, the employed UHPFRC exhibits a relatively low tensile strength (Table 2). This is mainly attributed to the partial segregation of the fibers within the mixing vessel that was observed. Obviously, the distinct flowability of the concrete and the fibers must be balanced in a better way.

4.2 | Experimental setup

All three test specimens are tested in a four-point bending test setup. Figure 7 shows the left halves of the three different beams. The reference beam is supported on hard fiber



FIGURE 9 Crack patterns of the (a) RC beam, (b) RC truss structure, and (c) hybrid concrete-steel (HCS) truss structure at failure



FIGURE 10 Required height ratios h/h_0 of material-reduced cross-sections for preserving the elastic bending stiffness at a residual volume ratio β

board (HDF) stripes, which are placed on steel half cylinders. These in turn are embedded in fitting steel elements with PTFE foil in order to avoid frictional constraints²⁹ and to simulate hinged supports. The loads $2 \times F/2$ on top are applied over a cross-beam on two steel cylinders with HDF stripes to ensure an even load distribution.

The RC truss structure is supported on $150 \times 150 \text{ mm}^2$ elastomeric bearings placed on steel. The loads are applied similar to the reference beam, however, via elastomeric bearings in the dimensions $60 \times 120 \text{ mm}^2$ on steel plates. The width of 60 mm corresponds to the web width of the upper flange to avoid transverse bending. The elastomeric bearings for the HCS truss structure are reduced to $100 \times 100 \text{ mm}^2$ at the supports and $40 \times 80 \text{ mm}^2$ at load application. Again,

the 40 mm correspond to the web width of the concrete flange to avoid transverse bending.

Displacements are recorded during the experiments by linear variable displacement transducers (LVDT). For each test specimen, two LVDT on each support and one at midspan are used (Figure 7). The effective deflection of each beam is then calculated by correcting the measured deformations at midspan by the measured values at the supports. This ensures that the large deformations of the elastomeric bearings do not distort the resulting load-deflection curves.

All tests are performed displacement-controlled with a speed of 0.5 mm/min. Strains are measured at selected points of the tensile struts using strain gauges glued on the reinforcing bars or structural steel, respectively.



FIGURE 11 Selected strain gauge data of the test specimens

4.3 | Results and discussion

The load-deflection curves obtained from the experiments are depicted in Figure 8. The reference beam shows a typical nonlinear behavior due to progressive crack propagation. The maximum load obtained yields 205.3 kN with an



FIGURE 12 Eccentricity/1st kernel ratio over load for the RC truss structure



FIGURE 13 Utilization ratio of the optimized truss structures. hybrid concrete-steel (HCS): a constant eccentricity of L/400 is assumed for each compressive strut when computing the stress ratio

associated deformation at midspan of 16.1 mm. In contrast, the RC truss structure shows an almost linear elastic behavior with a sudden drop when the maximum load is reached. It amounts to 192.7 kN which is 94% of the reference beam's one. However, it is achieved at a deformation of merely 8.1 mm. The HCS truss structure exhibits an approximately bilinear, elastic-plastic behavior with slightly greater stiffness than that of the RC truss structure. Maximum load is 225.1 kN, hence 10% higher than that of the reference beam. The corresponding deflection is 11.2 mm.

Obviously, both truss structures behave significantly stiffer than the reference beam. There are two reasons for this. The first reason lies in the increased height of the truss structures compared to that of the reference beam. The

TABLE 3 Simplified carbon footprint of the structures regarding the amount of cement and steel

	Weight				CO ₂ equivalent							
	Total (kg)	Concrete (kg)	Cement (kg)	Steel (kg)	Cement (kgCO ₂ e/kg)	Steel (kgCO ₂ e/kg)	Total (kgCO ₂ e)					
Reference beam	305	286.5	34.1	32.2	0.832	1.99	92.3					
I-beam	229	208.6	24.8	32.2	0.832	1.99	84.6					
RC truss	143	127.8	27.2	16.3	0.832	1.99	55.0					
HCS truss	51	23.7	8.4	29.1 ^a	0.832	1.55	52.1					

^aSteel fibers included.

second is due to the characteristic load bearing behavior, which is dominated by axial loads instead of bending and shear, thus leading to reduced crack initiation and, in particular, no shear cracks as can be seen from Figure 9. Using the HCS truss structure as an example, the significantly higher structural stiffness observed in the experiment will be examined in more detail. To do this, the approach used to estimate the required height to preserve stiffness is extended. In Figure 10, the lower curve represents the required height adjustment for a given residual volume ratio β , now taking into account a material-reduced cross-section consisting of different materials for the compression and tension zone. Furthermore, the area ratio of compression to tension zone is defined according to the ratio of the projected material strengths. The bottom curve depicted in Figure 10 is based on a reference beam's Young's Modulus $E_0 = 33,000$ MPa, a compression zone made of UHPC ($E_c = 48,000$ and $f_{\rm cm} = 110$ MPa) and a tension zone made of steel type S355 $(E_{\rm s} = 200,000 \text{ MPa} \text{ and } f_{\rm y} = 355 \text{ MPa})$. For given volume ratios β , it results in significantly lower required heights than the one used for the designs. To compare the reference beam's stiffness with that of the HCS truss structure, the compliance $c = F \cdot u$ of both is calculated. The compliance of the conventional RC beam at maximum load results to c = 3,305.3 kNmm. For a reasonable comparison, the compliance for the HCS truss structure is also computed for the reference load F = 205.3 kN and the corresponding deformation (u = 7.1 mm,cf. Figure 8). It yields c = 1,457.6 kNmm. In a direct comparison, the HCS truss structure's stiffness is thus 2.27 times higher than that of the reference beam. The mass ratio of the HCS truss to the reference beam is 17%. The corresponding volume ratio amounts to $\sim 13\%$ and the ratio of the structures' heights equals 425.7 mm/300.0 mm = 1.419. For β = 0.13 a required height ratio of $h/h_0 = 0.66$ can be determined from the lower curve in Figure 10. Assuming a simplified linearized relationship between height and stiffness, the ratio of existing height to required height for stiffness preservation corresponds to 1.419/0.66 = 2.15. This almost complies with the stiffness ratio (2.27).

The selected data of the strain gauges in Figure 11 give additional insight into the load bearing mechanisms and the causes of failure. As intended for the reference beam, both, the compressive (crushing) and tensile zones (yielding) fail simultaneously. Thus, full utilization of the bending capacity is achieved. The strain diagram at the top of Figure 11 shows this effect with strains exceeding $\varepsilon_c \geq |-2.0|$ % for concrete and $\varepsilon_s > \varepsilon_y \approx 2.5$ % for the reinforcing steel. The measured concrete strain is actually the strain of the rebar on which the strain gauge is glued on. For the sake of simplicity, a rigid bond between concrete and reinforcement is assumed here.

In contrast, the RC truss structure fails due to lateral splitting at the CCT node, causing a sudden drop of the load-deflection curve. Obviously, the stirrups deflect the compressive stresses of the upper flange. The resulting transverse tensile stresses progressively induce a longitudinal crack, which finally causes splitting off the concrete as there is no anchored reinforcement to bridge the crack. Yielding ($\varepsilon_y \approx 2.5 \%_0$) occurs within some of the tensile struts (Figure 11, center), while the compressive struts (No. 7) still show some reserves ($\varepsilon_c \ll -2.0 \%_0$).

On the other hand, the HCS truss structure exhibits a more ductile behavior. Referring to the strain gauge data in Figure 11 (bottom), yielding of the primary tensile strut (No. 4) at midspan can be observed. The maximum strain equals $9.52 \%_{c}$, which corresponds to a total longitudinal expansion of ~10 mm. The increasing expansion successively leads to an offset of the diagonal concrete struts, as a result of which they are additionally subjected to bending. The combined effect of axial force and ascending bending moment finally leads to failure. Figure 9 shows this secondary crushing induced by the initial yielding of the lower strut.

The visible cracks of the RC truss structure in Figure 9 (center) indicate that the struts predominantly transfer axial forces since cracks appear mainly circumferentially. For the RC truss structure, the strain gauge data from Figure 11 can be used to calculate the axial forces and bending moments during testing. In Figure 12, the resulting eccentricity e = M/N is plotted by the ratio to the first kernel of the strut's cross-

section over the load. Obviously, the members are predominantly subjected to axial stresses and only marginally to bending when the load increases. The greatest eccentricity is found for the main compressive strut (C1) at midspan. This is in accordance with the expectations, since the web causes a small design-related eccentricity.

In summary, both material-reduced structures achieve a similar maximum load and exhibit a significantly higher stiffness than the reference beam whereby the structures' heights are greater than that of the reference beam. If efficiency is defined as the ratio of ultimate load to self-weight, the test specimens can be compared even more vividly. The reference beam exhibits the lowest efficiency with a ratio of 67.4. It is doubled to 134.3 for the RC truss structure. The HCS truss structure shows the greatest efficiency according to this criterion due to its closest approach to a "fully stressed design" with a ratio of 436.9. This efficiency approach is illustrated in Figure 13, which shows the utilization ratio of both the RC and the HCS truss structure's struts. The ratio is defined by the achieved stresses relative to the concrete strength or the yield stress, respectively. Although a full utilization of all struts is not met completely, the HCS truss structure is obviously stressed more uniformly than the RC truss structure.

In order to make an approximate comparison of all beams concerning the environmental impact, the global warming potential of all structures should be estimated. Table 3 shows the comparison between the reference beam, an I-beam with equivalent load-bearing capacity and the two optimized structures with respect to the CO₂ equivalent. The I-beam is to be understood as an intermediate optimization step. Its design results from reducing the reference beam's crosssection to the compression zone required from bending and to a tension zone required for just covering the rebars. The web width is limited by the shear force transfer. As a result, a structure with $\sim 27\%$ less weight than the reference beam's is obtained. The embodied carbon values for the materials in Table 3 originate from the Inventory of Carbon and Energy database.³⁰ For the sake of simplicity, an average value was used for all cement types while a distinction was made between reinforcing and sectional steel. Obviously, a 40% reduction in the CO₂ equivalent can be achieved by the RC truss structure and 44% by the HCS truss structure. The reduction of the total weight does not directly correlate to CO₂ savings. This becomes particularly apparent when comparing the I-beam with the reference beam. Although a weight reduction of 27% can be achieved, the carbon footprint is only improved by 8%. However, it should be noted that this is only a simplified comparison in order to assess the ecological optimization potential in a direct comparison. Additional factors such as transport to and within the construction site will also have an impact in an exhaustive ecological assessment.

5 | CONCLUSIONS

It is demonstrated that a convenient optimization strategy for RC reveals material-appropriate, lightweight structures. The optimized structures exhibit similar load bearing capacities and significantly higher stiffness than a conventional RC beam with a rectangular cross-section, however, while having an increased structural height. Simultaneously, the material amounts could be reduced by 53% for the RC truss structure and 83% for the HCS truss structure compared to the reference beam. The conclusions can be summarized as follows:

- Further material reduction for the RC truss structure is primarily limited due to structural boundaries concerning the reinforcement, for example, minimum concrete cover and minimum distances of rebar. The concrete struts can therefore not be fully utilized. Additionally, the concrete cover of the tensile struts increases the overall weight considerably without significantly contributing to an increase in the load-bearing capacity.
- A consistent conversion of the optimization result requires a hybrid design in which the materials are structurally separated according to their specific properties. A thorough design, especially of the nodes, is essential, since each structural part becomes decisive when approaching a fully stressed design.
- An application of the presented method appears reasonable for structures with solid cross-sections.

Future research should address the following issues:

- An increase of the design space's height by 50% for the optimized structures is unjustified since the truss structures both exhibit a significantly higher stiffness in the experiments. Hence, additional material savings seem feasible through lowering the optimized structure's height. Furthermore, theoretical considerations on the test results show that stiffness preservation could be even possible without enlarging the structural height at all.
- The nodal design of the HCS truss structure needs to be improved since the nodes account for a relatively high proportion of the overall weight. They appear too massive, distract the slenderness of the structure, and have a negative impact on the carbon footprint. Additionally, more simplified steel components could further decrease the CO₂ impact of the structure.
- A modular assembly method will enable cost-effective and fast fabrication. In addition, such a modular design

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could allow for the spatial adaption of the individual struts and thus mean a further step to a fully stressed design with further material reduction.

• For practical application, the robustness and ductility of the optimized structures should be investigated thoroughly.

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