CICE2023 Rio de Janeiro – Brazil
11TH INTERNATIONAL CONFERENCE ON FRP COMPOSITES IN CIVIL ENGINEERING

DEVELOPMENT OF CARBON-REINFORCED HOLLOW CORE SLAB

Nazaib Ur Rehman, Technische Universität Dresden, Germany, nazaib.ur_rehman@tu-dresden.de
Harald Michler, Technische Universität Dresden, Germany, harald.michler@tu-dresden.de
Marina Stümpel, Technische Universität Dresden, Germany, marina.stuempel@tu-dresden.de
Birgit Beckmann, Technische Universität Dresden, Germany, birgit.beckmann@tu-dresden.de
Paul Penzel, Technische Universität Dresden, Germany, paul.penzel@tu-dresden.de
Lars Hahn, Technische Universität Dresden, Germany, lars.hahn@tu-dresden.de
Chokri Cherif, Technische Universität Dresden, Germany, chokri.cherif@tu-dresden.de
Steffen Marx, Technische Universität Dresden, Germany, steffen.marx1@tu-dresden.de

ABSTRACT:

Innovative materials, like carbon-reinforced concrete, are opening up new avenues for building design and construction. However, to fully leverage the potential of these materials, it's important to use intelligent construction techniques. One such technique is to build Hollow Core slab systems using special carbon "Netzgitterträger" (NetzGT) reinforcement structures (textile lattice girder) instead of conventional steel lattice girder. This approach can significantly reduce the amount of concrete material required compared to that of conventional Hollow Core ceilings or floor slabs made with prefabricated filigree slabs and cast-in-place concrete supplement. This results in cost savings and a lower carbon footprint. The basic reinforcement used here is a development of the TU Dresden. Hereby an optimized topology for the NetzGT element with trapezoidal geometry, featuring a net-shaped fabricated textile made of multiple diagonally offset rovings with overlapping edge strands was developed.

KEYWORDS: Non-metallic reinforcement; Hollow Core slab; net-shape textile; Textile reinforced concrete; Lightweight slab system.

INTRODUCTION

A slab or ceiling is a structural element with top and bottom surfaces parallel resulting in an extremely shallow depth relative to the span of the element. In recent decades, precast concrete slab construction has become more popular and competitive than cast-in-situ slab construction due to their faster production time, efficiency, and better quality control. In the designing of precast slab structural elements, researchers are interested in terms of weight and cost-effectiveness besides the load-carrying capacity (Mahdi & Ismael, 2021). This has resulted in the development of slabs with voids (cores) in the longitudinal direction, known as the Hollow core (HC) slab. A HC slab is a special type of combined precast and cast-in-situ slab typically used in the construction of floors in multi-story buildings that can provide low-cost and lightweight construction floor surfaces. This type of slab production has increased significantly in recent years due to its highly efficient design, and structural efficiency. The most popular core forms for HC slabs, which have been investigated over the past few decades, are round and rectangular core forms. All these hollow bodies have to cope with the problem of floating during concreting.

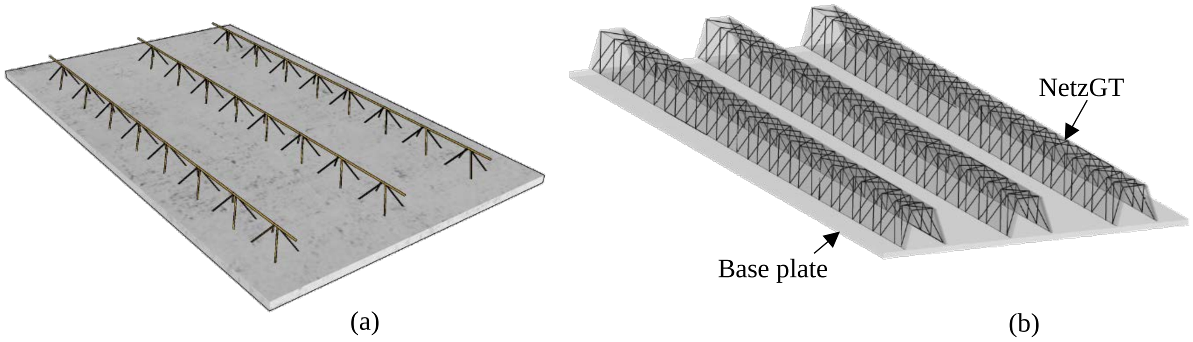
New materials allow new building designs and construction types and one of them is carbon-reinforced concrete (CRC), which is a composite material that has shown a high potential for use in building structures in the past few years due to its material efficiency, durability and high load bearing capacity. With intelligent construction strategies, it is possible to utilize the full capacity of the innovative CRC material. One impressive example is the construction of CUBE, the world's first carbon-reinforced building (Let's Get CUBE – Carbon-Concrete.Org). The CUBE has been recently constructed by the Institute of Concrete Structures (IMB), Technische Universität Dresden, Germany (Hegger et al., 2023), (Curbach, 2022), (Curbach, 2023). This composite material can greatly cut down on the building industry's massive resource usage as well as CO_2 emissions. The excellent properties of the composite material and high light weight potential are due to carbon fibers, which have higher tensile strength and lower density as compared to conventional steel bars (Tietze et al., 2022). Furthermore, the material offers the advantage of being corrosion-resistant, in contrast to steel, which is susceptible to corrosion over time. As a result, the need for concrete cover is reduced to merely ensure bond strength. This feature allows the construction of extremely slender structural components without any concern of corrosion (Koschemann & Scheerer, 2022), (Schumann, Michler, et al., 2018). Additionally, the carbon textile reinforcement allows for greater geometrical flexibility and permits the carbon grid-like structure to be bent or twisted into a variety of shapes which motivates the construction industry to build novel structural elements and designs by utilizing their beneficial properties (Friese et al., 2022). Such as the construction of an extremely light and slender precast bridge completely made of CRC (Rempel et al., n.d.), the aesthetic Pavilions in Chemnitz, Germany and the CUBE are completely made with CRC (Carbon Fibre-Reinforced Concrete Offers Innovative Solutions for Civil Engineering | TU Chemnitz) (*Let's Get CUBE – Carbon-Concrete.Org*, n.d.) and many other structures ("Carbon Composite Pedestrian Bridge Installed in Madrid," 2011), (V4.2 Vorgespannter Carbonbeton Für Straßenbrücken Und Flächentragwerke), (Schumann, May, et al., 2018), (Pavement Made of Carbon-Reinforced Concrete for Bridges). In recent times, research institutions have been prioritizing material efficiency and slender elements, with initiatives like the Sonderforschungsbereich (SFB-TRR-280) project in Germany, which started in 2020. This fundamental research project aims to provide the foundation for future construction processes by thoroughly reevaluating the principles of design, modeling, construction, and utilization of sustainable and resource-efficient building components made from CRC (Beckmann et al., 2021).

HC slab systems are designed to be lightweight and cost-effective and the use of carbon reinforcement instead of conventional steel reinforcement can further reduce the weight and increase the structural efficiency of the system and at the same place providing greater durability and corrosion resistance. As the construction of CRC opens up many new possibilities, one research idea is to make practical recommendations for the use of CRC in HC slab systems, where thin and lightweight ceiling elements can be constructed. Before conducting numerical and experimental investigations, it's crucial to have a clear understanding of the construction steps required to model and construct HC slab system. This article will provide clear and precise instructions for constructing the different models and executing the necessary steps for experimental investigations. The objective is to accurately present the construction process to ensure reliable and accurate results.

STEEL LATTICE GIRDER TO CARBON TEXTILE LATTICE GIRDER

It is very common to use steel lattice girders in the construction of slabs. These are used as filigree prefabricated parts for the formwork and as load-bearing elements of ceiling slabs. However, the idea is to replace steel lattice girder with carbon textile lattice girder, simply known as Netzgitterträger (NetzGT); see Figure 1.

Carbon NetzGT offer several advantages in building construction. One key advantage is their high strength-to-weight ratio, which means that they can support heavy loads while being relatively lightweight. This makes them much easier to handle compared to conventional steel lattice girders. Another important advantage of carbon NetzGT is its resistance to corrosion. Thus, it is possible to construct thinner slab elements by reducing the usage of material without compromising on safety or strength. Therefore, the replacement of traditional steel lattice girders with carbon textile lattice girders may provide enhanced performance and sustainability in building construction (Chokri Cherif, 2022).



(a) (b)

Figure 1: (a) Steel lattice girder in concrete slab (b) Concrete slab reinforced with NetzGT elements

NetzGT element

The production of an optimized NetzGT element is the first step. There are many factors that can affect the properties of the element, such as the angle at which the diagonal offset rovings are produced, the profile of the roving, and the number of overlapped edge strands.

The production process starts by creating a continuous textile net-shaped non-crimp fabric (NCF) made of multiple diagonally offset carbon fiber rovings using the multiaxial warp knitting process with a further developed yarn offset system. These net-shaped textiles are then processed through a special shaping and fixation method using polymeric resins (polyacrylate) to produce the three-dimensional NetzGT reinforcement element. During the textile production process, the carbon fiber rovings are directed in a specific pattern to achieve optimal anchorage. The rovings move vertically from the top to the bottom, then extended horizontally before sloping back up from the bottom to the top. The rovings then change position to the other side and the process continues. The entire procedure is carried out for each roving, and the number of rovings at the bottom tension zone of the NetzGT varies based on the desired production output. The zigzag pattern of the rovings created during the manufacturing process results in a net-shaped structure that offers good anchorage for the textile, and increasing the stability of NetzGT. The graphical representation depicted in Figure 2 illustrates the manufacturing process and outlines the production steps of rovings in a zigzag pattern.

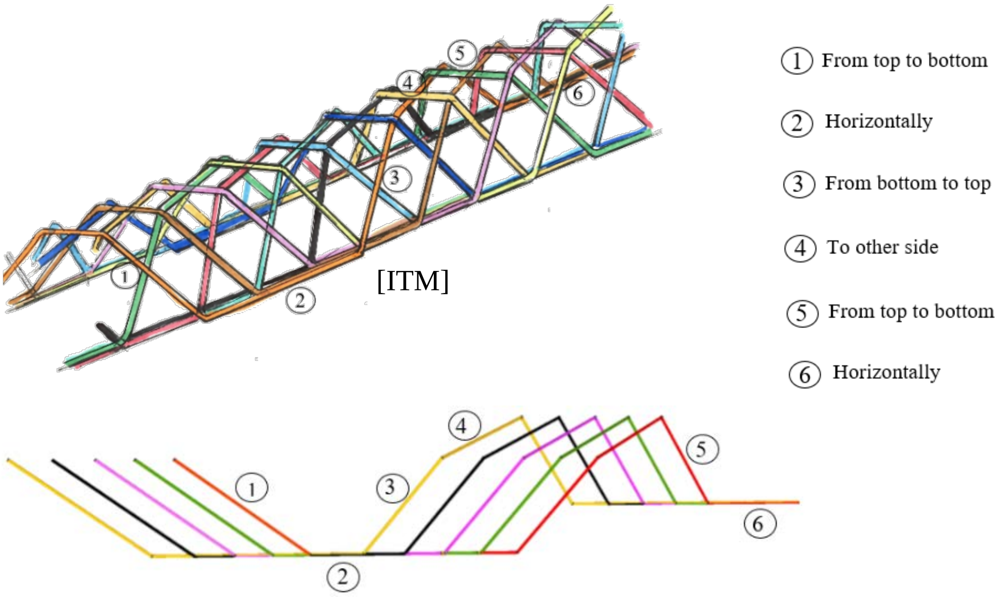


Figure 2: Production process of NetzGT rovings

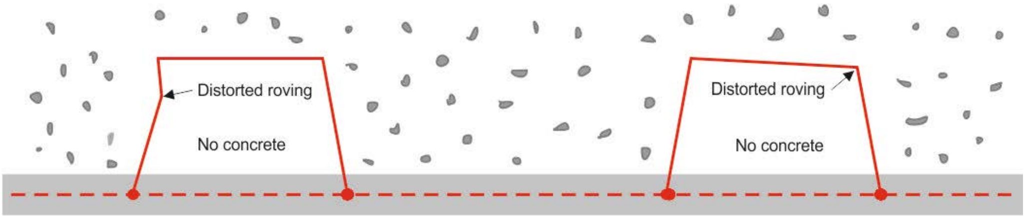
The angle at which the diagonal rovings are produced affects the shear strength of the slab system. If the angle is too steep or gentle, it may not effectively cross the shear cracks that can occur in the shear zones of the slab. Therefore, it is crucial to optimize the angle of the diagonal rovings to mitigate the risk of shear cracking. By optimizing the angle of the diagonal rovings, the overall shear strength of the system can be improved, making it more capable of supporting heavy loads. The Institute of Textile Machinery and High Performance Material Technology (ITM) and Institute of Concrete Structures in Dresden have so far manufactured rovings with three different angles, specifically 50 degrees, 60 degrees, and 70 degrees to experimentally evaluate the theoretical shear performance resulting from shear forces.

The profiling of the rovings is also important because it can strongly influence the bond strength between the roving itself and the concrete. This bond strength measures the adhesion between the rovings and concrete matrix (Penzel et al., 2022), (Abdkader et al., 2023). Optimizing the roving profile through careful design and production controls can ensure a strong and durable bond between the rovings and the concrete, improving the overall strength and durability of the NetzGT element and thus the corresponding HC slab system.

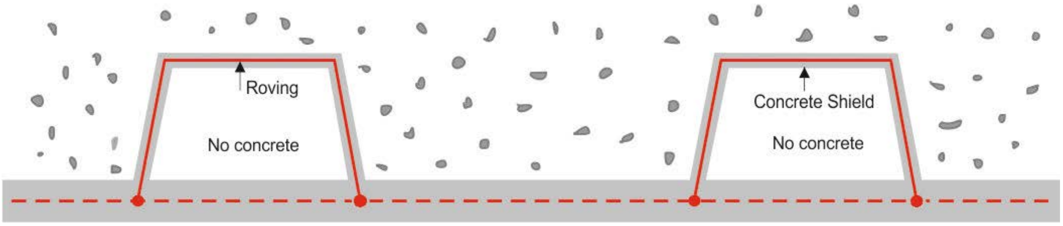
The number of edge-overlapped rovings used in the construction of NetzGT elements are primarily responsible for providing tensile strength to the slab. Therefore, it is important to strike a balance between using an optimized number of rovings to provide sufficient tensile strength.

Concrete shield

When incorporating NetzGT elements into a fresh concrete slab, it is important to ensure that the rovings are properly covered with a concrete shield; see Figure 3b. As the rovings are quite flexible and can be displaced or distorted if they come into direct contact with the concrete during pouring as shown in Figure 3a. To ensure proper cover of the NetzGT elements, it's important to use appropriate construction techniques and materials to maintain the required concrete shield thickness. The concrete mix used should be of a specific consistency to ensure that it flows around and completely covers the rovings. Additionally, self-compaction concrete can help to ensure that the NetzGT elements are properly covered.



(a) Distortion of NetzGt elements during concreting



(b) Concrete shield around NetzGT elements

Figure 3: Mitigating distortion of Netzgt elements with concrete shield

The construction of a HC slab with a NetzGT reinforcement is a specialized slab system that involves various steps, such as the optimization of the NetzGT element itself and precise control of the slab production process. This process requires special attention to ensure that the resulting structure has the desired properties, and fulfilling both the strength and serviceability criteria. Therefore, it is important to understand each step involved in the construction process to ensure that the structure is built to the required specifications and can meet the necessary performance standards. Following are the steps that need to be followed for its implementation in construction phase.

Concreting NetzGT element

In the first step, the NetzGT is partially encased in concrete; see Figure 4 and 5 (Step 1 to 4). During this step, the overlapped edge strand rovings are not concreted as they will be embedded into the fresh concrete plate to create a monolithic construction with the base plate as shown in Figure 5 (step 5).

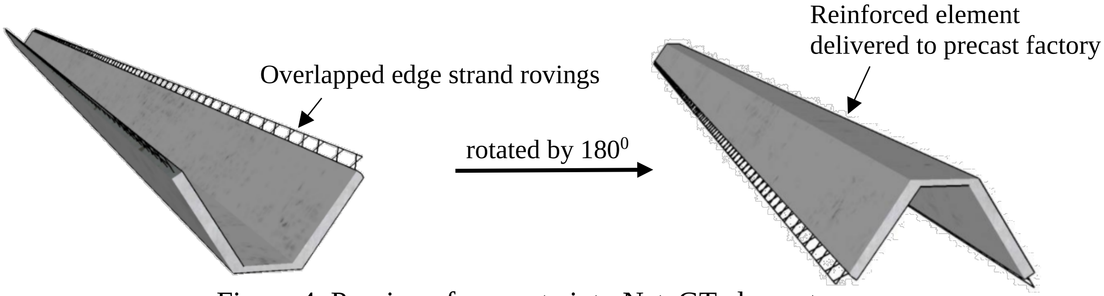
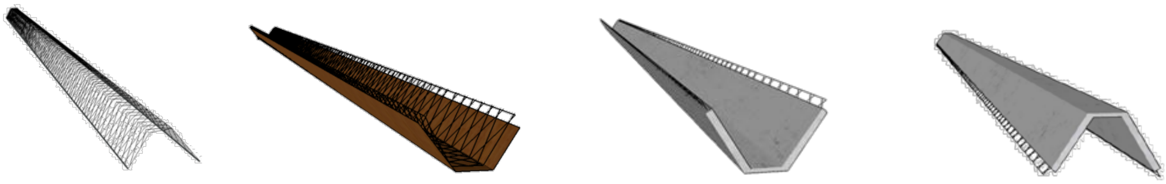


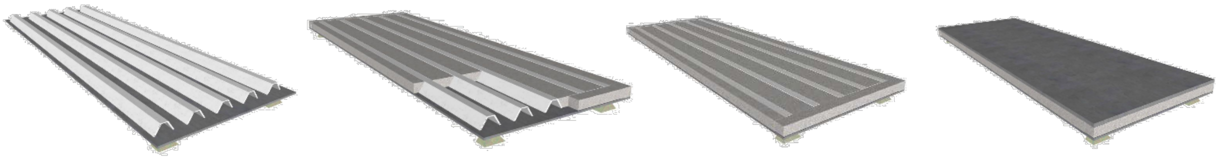
Figure 4: Pouring of concrete into NetzGT element

Embedment of NetzGT element

The next step is to embed the NetzGT element into a fresh concrete plate; see Figure 5 (step 5). During this step, special care should be taken to ensure that the NetzGT element is properly embedded and securely attached to the surrounding concrete and to ensure a monolithic bond. Then concrete will be poured in between the single NetzGT as shown in Figure 5 (steps 6 and 7). More contact points are established between the NetzGT and the surrounding concrete by roughening or chopping the surface of the NetzGT element, which enhances the frictional interaction between the two materials. This increased friction improves the adhesion between NetzGT and the concrete, ultimately leading to a robust bond that contributes to the structural integrity and overall performance of the construction. The pouring of concrete in between the NetzGT element can vary in height depending on the specific dimension model being used. The additional poured top plate is possible, if the core concrete should be a lightweight concrete. There are four distinct models proposed and explained in detail in the following section.



(1) NetzGT element (2) Formwork for NetzGT (3) Concreting in NetzGT (4) Rotating by 180 degrees



(5) Placing concreted NetzGT in fresh concrete (6) Concreting in between NetzGT (7) Concreting in between NetzGT (8) Top plate

Figure 5: Step-by-step guide for the construction of a HC slab system with NetzGT reinforcement

VARIOUS MODELS OF HOLLOW CORE SLAB SYSTEM

Designing a robust, lightweight, thin, and environmentally friendly carbon reinforced HC slab system is a challenging task, but it is an essential requirement for modern civil engineering projects. To achieve this goal, different models have been proposed (compression zone is adjusted to achieve different load-bearing capacities) and a comparative study can be conducted to determine, which model is the most suitable. The study could involve testing the structural performance of each model under various load conditions, analyzing the self-weight, and estimating the cost of each construction model. It may also be useful to consider other factors such as the ease of construction. The comparative study should provide a clear picture of the strengths and weaknesses of each model, allowing to make an informed decision about which model to choose. In any case, it's important to ensure that the chosen model meets the required specifications and standards, safety issues and shows a high durability.

Model 1:

The initial two stages of the construction process in the HC slab system, which include the covered NetzGT element and the high strength base concrete plate with additional bending reinforcement, remain consistent across all proposed models; see Figure 6. The subsequent step, which involves pouring concrete between the NetzGT elements, may be carried out either on the construction site or in a precast plant, depending on the specific model. This step varies among the models and are intended to achieve specific performance objectives such as structural performance and weight reduction.

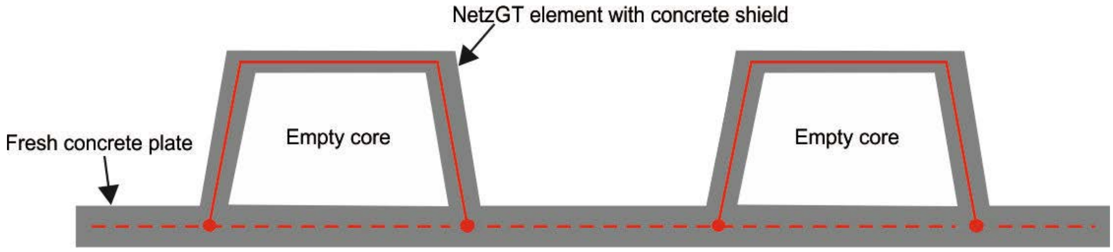


Figure 6: Cross-section view of a covered NetzGT element embedded in a fresh concrete plate

In Model 1, normal strength concrete is poured up to the height of the NetzGT element, as depicted in Figure 7. The NetzGT reinforcement is anchored at the compression zone through inclined concrete to ensure the required shear anchorage reinforcement. The main compression zone is the top zone of the NetzGT. The bond between the NetzGT element and the normal strength concrete is achieved through friction. Which means that the surface of the NetzGT element is likely to be designed in a way that provides roughness or texture to enhance the grip with the surrounding concrete.

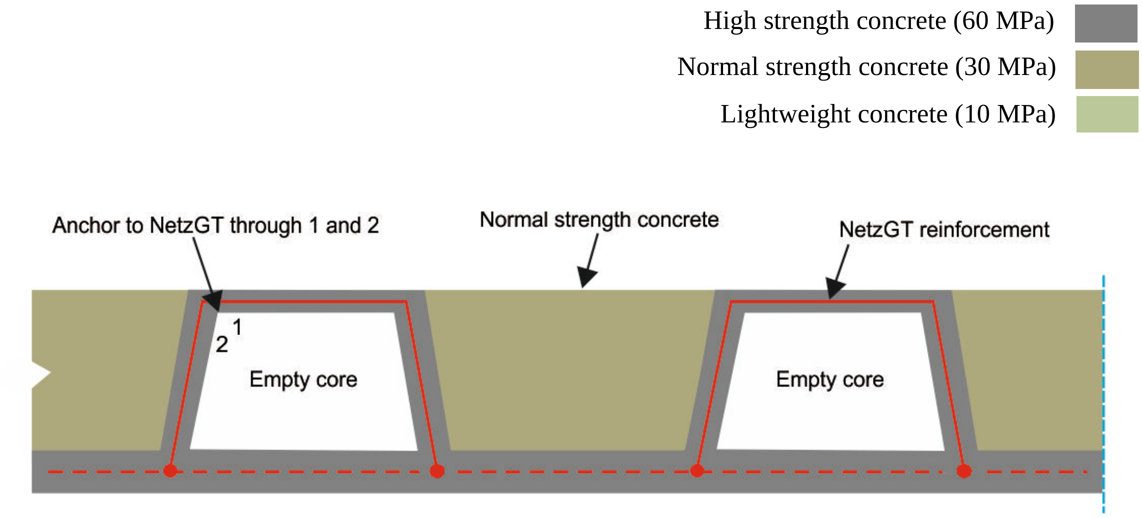


Figure 7: Cross-section view of Model 1

Model 2:

Both Model 1 and Model 2 will be produced partially in a factory as precast elements and partially on the construction site. However, in Model 2, the concrete is poured a bit higher than the height of NetzGT, providing more compression depth and additionally an extra textile grid reinforcement is provided at the compression zone, as shown in Figure 8. The aim of providing a top textile reinforcement layer is to increase its resistance to shrinkage and temperature stresses, allowing for an increase in the long-term load-carrying capacity of the slab system. In summary, Model 2 is expected to offer increased load-carrying capacity compared to Model 1 due to the added reinforcement and increased depth of the compression zone.

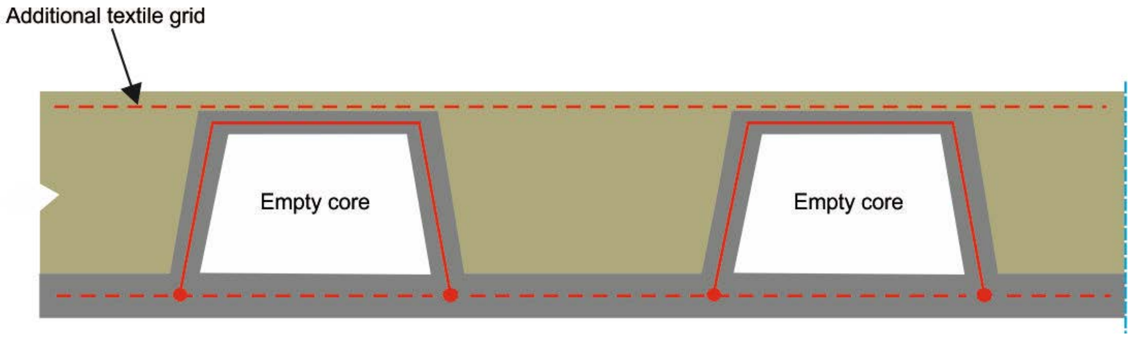


Figure 8: Cross-section view of Model 2

Model 3:
In Model 3, a high-strength compression plate is added on top of the NetzGT, which is made of the same strength concrete as the base plate. The use of high-strength concrete at the compression zone allows for the utilization of lightweight concrete or gypsum blocks between the NetzGT, leading to further reduction in the weight of the HC slab system; see Figure 9. This design modification results in a more lightweight and cost-effective structure. The lightweight concrete or the gypsum blocks has lower density compared to normal weight concrete, making it an ideal material for reducing the weight of the slab system without compromising its strength. This model will be produced fully in factory as a precast element.

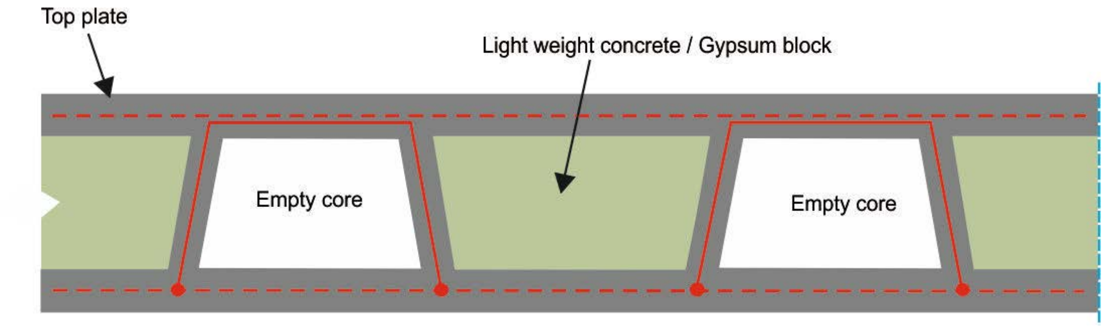


Figure 9: Cross-section view of Model 3

Model 4:
Model 4 is similar to Model 3 by utilizing the same high strength concrete at the compression zone, but it takes weight reduction one step further by removing the concrete between the NetzGT. This design reduces the weight of the slab system even further and can be an ideal choice for applications where weight reduction is a top priority. However, it's important to note that removing the concrete between the NetzGT may impact the structural performance of the slab system, and careful analysis and evaluation should be conducted to ensure the safety and reliability of the structure. It is also very important to consider that investigating the fire resistance of carbon reinforced slab systems is crucial before implementing them in any structural application. To understand how these materials respond at high temperatures and to make sure that the structural integrity is preserved in the event of a fire occurrence, fire performance testing and analysis are crucial to be carried out.

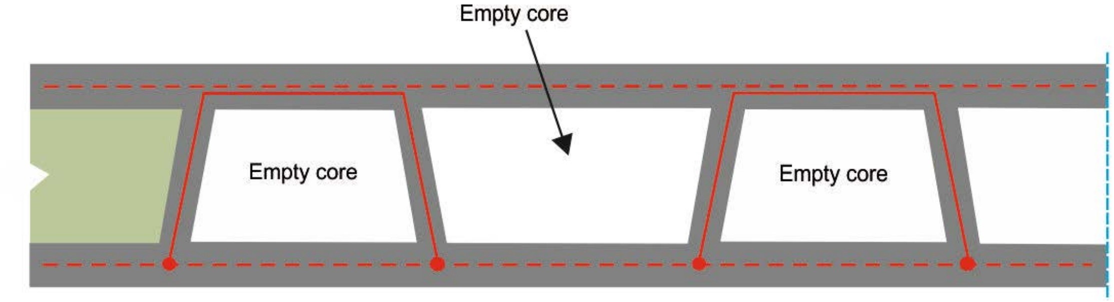


Figure 10: Cross-section view of Model 4

SUMMARY AND CONCLUSIONS:

The article discusses the potential benefits of using CRC for intelligent construction techniques, such as constructing Hollow-Core slab systems using carbon Netzgitterträger reinforcement instead of conventional steel lattice girder. Additionally, it also proposes the construction of a Hollow-Core ceiling element with a trapezoidal core form consisting of two inclined, non-parallel webs and two flanges located at the top and bottom. The use of this technique can significantly reduce the amount of material required, resulting in cost savings and a lower carbon footprint. This article focuses on the detailed instructions for constructing different models and executing the necessary steps for experimental investigations. It also highlights the advantages of using carbon textile lattice girder instead of steel lattice girder, including its high strength-to-weight ratio, resistance to corrosion, and lower carbon footprint. The use of three-dimensional NetzGT element could expand the use of carbon-reinforced HC concrete slab in construction, allowing for greater flexibility in the design of reinforced structures, and more innovative and sustainable construction practices. In the next series of publication regarding HC slab reinforced with NetzGT reinforcement, shear and bending tests is to be conducted on a NetzGT reinforced element and later on the complete slab system to understand its structural behavior. The data will be analyzed to determine the slab structural behavior, and numerical simulations will be used to compare with experimental results.

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ACKNOWLEDMENT:

The IGF research project 21556 BR of the Forschungsvereinigung Forschungskuratorium Textil e. V. is funded through the AiF within the program for supporting the „Industriellen Gemeinschaftsforschung (IGF)“ from funds of the Federal Ministry for Economic Affairs and Climate Action on the basis of a decision by the German Bundestag.

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.