HYBRID 3D WOVEN STRUCTURES FOR CONCRETE REINFORCEMENT UNDER IMPACT LOADING PART 1: DEVELOPMENT OF A BI-AXIAL CORE DESIGN

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ABSTRACT

Steel reinforced concrete (RC) is extensively used in the construction industry due to its high strength, durability, and versatility. Nonetheless, its resilience under dynamic loads, such as impact, remains particularly low. The research training group DFG GRK 2250 aims to significantly improve the impact energy absorption of existing infrastructures by applying thin layers of an innovative strengthening material composed of a strain hardening cementitious composite and a novel textile reinforcement. This paper investigated methods for manufacturing 3D hybrid woven fabrics with a core incorporating spatial elements in both the weft and warp directions, based on a bi-axial core design. The challenges associated with shaping spatial elements before and during the weaving process were discussed, with the latter proving to be the optimal choice when combined with carbon fiber towpregs. After developing the structural design, selecting the materials for each element, and establishing the fabric binding pattern, a demonstrator was successfully produced using a modified rapier weaving machine.

KEYWORDS

Woven cellular metals; 3D concrete reinforcement; Hybrid structure; Weaving technology.

INTRODUCTION

The most used building material in the world is concrete, a composite made of a cementitious matrix and solid filler aggregates. Even though concrete is cost-effective, versatile and has a high compressive strength, it is characterized by its brittle failure mode and low tensile strength. Consequently, it is conventionally reinforced with steel rebars (reinforced concrete - RC), mitigating crack initiation and propagation, and noticeable improving the overall mechanical properties under static loads [1]. Nonetheless, under dynamic loads, such as impact, it exhibits low resistance due to its poor energy absorption capabilities. Thus, other methods like continuous fiber reinforcement (textile reinforced concrete - TRC) or short fiber reinforcement (fiber reinforced concrete - FRC) are taken into consideration [2].

TRC replaces the conventional steel rebar or steel cages with either two- or three-dimensional grid-like layers of textile materials (continuous fiber reinforcement), such as carbon, alkali resistant glass or basalt [3] [4]. These have a substantially lower density and a higher tensile strength compared to steel. Furthermore, because they show excellent corrosion resistance, the need for a thick concrete cover, which is usually required for RC, is drastically minimized [5]. Thus, thinner structures with improved mechanical properties can be manufactured, which in turn positively affect the economy and the ecology (CO_2 emissions) [4], [6–8]. Despite these advantages, TRC faces some problems that are innate to the fiber materials themselves. Their high strength is usually coupled with low strain values (1 - 5%), meaning that little to no plastic deformation occur prior to failure. Consequently, even though these fibers have a great strength-to-weight ratio and can withstand noticeable higher tensile loads, their brittleness typically result in low energy absorption. Another crucial aspect for the performance of TRC is the bond between the textile material and the surrounding concrete, which ensures proper load transfer. It can be improved either chemically, with the use of more suitable sizing, or mechanically, through altering the surface topology of the reinforcement material (mechanical interlocking) [9], [10]. FRC, on the other hand, contains uniformly distributed, randomly orientated short fibers, that make up between 2% and 6 % of the total volume of the composite. They can be classified into micro fibers (5 - 20 mm in length and 0.02 - 0.20 mm in diameter),

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and macro fibers (30 – 65 mm in length and 0.4 – 1.2 mm in diameter). Commonly used fibers include those made from steel, glass and synthetic materials, like carbon, aramid, polypropylene, nylon, polyethylene, and polyvinyl alcohol [1] [11]. The benefits of FRC become apparent during the pre-cracking stage (stress transfer from the matrix to the fibers before macrocracks initiate), and during the post cracking phase (fiber bridging effect). The latter mechanism ensures effective stress transfer across pre-existing cracks, thereby controlling crack propagation rates and extending the structural integrity. Hence, because of its improved penetration, scabbing and fragmentation resistance, FRC is suitable for protective structures that have to withstand explosions and shock loads [12–15]. Therefore, it holds scientific value and interest to investigate the performance of a mineral-based composite that combines TRC and FRC for structural protection against impact events.

The Research Training Group GRK 2250 primarily focuses on the development of a composite material that acts as a thin protective layer on existing concrete structures. The constituents of this novel composite can be divided into two categories: the cementitious matrix and the textile reinforcement. The matrix is made of a special type of FRC, which is called strain-hardening cement-based composite (SHCC). It contains discrete synthetic microfibers (e.g. polypropylene) with a volume fraction up to 2%, which results in a high strain capacity, and a pronounced microcracking controlling behavior [16]. Due to the low strain-capacity of conventional two-dimensional grid fabric reinforcement (2DFT), e.g. carbon or glass [17] [18], a three-dimensional hybrid woven fabric (3DWT-M) was proposed and later developed at the Institute of Textile Machinery and High Performance Material Technology (ITM) at the TU Dresden (TUD). This novel reinforcement was manufactured on a modified rapier weaving machine Dornier HTVS4, and is based on the technology of three dimensional cellular woven structures for lightweight applications (metallic fiber based), also developed at the ITM [19] [20]. 3DWT-M synergizes the good mechanical properties of metallic fibers (e.g., tensile strength, ductility, workability) with the stiffness and high tensile strength of carbon fibers. It is characterized by a pyramidal metallic cellular core, that is achieved through a cleverly designed weaving pattern that utilizes preformed steel wires in weft direction (mono axial spatial reinforcement), and an in-plane reinforcement with carbon fiber tows at the upper and lower face of the structure. Moreover, high-speed tensile tests and impact tests show that 3DWT-M, in fact, perform better than 2DFT [21]. To gain a deeper insight into the behavior of 3DWT-M, a new in-situ sensor network was developed and integrated into the structure [22–24]. In addition, to improve the bond between the carbon fiber elements and cementitious matrix, profiled carbon fiber tows were later introduced [9] [10]. Nonetheless, due to the challenging scenario characterized by high impact energy, a thin protective layer, and complex interactions between different materials, it is essential to fully optimize the technologies and material-structural properties, particularly for the 3DWT-M. This paper therefore investigates the feasibility of enhancing the core structure from a mono-axial into a bi-axial spatial design (3DWT-B), and the results are illustrated using a demonstrator.

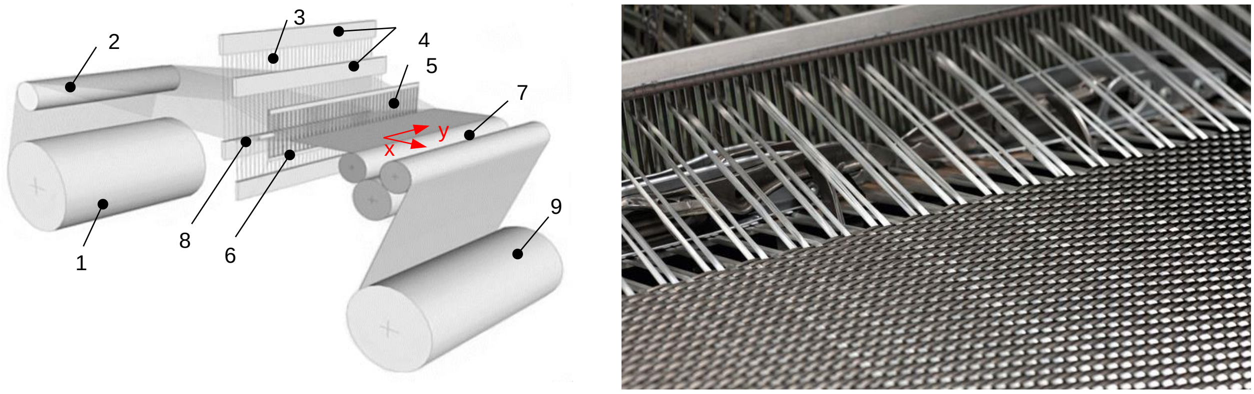
THEORETICAL BACKGROUND

Fundamentals of the weaving technology

A schematic with the basic set-up of a conventional dobby weaving machine is displayed in Fig. 1. A 2D woven fabric typically has two yarn systems: the warp yarn system, which runs in the direction of production (x), and the weft yarn system, which is perpendicular to it (y). Yarns in warp direction are stored either on a warp beam (1) or come directly from a bobbin creel. They are then individually guided by the back rail (redirection and force compensation component) into the healds (3), that are attached to the heald frames (4), and through the reed (5). The latter is integrated into the sley (6), sorts the warp yarns along the width of the fabric, and defines the warp density of the finished product. A dobby weaving machine can have up to 28 healds that individually move the attached warp yarn set either up (position I) or down (position 0), creating a space (weaving shed) to insert the weft yarns (b). There are different weft insertion systems available, but one of the most commonly used, delivering fast weaving speeds, high process stability, flexibility and efficiency, is the rapier system (single-, double-, or multi-rapier). During the beat up, the weft yarn is pushed forward by the reed (5), while the heald frames change position (shed change), and secure the yarn in the fabric edge. The take-off system (7) pulls the fabric at a preset speed and can be adjusted to produce different weft densities, which ultimately depend on the weaving pattern. Finally, the woven product is rolled on a storage beam (9). For 3D woven fabrics a linear take-off system is used instead (see Fig. 2(b)).

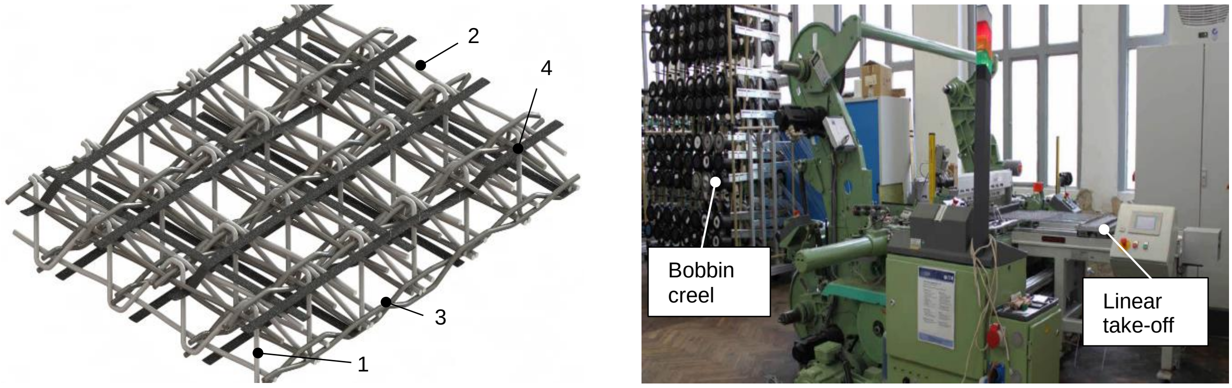
Reference structure

The reference structure (3DWT-M) described at the introduction is displayed in Fig. 2(a), and can be divided into three distinct sections: the core, and the upper and the lower face. The former is a woven cellular metal core, which is characterized by a pyramidal unit cell. This is achieved by inserting preformed steel wires (spatial element) in weft direction (1), that rest at an angle after the beat-up of the reed. The core is fixed due to the support of straight steel wires in weft (2) and binding wires in the warp (3), which form the upper and lower faces of



(a) (b)

Figure 1. (a) Basic set-up of a weaving machine. (1) Warp beam, (2) back rail, (3) heald eye, (4) heald, (5) reed, (6) sley, (7) fabric take-off, (8) weft insertion system, (9) fabric storage, (x) warp direction or production direction, (y) weft direction [25]. (b) Weft yarn insertion and delivery on a double sided single-rapier system [26].



(a) (b)

Figure 2. (a) CAD-Model of the reference structure. (1) Preformed steel wire, (2) weft wires, (3) binding wires in warp, (4) carbon fiber tow. (b) The modified rapier weaving machine Dornier HTVS4.

3DWT-M. Additionally, carbon fiber tows (4) (Teijin Tenax - E HTS40 F13 12K 800 tex) are woven into both faces, in weft and in warp direction, forming a grid-like pattern (12 mm x 15 mm). These were impregnated with a polyacrylate based sizing. Because of the subsequent application in concrete (thin layer), corrosion resistance is important; therefore, all the metallic elements are made of stainless steel wire (1.4301) with a diameter of 0.8 mm. For the core and the elements in the upper face, the wires have a higher tensile strength (approximately 1200 MPa). Conversely, elements in the lower face have a lower tensile strength, around 600-800 MPa, but a much higher elongation at fracture (about 35% higher). Thus, a structure with a gradient in mechanical properties is achieved, and as suggested by researches from previous studies, is ideal for energy absorption [27]. Moreover, it is imperative to highlight the open-cell architecture of 3DWT-M, which is necessary for the matrix (SHCC) to flow and properly cover all the elements of the reinforcement fabric. For this purpose, the fiber content of the matrix was also reduced from 2% to 1% [21]. The bond between the fibers and the concrete was then later enhanced by replacing the flat carbon fiber tows with profiled tows (Teijin Tenax-E STS 40 F13 48K 3200 tex carbon). These were manufactured in a profiling laboratory unit developed and built at the ITM [28]. Further, they have a polyacrylate-based impregnation agent (TECOSIT CC 1000), a polymeric dispersion with a solid content of approximately 50%, specially developed at CHT Germany GmbH (Tübingen, Germany) for an optimal compatibility with concrete. Pull out tests done in previous research showed a substantial increment in concrete bond strength compared non-profiled tows. The same investigation also shows, that the profiling of the tows results only in slight reduction in performance in quasi static tensile testing [9] [10].

MATERIALS AND MEHTODS

Requirements and restrictions

The requirements for the structure (see Fig. 4) are as follows:

- Spatial elements are to be implemented in weft and in warp direction (bi-axial core design).

- Upper and lower faces should absorb in-plane tensile and compressive forces, while the core should absorb compressive and shear forces.
- An Open cell structure is necessary to properly infiltrate 3DWT-B with the matrix (SHCC).
- A Periodic structure with same cell size, shape and regular distribution, because the striking location in a real scenario is unknown. Thus, the same mechanical properties along the whole fabric are needed.
- A Self-sustaining structure without the matrix to facilitate transport and assembly at the construction site.
- Corrosion resistant materials due to the later implementation in concrete (alkaline environment).
- A variety of fibers (metallic and synthetic) are needed to achieve a high strength and stiffness while possessing some ductility (gradient architecture and energy absorption).
- A reproducible and stable manufacturing process is desired.

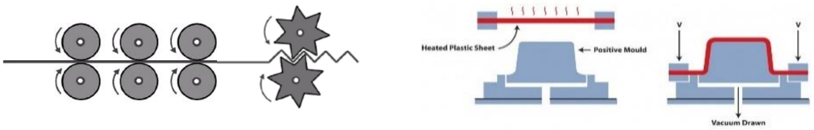
After establishing the overall requirements, it is necessary to evaluate the cases for implementing spatial elements in warp direction (see Fig. 3). The first case (I) involves forming these elements prior to the weaving process separately, while the second case (II) involves forming them during the weaving process. Further, a distinction regarding the processed materials has to be made. While fiber-based materials can also be metallic, the term “fiber-based” used here refers specifically to synthetic fibers made either from natural or synthetic polymers [25]. The term “metallic” refers to monofilament metallic fibers with a diameter ranging between 0.02 mm up to 6.00 mm. The geometry of the cross section can also be other than round, e.g., rectangular. Similar to the preformed elements used in [21], metallic elements in case (I) can be shaped to the desired geometry through cold forming [29]. On the other hand, fiber-based materials, such as carbon fiber with a thermoplastic matrix, can be formed through thermoforming [30]. For case (II), three methods were taking into consideration, which involve using a pre-impregnated yarn and fully curing it after the fabric is woven: foulard, prepreg and powder coating. The foulard technique involves drawing a dry yarn through an impregnation bath that contains a set amount of rollers, which spread the yarn and improve the process quality [31]. The term “prepreg” describes a composite that consists, in this case, of a dry yarn that is pre-impregnated with a polymer matrix, and is then partially cured. Because heat accelerates the polymerization process, prepregs usually have to be stored at cool temperatures. In this way, the chemical reaction is drastically slowed down, and the prepreg can be stored for months or years before being used [32] [33]. The third method is a powder coating technology. In a continuous process, yarns are guided, spread, and coated with a powdered matrix, usually thermoset (epoxy), and then heated for the impregnation. Similar to the prepregs, the matrix is not fully cured, but due to the high initial glass transition temperature of epoxy powder, it does not have to be stored at cool temperatures [34–37].

Limitations for case (I):

- A feeding and guiding system into the weaving machine has to be designed to avoid undesired rolling, yawing and pitching of the spacer elements during the weaving process, specially between the machine components 1 and 5 (see Fig. 1).
- Necessary methods or technological modifications to the machine to regulate warp tension. Excessive warp tension can lead to deformation (metallic) or fracture (fiber-based).

Forming of spatial elements prior to the weaving process

metallic fiber-based



(a) cold forming (b) thermoforming

Forming of spatial elements during the weaving process

fiber-based

(c) foulard (d) prepreg (e) powder coating

Figure 3. Forming of the spacer elements in warp direction. Forming prior to the weaving process: (a) cold forming [20], (b) thermoforming. Forming during the weaving process: (c) foulard [38], (d) prepreg [39], (e) powder coating [34].

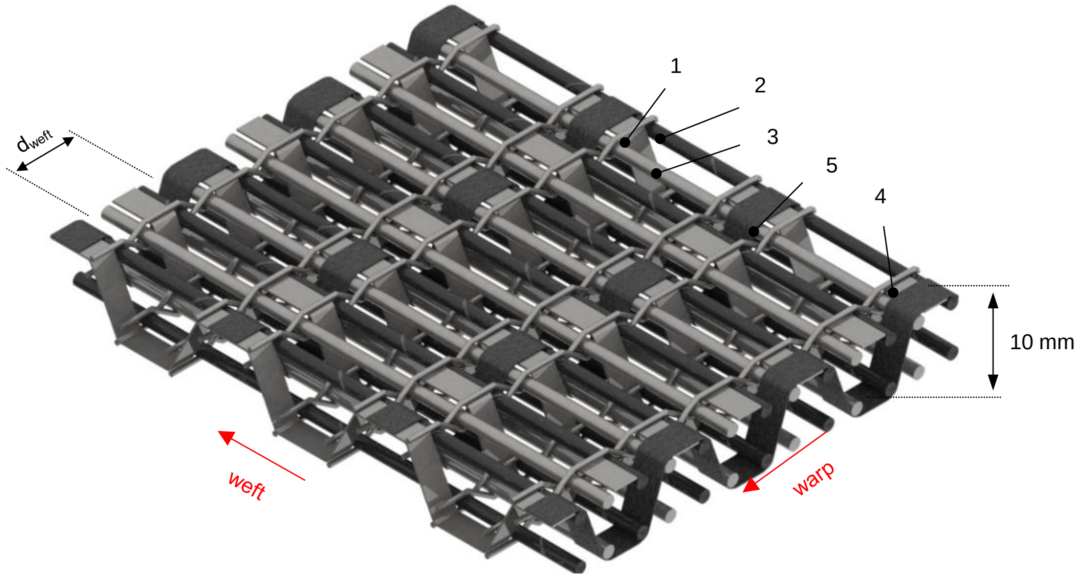


Figure 4. CAD-model of the novel reinforcement concept structure with spacer elements in weft and in warp direction. (1) Steel spatial element in weft, (2) carbon fiber profiled tow, (3) steel rod, (4) carbon fiber tow as spacer element in warp, (5) binding steel wire.

- Reduction of the shed geometry due to the height of the elements (instead of flat yarn) may lead to conflicts with the path of the rapier.

Limitations for case (II):

- Foulard: The impregnation bath process and design of the bath has to be carefully conceptualized. It has to be allocated between the bobbin creel and back rail, and should not interfere with the yarns and steel wires being delivered from the bobbin creel. Further, resin spilling on the machine may be a problem for the moving components of the weaving machine.
- Prepreg: Due to its pre-impregnated form, the stiffness might hinder the formability, and the tack might increase the friction with several machine components (back rail, healds, reed). Further, the shelf life in and out storage temperature is relevant for the mechanical performance of the composite.
- Powder coating: A powder deposit unit has to be developed first, as there are no known industrial suppliers for a finished powder impregnated yarn.

Technology, structural development and material selection

Using the Analytical Hierarchy Process (AHP) and the Weighted Sum Model (WSM), Case (II) - “Forming of spatial elements during the weaving process” and the method “prepreg” emerged as the optimal choice for enhancing the core of the 3D textile structure with a spatial reinforcement in warp direction. Relevant criterions were: tooling costs, material costs, manufacturing complexity, assembly effort, development costs, the number of suppliers. A structural model was then designed in SolidWorks based on the requirements outlined in Section 3.1, and is displayed in Fig. 4. It consists of three elements in weft direction (1-3) and two elements in warp direction (4-5). (1) and (4) build up the core, while (2), (3), and (5) form the upper and lower faces. (2) and (3) alternate on the sides of (1) and are held together with (5). (4) is woven along the weft elements, alternating between the upper and lower faces. Similar to a sandwich-structured composite, the upper and lower faces (2, 3, 5) are designed to take in-plane and bending forces, and the core (1, 4) shear and compressive forces. Furthermore, the open cell structure facilitates pouring and covering the entire reinforcement with concrete. An evaluation of the mechanical performance with and without the matrix (SHCC) is not the scope of this work, and is intended for later research.

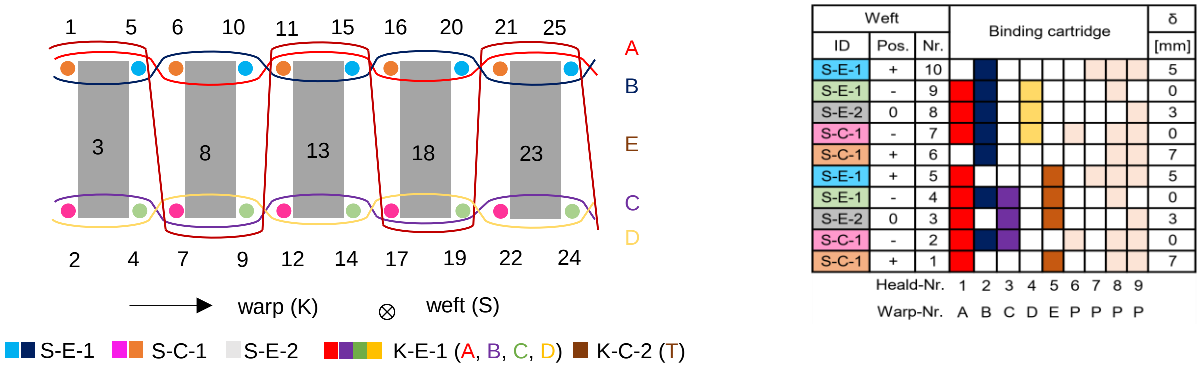
The steel spatial element (1) is made of a flat stainless-steel wire (1.4016) with a cross section of 4.0 mm x 0.3 mm and a tensile strength of 984 MPa (Studer Biennaform). The 3D geometry was achieved through cold forming [20], and has a height of 10 mm. The profiled carbon fiber tows (2) were manufactured according to Section 2.2, and have a diameter of 2.2 mm. The rods are made from stainless steel (1.4301), possess a diameter of 2.0 mm and have a tensile strength of 928 MPa (Messinghaus Rehlken GmbH). A carbon fiber prepreg tow (towpreg) is used as a spatial element in warp (4), and has a width of 5.0 ± 0.5 mm. The dry yarn is a Toray T700-SC-24K-1650 tex, and the tensile strength of the cured towpreg is about 2880 MPa with an expected fiber volume fraction of 65% (Kümpers GmbH). Further, it has shelf life of 30 days at room temperature, and has a cure profile of 0.5 h at 120 °C, followed by 4.0 h at 140 °C. The binding steel wires for the top and bottom faces are the same as for the reference structure (Section 2.2)

Woven fabric development

Based on the modeled concept and the selected material, a weave pattern was developed and later converted into a binding cartridge, which must be provided to the weaving machine in a coordinated file. For this purpose, the cross section of the structure in warp must be displayed (see Fig. 5), and all included elements should be categorized individually: warp (K) or weft (S) direction, metallic (E) or carbon fiber (C) type, and planar (1) or spatial (2) form. Hence, for the weft direction: S-E-1, S-C-1, S-E-2, and for the warp direction: K-E-1 and K-C-2. Furthermore, the sequence of the smallest repeating unit in the weft (1-9) is identified and color-coded, and for each step in the sequence, the pull-off length (δ_0) of the fabric is set. The distance between each repeating unit in weft (d_{weft}) was set to 11 mm for one section and 16 mm for another section of the fabric (see Fig. 5 and Fig. 7). The warp density $\rho_{f,warp}$ was inferred directly from the CAD model (see Fig. 6), from which a tailored reed (STEVEN Reeds GmbH) was manufactured. Each of the elements in warp are then assigned to a heald frame. This results in the weaving pattern shown on the right of Fig. 5. The wires were best suited for the heald frames at the front (1 to 4) because the farther the heald frames are from the weaving reed, the larger the stroke required to form a proper shed geometry. Consequently, the wires would experience excessive bending, which is undesirable. Furthermore, circular heald eyes were used for the wires and double flat heald eyes (TWINTec) for the towpreg. Additional towpregs (P) are woven into a plain weave pattern on the top and bottom surfaces to stabilize and secure the edges of the fabric. After calibrating the weaving machine (Dornier HTVS4), a fabric sample (500 mm x 200 mm) was manufactured. It was then removed and put in an oven at 120°C for 0.5h and at 140°C for 4h to consolidate the towpreg.

CONCLUSIONS

The aim of this paper was to develop a novel type of woven reinforcement structure (bi-axial core design), while taking into account the constraints of the weaving technology and the requirements for its application in concrete under impact stress. The manufactured reinforcement fabric (3DWT-B) is shown in Fig. 7 before (left) and after (right) curing the towpreg. It can be observed that the carbon fiber towpregs were successfully integrated into the structure during the weaving process, and alternating between the upper and lower faces resulted in the desired spatial reinforcement (3D) in the warp direction. Depending on the pull-off length δ_0, the weft density $\rho_{f,weft}$ and the angle formed by the interlacing towpreg (α), which are proportional to each other, can



Weft			Binding cartridge									δ
ID	Pos.	Nr.										[mm]
S-E-1	+	10		🟦					▨	▨	▨	5
S-E-1	-	9	🟥	🟦		🟨				▨		0
S-E-2	0	8	🟥	🟦		🟨					▨	3
S-C-1	-	7	🟥	🟦		🟨		▨		▨	▨	0
S-C-1	+	6		🟦						▨	▨	7
S-E-1	+	5	🟥				🟫		▨	▨	▨	5
S-E-1	-	4	🟥	🟦	🟪		🟫			▨		0
S-E-2	0	3	🟥		🟪		🟫				▨	3
S-C-1	-	2	🟥	🟦	🟪			▨		▨	▨	0
S-C-1	+	1	🟥				🟫			▨	▨	7
	Heald-Nr.		1	2	3	4	5	6	7	8	9	
	Warp-Nr.		A	B	C	D	E	P	P	P	P	

Figure 5. On the left a schematic representation of the woven structure: cross section in warp. S (weft), K (warp), E (steel), C (carbon fiber), I (1D), II (2D). On the right the resulting binding cartridge.

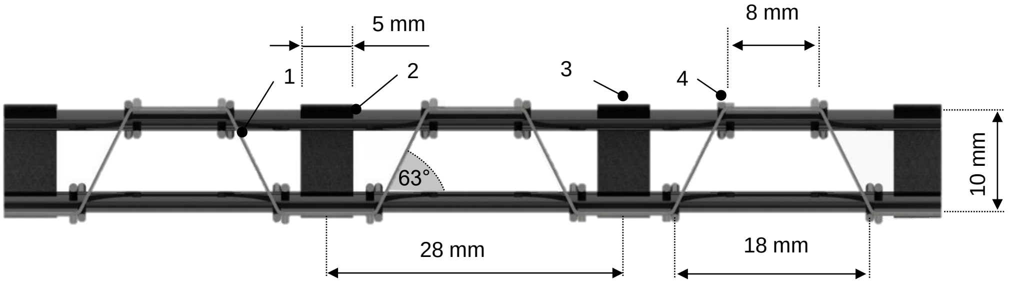


Figure 6. CAD model of the 3DWT-B concept: cross section in weft. (1) Steel spatial element in weft, (2) profiled carbon fiber tow, (3) carbon fiber towpreg as spacer element in warp, (4) binding steel wire.

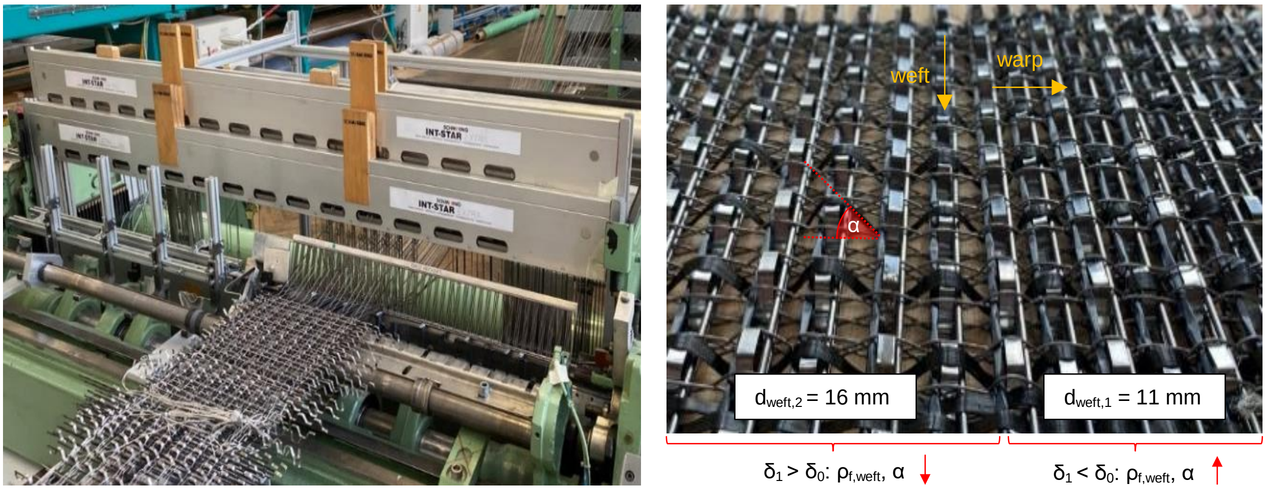


Figure 7. Manufacture of the novel reinforcement structure with the weaving machine Dornier HTVS4 on the left. Cured fabric on the right.

be increased ($\delta_1 > \delta_0$) or decreased ($\delta_1 < \delta_0$). The more acute α is, the less is the structural stability the towpreg provides across the thickness of the fabric. Additionally, the lower $\rho_{f,weft}$ may result in a reduced bending resistance of 3DWT-B in warp direction but increased flowability of the SHCC matrix into the fabric, due to the bigger gaps. The situation is inverse for a greater angle α and a higher $\rho_{f,weft}$. Thus, an optimal balance between the mechanical properties of the fabric and the flowability of the matrix into the structure has to be found. Poor casting of the SHCC into the reinforcement may result in air pockets and reduced mechanical performance of the mineral-based composite. It can also be observed that the geometry formed by the towpreg more closely resembles a sinusoidal shape rather than the trapezoidal geometry seen in the conceptualized CAD model (see Fig. 4). Moreover, the towpreg remained adhered to the structure after curing, but with repeated flexing, it started to detach locally until it could freely move sideways. This means that higher warp tension and additional elements in weft direction that press against the towpreg's surface may be beneficial for achieving the desired geometry. In that regard, if the warp tension is too high, friction also increases and may result in an undesired spreading of the yarn or even damage to it. Despite that, this work showed that it is a feasible to use carbon fiber towpregs with the forementioned weaving machine to enhance the core of the reinforcement fabric in warp direction. For future work it is necessary to conduct a study regarding the flowability of concrete into the reinforcement and the performance of the novel mineral-based composite.

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