

Variation Braiding: from 4x4 to 6x6 – new application potential through more complex 3D braiding structures

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ABSTRACT

In this article, new possibilities about the patterning on a variational braider with 6x6 horn gears are presented. Various types of braided structures, such as bifurcation braids, knotless nets or textile chain elements were developed using braiding pattern techniques and were manufactured on braiding machines with a wide range of materials (synthetic fibers, carbon fibers, glass fibers, ceramic fibers, natural fibers). Additionally, by using the new 6x6 variation braider, the existing patterns and products of the 4x4 braiding machine are being optimized and expanded.

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1 Introduction

Braiding technology offers large technical possibilities beyond the production of strands, cords or ropes [1-3]. The trend is towards even lighter, more stable constructions with additional properties. Meeting these requirements constantly calls for new machines, new ways of thinking and new solutions. With the variation braiders from Herzog GmbH (Oldenburg, Germany), the Institute for Materials Science (ifm) at Hof University of Applied Sciences has the possibility to develop and refine innovative, lightweight and multifunctional braided structures for use in the fields of medicine [1-3], aerospace [4], agriculture [5,6], and others. In contrast to conventional braiding machines utilized for laces and ropes, these machines represent a complete departure in design and function. They are not equipped with a round braiding bed like a traditional machine, but are based on a square matrix which has programmable cross units between its horn gears, that enable the production of bifurcated braids (Fig. 1). The variation braiding technology thus allows the realization of various special forms of braids for technical textiles, such as nets, chains or blood vessel replacement structures.

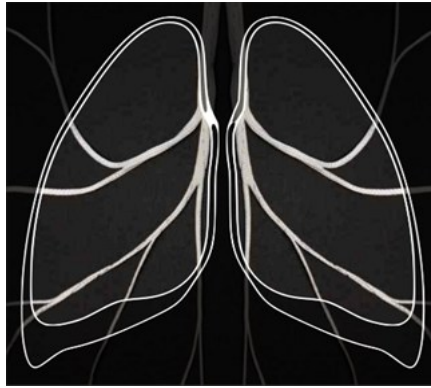


Fig.1 Multi-bifurcated braiding: Production on a VF 1/(4-72)-140 from Herzog GmbH.

2 State of the art

The use of three-dimensional (3D) braided preforms is changing the design of composite materials. They offer superior delamination and impact resistance, making them ideal for aerospace and medical applications [7,8]. A key driver of this progress is the development of variation braiding technology. It overcomes the fixed geometry of traditional maypole braiding machines by dynamically reconfiguring carrier paths at specific manufacturing steps [9]. This capability, first systematically described by Kyosev in [9], marks a significant advancement in braiding technology. It allows the production of complex structures such as multilayered and branched (bifurcated) geometries that were not possible with conventional systems [9-11]. The August Herzog variation braider is the commercial version of this innovation. It uses a 4 x 4 horn gear matrix with 24 independently controlled switches to enable precise and flexible carrier movements [11]. Berger's invention of steerable switches in 1975 was a major breakthrough [12], it overcame a key limitation of early 3D braiding systems. Later advances, such as Bogdanovich's dual-carrier system in 2002 [10], allowed more carriers to be used simultaneously. Schreiber's hexagonal arrangement [13,14], with six carriers spaced at 60° angles, enabled tighter, more efficient packing inspired by natural structures, greatly expanding design options. Despite these improvements, the field still lacks strong theoretical foundations. Pattern books provide many designs for tubular and flat braids, but they do not offer complete solutions for avoiding collisions between carriers in complex patterns [15-18]. Because of this gap, planning now relies on CAD-assisted tools like CabRun or TexMind's Configurator [19-21]. These tools help to prevent carrier collisions during 90° rotations or when switches are repositioned [22]. New computational methods, such as an algorithm that identifies all collision-free switch positions in 4 x 4 setups, are improving braiding processes [23]. Digital twin technology is also being used to systematically optimize machine operation and enhance final product performance [24]. Together, these advances mark a shift from trial-and-error methods to data-driven, systematic design [25]. They help overcome the lack of theoretical foundations that has long limited the large-scale industrial use of 3D braiding [26].

The possibilities of the variation braiding technology in terms of pattern and application diversity reflect its great potential. Compared to classic braids, such as packing and tubular braids, it is now possible to produce spiral braids, lace-making techniques and knotless nets (Fig. 2) on a single machine. Variation braiding is widely used in the medical sector, e.g. for suture materials made from braided tubes and stents for branched vessels and bifurcated tubular structures. It also can be used in other fields of interest, e.g. as textile securing systems [27,28].



Fig. 2 Braiding options on the variation braiders – from left to right: packing braid, tubular braid, spiral braid, knotless net

3 Material and methods

A variation braider (VF) is based on square set of horn gears with cross units between each two horn gears, see Fig. 3. The cross units can change their position by pneumatic actuators so that the track get adjusted for keeping the carrier on one horn gear or passing it on to another. These cross units enable the machine to produce braids with changes in the pattern and cross-section, and to develop bifurcations. Specialized software is used to program the carrier movements and execute them as often as required. A change in the take-off speed causes variations in the braid density and shifts the braiding point to a new position. The carrier path, associated partial lengths, total lengths, take-off speeds and braiding point heights can be saved in the products file. This enables the braiding machine to systematically store configurations for multiple products and ensures consistent reproduction through programmable, repeatable processing sequences. A wide range of normal and 3-dimensional braids in all known fiber types can be produced. The technology was tested with different fibers such as Dyneema® [29], ceramic and carbon fibers [30] as well as metallic wire and nano yarns [1,2].

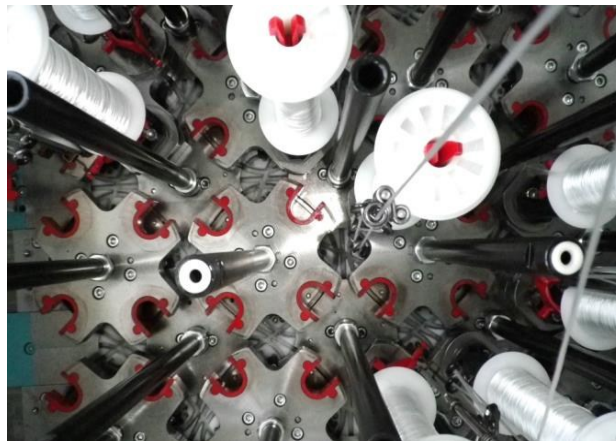


Fig. 3 View into the braider with the square matrix like arranged horn gears and associated cross units.

3.1 Variation braiding

In this study, the pattern from the widely used 4x4 matrix braiding machine (VF 1/(4-32)-140) [11] were analyzed and transferred or extended to a novel braider with a 6x6 horn gear set up (VF 1/(4-72)-140). Table 1 shows the corresponding machine parameters.

Table 1. Machine parameters of the VF 4x4 and 6x6.

Braiding machine	4 x 4	6 x 6
	VF 1/(4-32) – 140	VF 1/(4-72) – 140
carrier number	4 – 32	4 – 72
horn gear matrix	4 x 4	6 x 6
core-yarn feeders	9	25
mid-yarn feeders	16	36
horn gear speed (rpm)	50 – 200	50 – 200
pneumatic cross units	24	60

There is a wide variety of patterns that can be produced on the variation braider, which includes:

- tubular braids,
- packing/square braids,
- core-sheath braids,
- bifurcated braids: single to multiple up to net braids,
- spiral and flat spiral braids can also be produced through complex patterning enabled by varying the positions of the crossing units.

All braid types can be combined and merged with each other through specific cross unit settings and programming of the machine.

This knowledge has so far been implemented and demonstrated on a VF 1/(4-32)-140 machine [29,31-33]. The VF 1/(4-72)-140, which has recently become available, is presented here and the possible braid configurations developed to date are illustrated in the following sections.

3.2 Complex 3D braid structures without bifurcation

Tubular, square and core-sheath braids are among the braided structures that can be bifurcated but also create interesting structures, if they are not branched.

Changing the cross-unit positions within the braid during the braiding process does not necessarily result in bifurcation. If different types of patterns are combined with each other, effects such as a change in the product volume can be achieved. This results in a change of dimension of the braid's cross section. This makes it possible to create hollow structures without a core system, see Fig. 4. This type of structure can be created not only on the VF 1/(4-72)-140, but also on the VF 1/(4-32)-140. The difference lies in the intensity of the effect, which depends on the number of carriers used. A low number of carriers reduces the intensity of volume variations during pattern changes. An alternative method to modify the appearance and mechanical properties of the braid, without changing the carrier path, is to change the carrier arrangement on the braiding bed. There are generally three main types of arrangement to manipulate the braid:

- Full arrangement: Each horn gear with four slots is equipped with two carriers and two empty spaces. The sequence of carriers for each track alternates *1-full, 1-empty*
- Half arrangement: Half of the carriers are removed from the full arrangement in each track, so that each track contains a staggered sequence of *1-full, 3-empty*.
- Tandem arrangement: Here, the carriers always travel in pairs, one behind the other (*2-full, 2-empty*). In the case of horn gears with four slots, a tandem arrangement of up to *4-full, 4-empty* is possible. The greater the number of slots on a horn gear, the higher the possible number of carriers in a tandem arrangement.

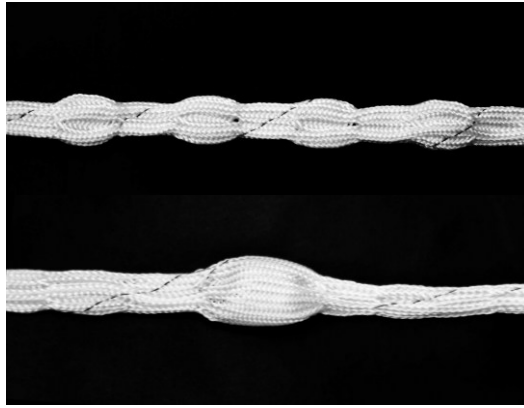


Fig. 4 Hollow structures with different diameter created by cross unit changes during braid production.

3.3 Square braids

In general, both the VF 1/(4-32)-140 and the VF 1/(4-72)-140 equipped with a full carrier arrangement can be shifted from tubes to core-sheath braids. Square braids cannot be produced using a full carrier arrangement. The carrier arrangement of a square braid is determined by the number of different paths intersected by a single carrier, as shown in Fig. 5. The first sequence of images shows how the green bobbin follows its designated green track while crossing the red track. If a carrier was positioned at the location marked with a star, a collision would occur during the new positioning of the carrier. The carrier has moved forward (as seen in the second image of sequence 1) and would now collide with a second carrier (second star) on the red track – if one was present.

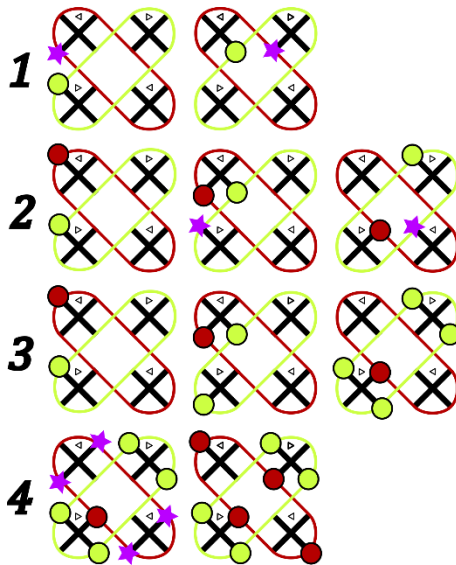


Fig. 5 Explanation for carrier placements in square braid configurations.

The second set of images illustrates the placement of an additional carrier on the red track, positioned in an area that was previously free of collisions. When the carrier moves to the next step, two new collision points occur as the red carrier crosses the green track. In the third set of images, an additional green carrier is placed starting from the collision position identified in the second image. A third green carrier is then added following the same pattern. Finally, the last green carrier is inserted to complete the track in a “one full, one empty” arrangement. With all green carriers now correctly positioned, the red carriers can be placed based on the resulting collision points, enabling a stable square braid pattern. The green track is crossed only by the red track, resulting in a consistent “one full, one empty” carrier arrangement along each track. This principle can be consistently applied and reproduced across different machine sizes – including the 3×3, 4×4, and 6×6 braider configuration. As seen in Fig. 6, the 3×3 setup follows a slightly

different filling pattern: 1-full, 2-empty, because each bobbin crosses two additional independent tracks, increasing the spacing between active carriers.

As a result, the VF 1/(4-32)-140 can produce square braids using a maximum of 16 carriers in a half arrangement (1-full, 3-empty). In contrast, with the VF 1/(4-72)-140 six tracks are crossing, meaning the next possible arrangement for a square braid is a 1- full, 5-empty pattern. Consequently, a full square braid can only be realized across the entire braiding bed with a maximum of 24 carriers in total – as illustrated in the comparison between Fig. 7 and Fig. 8. This represents just a quarter of the maximum possible number of carriers on the braiding bed.

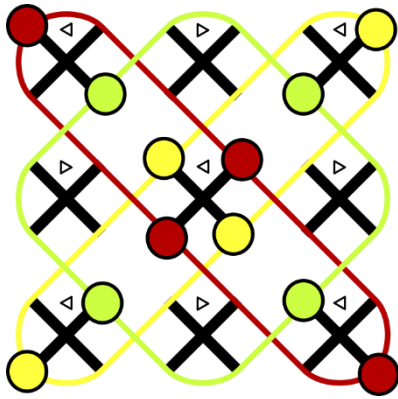


Fig. 6: Square braid in a 3x3 matrix with three tracks and 9 carriers

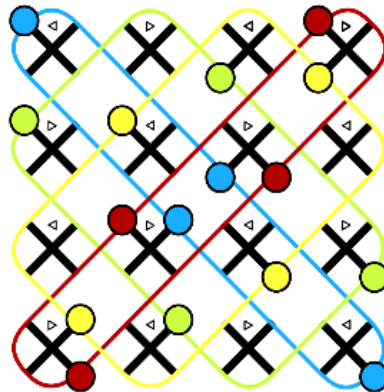


Fig. 7: Square braid in a 4x4 matrix with four tracks and 16 carriers

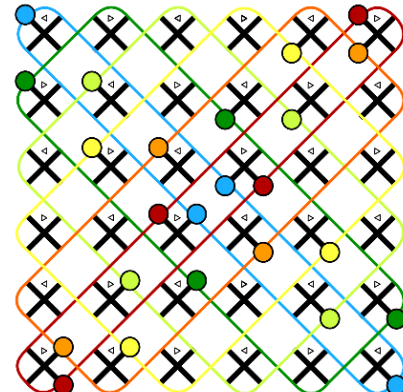


Fig. 8: Square braid in a 6x6 matrix with six tracks and 24 carriers

3.4 Complex 3D braid structures with bifurcation

Trough variation braiding technology the braiding of complex bifurcated branches is easily achievable. The bifurcation process depends on the selected braid pattern and the carrier positions. Some bifurcations require multiple steps. This means transitioning from one track pattern to another is not always possible within a single quarter turn and a simple setting of a few cross units. In general, the more complex the initial track pattern and the corresponding carrier position/arrangement, the more steps are required for the transition. Depending on the selected braiding pattern (braiding bed configuration), such transitions can result in a branched or unbranched braid structure.

The smallest possible braid requires three carriers. To create the interlacing, the carriers must follow a figure-eight path guided by two horn gears. Given this configuration, the VF 1/(4-32)-140 can produce up to eight individual braids. Consequently, the VF 1/(4-72)-140 allows for up to 18 individual braids. The smallest balanced braid requires at least four carriers and a horn gear matrix of two by two. In this case, up to four balanced symmetrical square or tubular braids can be produced with the VF 1/(4- 32)-140. With the VF 1/(4-72)-140, up to nine balanced symmetrical braids are possible. The product size is only limited by the maximum carrier number in pattern and the material length on the bobbin.

This knowledge enables the production of knotless braided nets. Three different types of knotless nets can be distinguished:

- Nets in which the nodes are connected to each other (rigid mesh structure): The individual mesh size can be varied, see Fig. 9, point 1 and 2.
- Nets in which the individual strands are not connected to each other but are twisted together in the braiding, thus creating a flexible mesh structure, see Fig. 9, point 3.
- Combination of both net types to create 3D-flexible net structures.

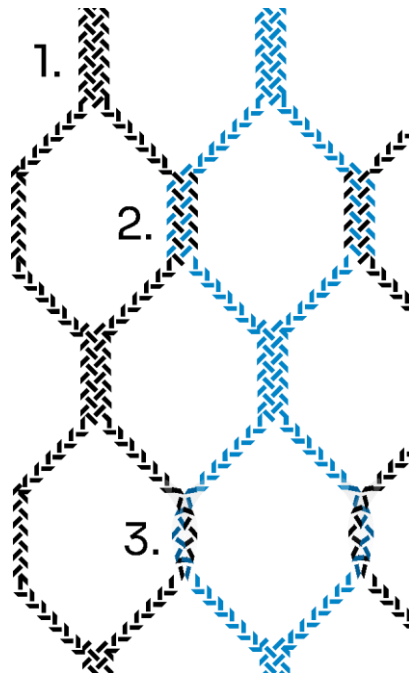


Fig. 9 Knotless net: 1. Strand with bifurcation, 2. Combined strand, 3. interlocking bifurcates strands.

All net types can be round or flat and can also be combined with various braiding patterns. Additionally, structures from lace-making can be integrated into the design. Furthermore, the number of net rows and mesh size can be varied during production. The mesh can therefore have different zones and diameters.

While knotless nets with connected knots are known from the field of sport or safety technology, the development of flexible net structures is a novelty in this field. Here, several individual strands, each equipped with simple double bifurcations, are intertwined with each other within the bifurcation in such a way that they twist around each other but are not firmly braided together, see Fig. 9, point 3. This type of twisting leads to the possibility that the area without bifurcation (Fig. 9, point 1) can be cut, see later in Fig. 10, step 2. A structure assembled in this way creates a chain-like appearance and behavior. This type of braid is protected by patent *WO2018153813A1 (Loop structure, method for producing a loop structure and element)*.

4 Application areas

In this section, braided structures produced by the above-mentioned methods will be described.

4.1 Textile chain

Textile chains can be a flexible, lightweight, tear-resistant, and durable alternative to metal chains, making them ideal for storing, securing, and handling cargo, such as lifting, towing, and tensioning. They are used throughout the transport industry, especially in aviation and shipping [34]

Fig. 10 shows the three production steps in the manufacture of a textile chain. The production of the chain was carried out fully automatically using pattern programming. In the first step (Fig. 10, step 1) a bifurcated braided branch is produced, which is connected to a second bifurcated braided branch by using an interlocking technology. The interlocking always takes place between the individual branches by connecting the first branch with the second branch in the previous and subsequent bifurcation. The resulting structure is cut (Fig. 10, step 2) at the strand area between the bifurcation leaving only the individual bifurcations interconnected as rings. This enables the individual links to move, achieving the desired chain-like behavior. Further finishing steps can be used if necessary to adapt the textile chain to the typical appearance of steel chains (Fig. 10, step 3).



Fig. 10 Three production steps in the manufacture of a textile chain from left to right: braiding, cut braiding, ready-made braiding (manufacture on VF 1/(4-32)-140).

4.2 Knotless nets and branch structures

Further design possibilities include intertwined branching structures (Fig. 11), enabling a chain mail-like net structure in which each individual link remains freely movable (Fig. 12). To maximize the number of individual branches, either three or more carriers can be assigned to each bifurcating element. However, if large individual branches are required, as in medical applications such as stents, multiple carriers are needed for a tubular braid. It should be noted that a simple division of a tubular braid can result in the formation of a hole at the transition area. In a medical product, this hole within the bifurcation is disruptive, as it can lead to tissue ingrowth and reduced medication in the lesion area. By arranging the carriers on the braiding bed using cross-unit positions, a hole closure is created which counteracts this problem. The following patent was derived from this manufacturing process (*WO2019158760A1 Braided structure, in particular stent, and method for braiding a braided structure* [35]).

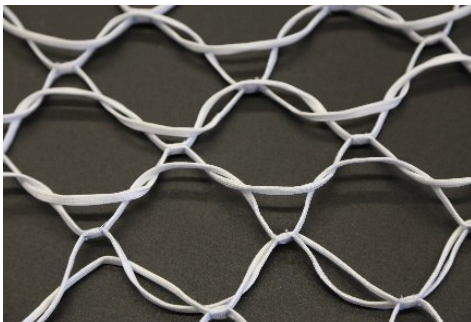


Fig. 11 Several braided strands interlock together to form a net.

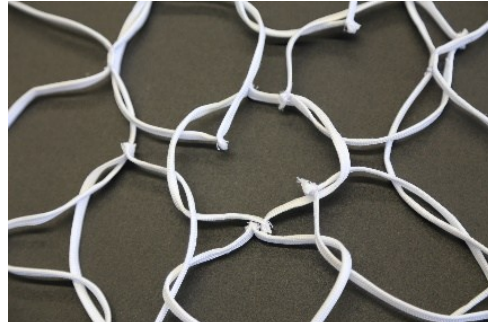


Fig. 12 After the strands have been cut, they create a chain mail-like mesh

4.3 Combination of flat and tubular braids

The combination of flat and tubular braids enables the creation of structures with defined lateral cavities, for example piping, see Fig. 13. Furthermore, two flat braids can be joined crosswise to form an X-Wing structure, see Fig. 14. Such braid structures could be of future interest for applications in fan blades or paddle wheels. Both structures were manufactured on the VF 1/(4-72)-140 machine using a full carrier arrangement.



Fig. 13 Braided piping tape manufactured on a VF 1/(4-72)-140 (cross-section on the left side).

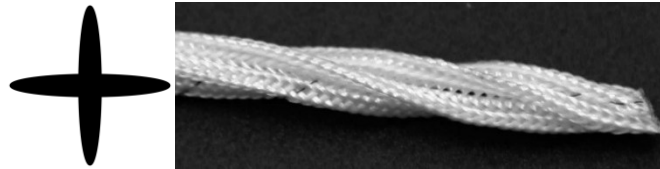


Fig. 14 Braided X-Wing structure manufactured on a VF 1/(4-72)-140 (cross-section on the left side).

5 Conclusions

This work demonstrates a range of new products, providing an overview of the new possibilities for producing complex braided structures on a variation braiding machine with 6x6 horn gear set up. These capabilities include textile chains designed to replace steel chains, as well as knotless or braided nets with flexible connection areas. The larger machine allows additionally the production of stents for coronary bifurcations treatment featuring closed transition areas in the bifurcation for improved healing. Additional applications include ceramic-based bifurcated tubular structures and the processing of nanofibers into high-strength ropes for lightweight, high-tensile-strength composite materials.

Author Contributions

F. Ficker: supervision, project administration; R. Kocaman: conceptualization, writing – review and editing; C. Anzer: conceptualization, supervision, project administration; R. Miksch: conceptualization, writing – original draft, pattern development, experimental work; K. Großer: conceptualization, writing – review, visualization, pattern development experimental work. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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