3D Textiles Based on Warp Knitted Fabrics

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Fibre-reinforced composites (FRCs) are already well established in several industrial sectors such as aerospace, automotive, plant engineering, shipbuilding and construction. The technical advantages of FRCs over metallic materials are well researched and proven. The key factors for an even wider industrial application of FRCs are the maximisation of resource and cost efficiency in the production and processing of the textile reinforcement materials. Due to its technology, warp knitting is the most productive and therefore cost-effective textile manufacturing process. In order to produce resource-efficient textile structures with these technologies, a high degree of prefabrication is required. This reduces costs by reducing the number of ply stacks, and by reducing the number of extra operations through final path and geometric yarn orientation of the preforms.

Keywords: warp knitting ; 3D textiles ; spacer fabrics

1. Warp Knitted 3D Non-Crimp Fabrics

Non-crimp fabrics (NCFs) are mainly made from homogeneous 2D textile structures in the form of rolls with constant yarn spacing and widths [1].

The manipulation of a 2D NCF to create the desired shape or form is called draping for the processing of 3D fabrics. This is typically done by laying out the 2D NCF and then folding, pleating, or otherwise manipulating it to achieve the desired shape. As a basis for composites fabrication, the resulting shape is then pinned, sewn or impregnated to hold it in place [2].

The underlying mechanism of draping is the stretching and compression of the warp knitted fabric. When the fabric is manipulated, by applying forces to the outer edges, it is stretched in some areas and compressed in others, creating a pattern of tension and compression across the material. The effects of draping on textiles have important implications for the manufacture of fibre reinforced composites (FRCs).

NCF can be divided into three categories according to their three-dimensional configuration and shaping. Material (a): Binding and reinforcing yarn densities are constant, draping due to lack of structural stretch in the warp knitting thread [3]. Structure (b): Constant binding and variable reinforcing yarn density and orientation [4][5]. Process (c): Variable binding (by adhesive or warp knitting thread) and constant reinforcing yarn density and orientation [6][7].

The advantages and disadvantages of each class in terms of their applicability to complex three-dimensional composite components are discussed below. There is no known research into the use of a combination of variable binding, variable reinforcement yarn density and orientation.

1.1. Variation through Material and Structure Modification

Material

In this category, there are two options for the subsequent drape of the NCF. Option 1: The differences in warp knitting thread lengths required for a draping process are achieved through thread shifting during the draping process. Option 2: The differences in thread orientations required for a draping process are achieved through stretching and twisting of the warp knitting thread during the draping process from 2D to 3D.

An example for draping due to lack of structural stretch of the warp knitting threads is the NCF with partial weft fringe binding “Drapetex” from the company Gerster TechTex (Biberach an der Riß, Germany). NCF with material variability are neither close to contour nor a preform, and orientation of the reinforcing yarns according to the load path is not possible. Such NCF can be produced on conventional multiaxial warp knitting machines without further development and adaptation of the machine technology. Depending on the complexity of the part, subsequent draping of such an NCF can produce a wrinkle-free and gap-free fabric surface over the preform surface. However, this results in unavoidable wrinkles and gaps outside the preform surface and therefore unavoidable waste. In addition, it is not possible to orient the reinforcement yarns (weft and warp) during the draping process in accordance with the load [3][8].

Structure

Multiaxial warp knitted fabrics are basically composed of three yarn systems. 1. The warp knitting yarns (threads), 2. The warp yarns and 3. The weft yarns. For all and within all three yarn systems, forces act on the yarns to induce stretching and wrinkling when the NCF is draped. Therefore, one starting point for producing NCF with a high degree of prefabrication is to determine the forces/stresses that occur prior to NCF production and to design the yarn systems accordingly so that the forces/stresses that occur during draping are minimal. In theory, this means that wrinkles, overlaps and gaps in the preform can be avoided without the need for structural over-dimensioning, e.g., through additional yarn layers, in order to compensate for these defects. Since NCF made from high-performance fibres, such as carbon or glass, have only a low material ductility, even relatively low draping forces lead to large displacements of the yarn layers. A promising approach to compensate for the different draping forces in NCF is to give each yarn a pre-defined individual length based on the final three-dimensional shape in the draped state, hereafter referred to as the yarn reserve [4][5][9][10][11][12]. These yarn reserves may be unevenly distributed over the yarn laid down (inhomogeneous yarn reserve) or evenly distributed over the length of yarn laid down (homogeneous yarn reserve).

A homogeneous yarn reserve is based on the compensating for the different forces during draping by feeding yarn material from the components that were not originally in the preform area. This overlaps with the material approach.

The principle of inhomogeneous yarn reserve is based on the work of Sankaran et al. [4], where yarn reserves are created in defined subsections of the warp reinforcement yarns. These yarn reserves correspond to the yarn section lengths required for subsequent draping. Based on this, a technological approach for the additional creation of a weft reserve was developed in further research at the TU Dresden [5][10]. The two developments approaches for creating an inhomogeneous warp and weft reserve are described below.

Structure—Warp Yarn Reserve (0°-Direction):

In the field of technical textile production, warp reinforcement yarns are provided on bobbins. Warp beams for reinforcement yarns are not known. Since each yarn comes from its own pay-off point, there is basically the possibility of warp yarn reserve. The stitch formation process is discrete in time. The warp thread moves at a constant speed, independent of the stitch formation process, if it is wound up with a constant tension force. If the take-off speed/take-off force is changed in a warp thread-specific manner, the distances between the stitches in the formed fabric are changed in the warp direction (directly proportional). In this way, warp yarn reserves can be generated. The change in take-off force can be achieved, for example, by means of a single-yarn take-off or a mechanical shaping located between the take-off and the knitting point. The single yarn take-off (in combination with a single yarn delivery to reduce the required take-off forces at the differential doffing system) was developed technologically and structurally by Sankaran et al., It was implemented on a KARL MAYER Malimo 14024 multiaxial warp knitting machine manufactured by KARL MAYER Technische Textilien GmbH (Chemnitz, Germany).

Technical limitations are the length of the warp reserve (in Sankaran's implementation, the excess length factor was 1.5) [4]. However, without a change in weft spacing and weft lengths, crease-free draping is not possible with warp reserve alone [10]. Width incursion transverse to the warp direction, caused by the weft yarns of different lengths, remains. Since the number of yarns fed per unit of width (warp yarns) and per unit of length (weft yarns) remains constant over the working width or in the weft lay-up, different material requirements (in this case number of yarns/density) caused by 3D shaping/contouring cannot be compensated, so that local deviations in the basis weight within the NCF inevitably occur. The ITM of TU Dresden is currently developing solutions for inline manipulation of warp density (final contour-optimised NCF). A research project on the manipulation of weft density is planned for the end of 2023.

Fundamental research activities by Sankaran et al. led to the development of curved reinforcing grids that can be specifically adapted to geometric shapes through variable single warp yarn delivery [13]. The application of this technological approach is limited to simple 3D contours. In the case of complex component shapes, significant, undesirable deflections of the reinforcing filament course (structural distortions) occur, leading to a reduction in the load-bearing capacity in the later component [4].

In the case of complex component shapes, significant, undesirable deflections of the reinforcing yarn course (structural distortions) occur, which lead to a reduction in the load-bearing capacity in the later component. Semi-finished textile products that meet the requirements and can be precisely adapted to a given component geometry can only be produced if the lengths of both the warp and weft sections can be flexibly varied locally between the bonding points [5][10].

Structure—Weft Reserve (90°-Direction):

In all known methods for forming the inhomogeneous weft reserve, the yarn reserve is formed mechanically, i.e., by means of mechanical forming tools.

The limitations of mechanical forming of the yarn reserve lie in the space required for the forming elements and the forming movement. As a result, only lattice structures can effectively be produced if the high productivity of multiaxial warp knitting technology is to be maintained. Geometric design is therefore limited in this respect (for a hemispherical preform, for example, the maximum radius that can be converted is 0.64 × working width) [5][10]. The time of the width indent is therefore shifted directly into the manufacturing process. As a result, the NCF produced already has a variable outer contour after production, even before draping. Furthermore, gaps are built into the fabric during weft yarn formation. Rather than increasing the material requirement of the fabric “from the outside”, the spacing between the yarns is adjusted. This reduces the yarn density/area mass in the drape area. Therefore, inhomogeneous yarn reserves can only be used sensibly if they are combined with measures for force-flow conformity (fibre follows force).

The advantage of the yarn reserve principles is that it is easier to automate than draping, e.g., Drapetex. The semi-finished textile product must be precisely positioned in the mould in two planar coordinates and one angular coordinate. There is no need to apply additional forces to move and stretch the threads. The automation technologies therefore need to be less complex than for conventional 2D textiles or material-based drapability optimisation.

1.2. Variation through Process Modification

Investigations by Krieger et al. show approaches to influence the draping behaviour of NCF by changing the binding type of the warp knitting thread in the NCF during the production process [14]. The so-called tailored non-crimp fabrics (TNCFs) have been developed to achieve sufficient drapability or low shear stiffness for forming into double-curved geometries on the one hand and high dimensional stability or high shear stiffness for automated handling on the other hand. As a result, they developed a TNCF with a stitch length of 2 mm, a stitch gauge of E6, and a change in stitch type from chain to tricot.

An alternative stitch-free approach was taken by Rittner et al. by replacing the knitting yarn with a chemical binder, solidified by heat and pressure, in combination with a CAE-simulation to investigate the optimal binding in a two- or four-layer NCF, depending on the drape geometry [6][10]. The freedom in shaping is not yet as great as with the aforementioned approaches, but a combination of this process with the structure approach potentially offers possibilities for generating force-flow-oriented textiles with a high degree of prefabrication. However, accurate positioning on the mould is a prerequisite for obtaining a draped fabric free of wrinkles and warping. This requires a clear positioning rule, e.g., by marking points on the NCF, which results in increased demands on the entire production process chain.

2. Warp Knitted Spacer Fabrics

According to Hu et al., the advantages of three-dimensional warp knitted spacer fabrics are as follows [15]:

- Inexpensive and easy to manufacture;
- Handling of preforms layers prevented from moving through stitching;
- Better impact damage tolerance;
- Improved delamination resistance to ballistic and blast loads;
- Improved interlaminar fatigue resistance;
- Improved joint strength under monotonic and cyclic loading.

2.1. Variation through Material and Structure Modification

There are several textile technological options for the production of warp knitted spacer fabrics.

In order to achieve a straight yarn orientation of reinforcing yarns, they must not form a mesh by themselves. Therefore, each reinforcement yarn system must be held in place by a warp knitting thread. The following explains how the reinforcement yarn layers can be integrated into the spacer fabric in the x, y and z directions based on the double needle bar warp knitting technology.

In order to achieve a straight reinforcement yarn position across the width in the X-direction, defined as the working width direction of the warp knitting machine (or 90°-direction), it is necessary to integrate weft yarns, e.g., in the form of a long weft or magazine weft. A warp knitting thread system with a pillar stitch is a suitable structure for binding these weft yarns in the spacer warp knit. It is also possible to integrate segmented straight yarn sections across the working width by means of a partial weft structure known as inlay warp knitting. The pillar stitch binding is also suitable for holding the inlay yarns in place [16][17].

The integration of a reinforcing layer in the Y-direction can be achieved either by a partial weft lay staggered over a needle lane and combination of elastic and inelastic yarn material. The Y-direction, or 0°-direction, is defined as the production direction. The Y-thread has to consist of low elasticity material that has to be drawn to a straight thread. The yarn supply is therefore low. The low-elasticity material yarn needs to be bound with an additional loop yarn system (e.g., tricot or atlas binding) consisting of an elastic yarn. Another way of integrating straight yarns in the y-direction is to use filler yarns, which are located and remain in a needle lane. They can be bound either by a weft yarn system in front of them or in combination with a loop thread system in front of them, e.g., by a pillar stitch, or the filler yarn can be integrated between two yarn systems of the outer surfaces, forming crossed wales (e.g., tricot binding) [16][17].

Pile yarns present in warp knitted spacer fabrics can also have a reinforcing function in the Z-direction (thickness direction). Basically, the shear strength, compressive strength and thickness of the spacer fabric are determined by the material used and the warp knitting integration of the pile yarn. The pile yarns can be placed in between the textile cover surfaces in a straight form. It is essential that the pile yarns are crimped in the area of the surface layers to enable fixation there. In general, the pile yarns can be fixed within the textile face layers by open or closed loops [16][17].

The binding of the pile yarn system defines the orientation of pile yarns in the cross section of the spacer warp knit. A possible structure for the pile yarns with a straight orientation is in a 90° I-orientation, realised with a pillar stitch lapping in pile yarn system and at least one thread system. Another option is to incorporate the pile yarns at a defined angle (V-orientation), depending on the yarn threading and machine gauge, as well as the lapping as tricot/cord/atlas. This can be implemented with one or preferably with two thread systems. Another option is the X-shaped binding of the pile yarns in the spacer fabric cross-section. This is realised by 2 pile yarn systems and a counter lapping of a tricot, cord or atlas lapping [16][17]. The highest shear strength is achieved with the combination of I and X-shaped binding of the pile yarns in the spacer fabric cross-section.

3D reinforcement structures made of warp-knitted spacer fabrics have been used for concrete reinforcement in recent years [18][19]. 3D warp-knitted spacer fabrics offer the advantage that two layers of reinforcement can be integrated into one textile and can be designed variably. This allows the degree of reinforcement to be freely adjusted via the mesh size. The high stiffness of the spacer yarn enables the reinforcement layers to be fixed to each other in a precise position, which is essential for reinforcing concrete.

The individual layers are similar to the two dimensional, lattice-like NCF and consist of reinforcing yarns in 0° and 90° directions and a warp yarn connecting them. The spacing between the layers can be adjusted during production [20][21].

Another application involving integration of functional materials in the z-direction is spacer-knitted thermoelectric generators (TEGs). Metal wires have been integrated as functional and reinforcing materials in different structures in z-direction, which can generate electric current from waste heat. The TEGs achieve an electrical power of 1.78 μW [22].

2.2. Variation by Process Modification

In order to produce more complex spacer fabrics with additional spatial curvatures, machine modifications of the double needle bar warp knitting technology are necessary. In principle process modifications in the double needle bar warp knitting process and thus product changes can be achieved by (1) varying the trick plate spacing and position, (2) by varying the fabric take-off and yarn tension and (3) by integrating additional technologies.

An overview of the known technologies for the production of modified warp knitted spacer fabrics is given below.

A further embodiment of the double needle bar warp knitting process is the use of a knitted fabric take-down with frictionally engaged conical take-down rollers [23]. This makes it possible to produce arc-shaped closed reinforcing knitted fabrics with in-plane curvature.

Further developed double bar warp knitting techniques also make it possible to produce spacer warp knits with alternating distances between the partial areas within the working width and thus contoured closed and/or lattice-like surfaces [24].

In parallel, research by Gries et al. looked at local reinforcement using inserts, for example for shell-stringer structures. For this purpose, a multiaxial warp knitting machine was modified, with which the production of the NCF and the connection with an already prefabricated textile stringer structure are carried out in a single operation [25]. However, these spacer warp knits do not allow for a curved reinforcing yarn path, requiring near net structures.

Franz developed warp knitted spacer panels [26] and tubular warp knitted spacer fabrics [27]. Tubular warp knitted spacer fabrics are producible by varying the fabric take-off and yarn tension. Based on this technology, fibre-reinforced lightweight components can be developed in a highly productive manner for large-area components such as ceiling, wall or floor elements, as well as for double-walled pipes. Compared to conventional structures available on the market, such as honeycombs and glass spacer fabrics, the spacer structures produced in integral design have a six-fold higher compressive strength.

Lüling has developed a technology for lightweight building components by combining 3D spacer fabrics with 3D printed objects. Such products can be used, for example, as textile façade shells for targeted shading and insulation. A key focus in the development of such structures has been to use the same groups of materials for both the print and the textile material, making the recycling process easier [28][29].

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