Complex concrete casting: Knitting stay-in-place fabric formwork

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Abstract

The paper presents initial results of research focused on developing a novel type of formwork for concrete based on pre-stressed fabric formwork principles. It aims at creating geometries that are fabricated in one piece by knitting technical fibers, which could ultimately be used as reinforcement for concrete. This approach would result in a spatial textile that minimises the need for patterning, sewing, welding or gluing compared to a conventional approach to fabric formwork and textile reinforcement based on woven fabrics. It makes it possible to create directional material properties aligned to the internal force flow. This paper presents an overview of the proposed prefabrication technique and exemplifies its feasibility through small-scale experiments.

Keywords: knitted fabric formwork, textile reinforcement, stay-in-place formwork, complex concrete geometry

1. Introduction

Concrete is a versatile construction material particularly because of its moldability into almost any desired shape, a property that makes it a very attractive material for complex architectural expressions. However, complex concrete structures are not that common today. This is a result of the need for specialised formwork and its increasing cost when used as a one-off. Not only does formwork account for 30-60% of the cost for concrete structures (Lloret et al. [8]), it also generates a great deal of waste. Figures 1.a and 1.b show the distribution of cost for a cast in place slab and wall respectively (Hanna [4]).
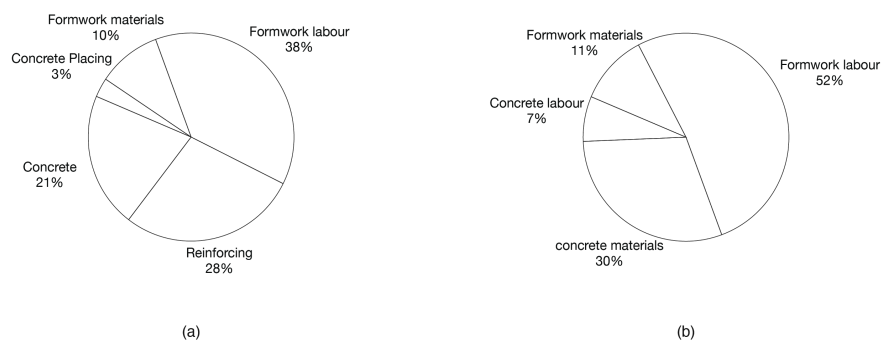

Figure 1: Cost distribution for a cast in place concrete: (a) slab; (b) wall (after Hanna [4])

Additionally, non-standard reinforcement strategies need to be developed. As a result, industry and academia alike have shown an increased interest in flexible or stay-in-place formwork systems that can act as reinforcement after hardening.

2. Background

Digital fabrication techniques have been used extensively for the creation of complex geometries. This has resulted in a very precise production of formwork and a relatively less time consuming process. However, the system as a whole has remained largely unchanged and is still very wasteful. The past years have seen an increase in research into flexible formwork techniques that would enable a more cost and material effective solution to bespoke formwork. Some of the possible solutions for these problems are described below.

2.1. Flexible and stay-in-place formwork

Flexible moulds focus on the creation of a system that can be easily adapted to various geometries, hence allowing the formwork to be reused for non-repeated geometries. Examples of such systems, used on site, are those developed by PERI. RUNDFLEX is a system offering the possibility of creating single curved walls with ease (PERI [11]). However, this does not allow for double curvature, which is very often found in complex geometries.

Solutions addressing doubly curved elements have been developed at research institutions such as ETH Zurich, TU Delft and TU Eindhoven. Kine-mould developed at TU Delft and TU Eindhoven is focused on using a grid of linear actuators for creating various double curved geometries (Schipper [14]). This solution focuses on the creation of prefabricated elements.

Similarly, prefabricated moulds could be used as stay-in-place formwork, eliminating the labour intensive process of stripping formwork. Pier Luigi Nervi routinely used precast ferrocement elements as structurally active stay-in-place formwork for his domes and other structurally optimised structures. One such example is that of Palazzetto dello Sport, built in 1957 (Iori and Poretti [7]).

Perhaps one of the most impressive and recent examples of stay-in-place formwork is that of the Taichung Metropolitan Opera. The doubly curved surfaces would have been extremely costly to produce and reinforce with traditional approaches. Therefore, the complex and extensive reinforcement has been used as formwork instead. (Hauschild and Karzel [5])

2.2. Fabric formwork

Fabric formwork is one avenue of research that has proven to yield appropriate results for building complex and optimised structures (Veenendaal and Block [15]). Some of the advantages of using a flexible formwork system as opposed to the classical rigid formwork system is the minimisation of material use, the lightness of the system and ease of prefabrication and transportation.
Various beam, column, and slab geometries have been investigated by the former C.A.S.T group at the University of Manitoba, Canada (West [17]).
The material saving and structural optimisation possibilities are illustrated through work carried out at the University of Bath (Orr et al. [10]) and at ETH Zurich (Veenendaal and Block [15]).
When applied to specific shapes, this approach demands the creation of cutting patterns for the fabric, such that the 3D geometry can be constructed out of initially flat pieces. Furthermore, if the the system has to be tensioned to be stable, geometry has to be anticlastic.

2.3. Textile reinforcement

Textile reinforcement of concrete relies on the use of materials such as alkali resistant glass fibre and carbon fibre mats instead of steel. These textiles are generally produced as multi-axial woven or nonwoven mats. Spacer fabrics have also been developed for use as textile reinforcement. Examples such as the *betoShell®* system (Hering [6]) used for facade panels in the Arnhem train station prove the feasibility of using textile reinforcement in creating lightweight and material-efficient solutions.

Figure 2: Textile reinforcement, *betoShell*® used for facade at Arnhem Central Station (image: Robert Mehl, Hering[6])

The fibrous nature of these solutions could allow for a greater flexibility in the shaping of reinforcement compared to steel. Additionally, these materials do not corrode, which results in significant material savings from the reduction of concrete covering alone.

3. Knitting stay-in-place formwork

While several good solutions have been provided for addressing the problems of formwork reusability and material efficiency, they each only address one problem at a time, asking for a more integrated approach. Several elements could be combined into one integral system for the creation of a cost-effective, waste-reducing and optimised approach to formwork and reinforcement.

This paper proposes the combined use of textile reinforcement and fabric formwork for the creation of a prefabricated, prestressed, spatial textile with tailored properties that can act as stay-in-place formwork and reinforcement.

Fabric formwork and textile reinforcement are most commonly made of woven textiles. For the creation of a desired geometry, patches are cut out of flat sheets and sewn, glued or welded together. This can prove to be challenging for complex geometries. In the process, fibres are cut and become discontinuous and material properties are non-directional. Additionally, layering, spacing and proper orientation of fibres to stresses need to be taken into account for reinforcement.

3.1. Knitting technology and textiles

Knitting has been used extensively in the garment industry, but has slowly made its way into the world of technical textiles and composites. Some of the advantages of knitting are the possibility to create directly three-dimensional geometries, variable widths, openings without the need for cutting the fibres and diversified material properties. Complex geometries with integrated channels and grooves can be created with ease by means of CNC knitting, as is the case with knit performance sports shoes. It can also be used at architectural scale within hybrid bending active systems (Ahlquist and Arbor [1], Ramsgaard Thomsen et al. [13]). Knitting is very well suited for bespoke prefabrication as the process can be easily adapted for the creation of various geometries, knit architectures and use of varied fibres, including high E-modulus yarns such as glass, carbon or aramid fibre.

3.1.1 Knit formation

Knit fabrics are created through the interlocking of consecutive loops. This is done with the use of needles that catch the yarn and pull it through a previously formed loop. Fabrics can be characterised in two ways depending on the direction in which the loops are formed. *Weft* knit fabrics form loops in consecutive courses using a single strand whereas *warp* knitting forms loops by pulling yarn through the adjacent loops using multiple parallel strands (Figure 3).
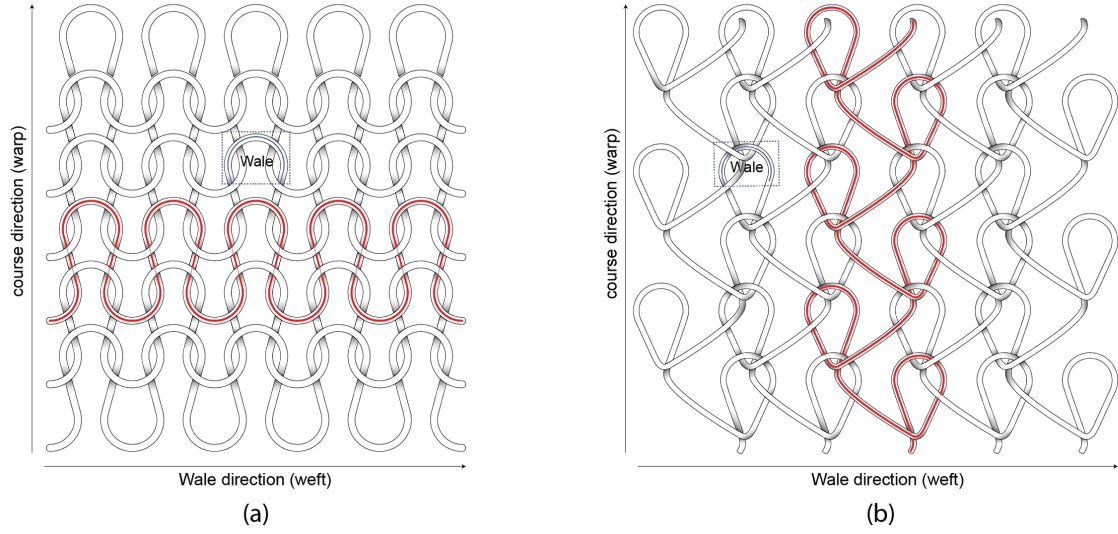
Figure 3: Knit textile formation types: (a) weft knit textile formation; (b) warp knit textile formation

The way in which these fabrics are formed has consequences on material stability and speed of production. In this research, weft knit fabrics are used and further described. Machines for the creation of weft knit fabrics can be flat bed or circular bed machines depending on the way the needles are laid out. Flat bed machines can be equipped with multiple needle beds (Banerjee [2]). A machine with a double bed has two needle beds, often called main bed and ribber, facing each other (Figure 4). The fabric can be created on the two beds separately (Figure 4.a) or interconnected (Figure 4.b). This enables the creation of diversified loop types and arrangements, and offers the possibility to create spacer fabrics.
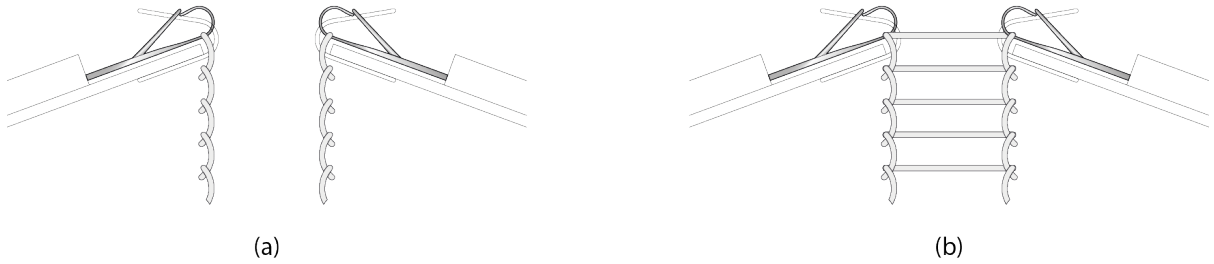

Figure 4: Double needle-bed layout for a flat knitting machine: (a) individual knitting on the two beds; (b) connected knitting on the two beds allowing for the formation of diversified loop types and spacer fabrics.

3.1.2 Knit geometry

A loop is the defining unit for the knit textile. The textile properties in course (weft) and wale (warp) direction as well as the dimensions of the fabric are defined depending on the loop width and height and the number of loops. The geometry and length of the loop is dependent on several machining factors. These are: gauge, knit point, yarn diameter, and tension. These characteristics have been investigated and described in more detail in Munden [9] and Popescu et al. [12].

4. Methodology

The approach focuses on prestressed fabrics. The prestressing of a membrane or network to reach equilibrium implies that the initial unstressed shape (net shape) is different to the final shape (target shape). Figure 5 gives an overview of the workflow needed for the creation of the knitting pattern of the desired fabric.
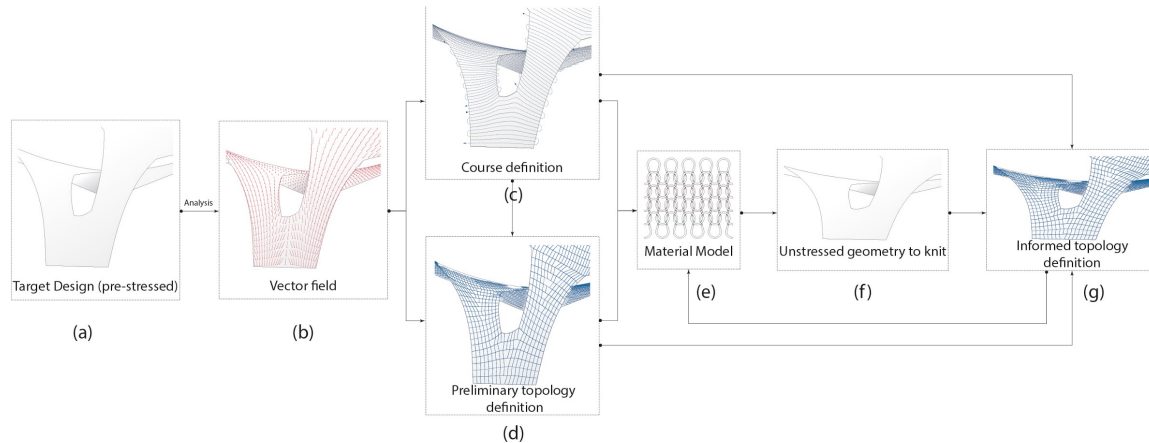

Figure 5: Workflow for computation of the initial shape and final knit pattern based on the known stresses and material model.

Given an anticlastic geometry with known stress paths, one can calculate the initial, unstressed geometry to be produced. For this, a material model is needed to compute the expected deformations. Knit fabrics have different properties in different directions, meaning that they can deform or stretch differently in the course or wale direction. Therefore, the orientation of the fabric needs to be defined for the target geometry. This orientation is defined by the generation of the courses over the geometry (Figure 5c). These are defined based on the known course spacing resulting from the loop geometry and informed by e.g. the principal curvature or the force flow. The course definition would be enough for the material model if the fabric structure were to be uniform, meaning there are no variations in the loop density. However, if the loop topology of the fabric is very diversified, the material model becomes more complex and highly anisotropic. The definition of courses is no longer enough to inform an accurate material model. Therefore, it is necessary to define a preliminary topology of the loops within each course (Figure 5d).

The strategy for defining the knit topology is based on describing the geometry as a mesh where each face is a loop. Such approaches have also been employed in computer graphics for the simulation of knit fabrics at yarn level (Yuksel et al. [16]). This results in a quad-dominant mesh with triangular exceptions (Figure 5d). These exceptions represent the so called *increases* and *decreases,* identifying/representing where within a course a loop is either added or removed.

Finally, knowing the course direction and the preliminary knit topology, the material model (Figure 5e) can be defined and the net shape (Figure 5f) can be calculated. With this net shape the courses and knit topology can be adjusted and the final knitting pattern can be generated.

5. Case studies

Machining properties and parameters need to be taken into account to translate the digital model into a physical, knit textile, which can be tensioned into the target geometry. One important aspect is the definition of a sequence in which the textile has to be knit, as the right geometry cannot be achieved without a proper sequencing. The following case studies investigate the relationship between geometry and machining sequence. They also aim to show the versatility of knitting of three-dimensional shapes without the need for patterning. The case studies offer insight into how structural aspects can be

addressed. The versatility of knitting allows for the creation of complex geometries and the tailoring of material properties such that they can be aligned to force flows. Furthermore, the possibility of creating complex joints as monolithic elements addresses the problem of assembly.

5.1. Non-orientable surface

Research at the University of Florida looked into the digital form finding and fabrication of a complex non-orientable surface for curved concrete (Belton [3]). The formwork for this surface was realised with the use of a prestressed membrane. For the fabrication of the membrane, several patches of flat material needed to be sewn together. To illustrate the potential of knitting for fabric formwork, a topologically identical was modelled and subsequently knit in one piece. Figure 6 shows the two surfaces side by side, on the left the surface created through stitching (Belton [3]) and on the right the knit seamless surface.

An electronic Brother KH-970 knitting machine was used for knitting this surface. The machine is equipped with a double needle bed. This enables the alternate use of needles and beds for the creation of a seamless textile. A detailed description of the process is given in Popescu et al. [12]
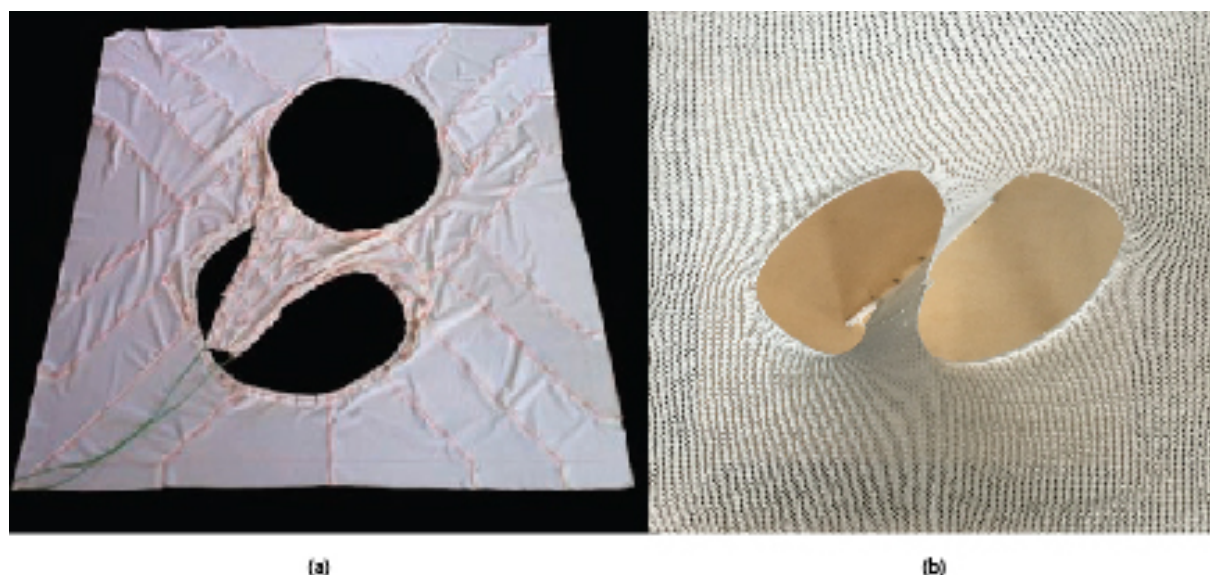

(a)   (b)

Figure 6: (a)conventional and (b) knit textiles for a non-orientable surface to be used as fabric formwork (left image: S.Belton [3])

5.2. Six-directional node

The following case study focuses on the creation of a six-directional node (Figure 7: (3) Node). This example illustrates the versatile geometric possibilities offered by knitting and the process needed to achieve such geometries. Figure 7 (3) shows the tensioned six-directional node which was knit using the same Brother KH-970 knitting machine. Creating monolithic joints has implications for construction. It offers the possibility to move the connection between elements to a place in the structure where forces and moments are minimal.

The knitting techniques needed for the creation of three-dimensional geometries are as follows:

1. The use of increases and decreases for varying the widths of the fabric;
2. the use of so called short rows for shaping a three-dimensional geometry: in this case for the out-of-plane shaping of elements in the direction perpendicular to the fabric created on the two beds;

3. alternation between connecting and disconnecting loops on the two needle beds: enables the creation of the vertical and horizontal cylindrical elements.

The following steps are followed for the fabrication of the node (Figure 7 steps 1-6):

1. yarn is cast on 40 needles and 20 circular courses are knit; by alternatively knitting on the two beds and connecting only the last loops of both beds. (Figure 7. Step 1; (1) Circular knitting)
2. 15 extra needles activated both left and right; we now have a total of 70 loops (Figure 7. Step 2)
3. 5 courses with separate strands of yarn are knit over both beds (Figure7. Step 3)
4. shaping of out of plane nodes through short rows: needles on the left or right side of the bed are set to holding position, meaning no additional loops are formed on those needles (Figure7. Step 4; (2) Cast off)
5. 15 loops to left and right on both beds are cast off through grafting, this creates a seamless connection between the loops on the two needle beds (Figure 7. Step 5)
6. step 1 is repeated for 20 courses (Figure 7. Step 6)

Step 1

Step 2

(1) Circular knitting

Step 3

Step 4

(2) Cast off

Step 5

Step 6
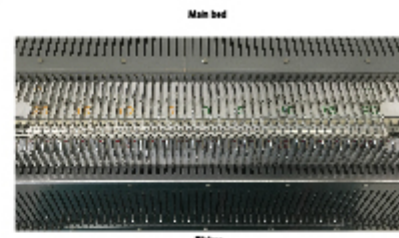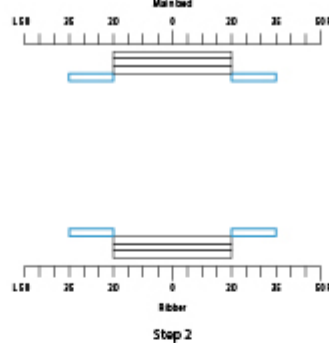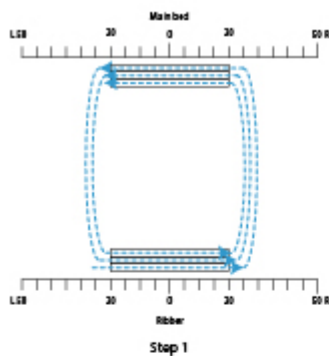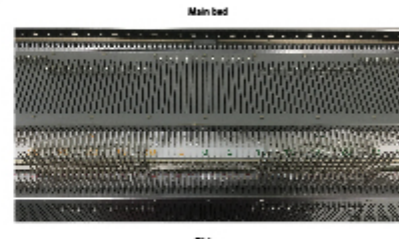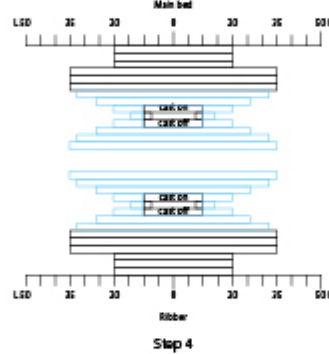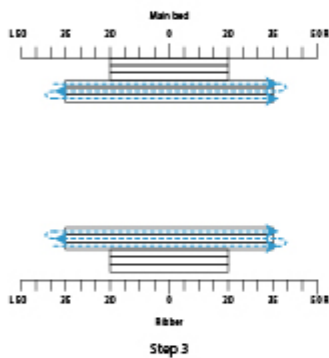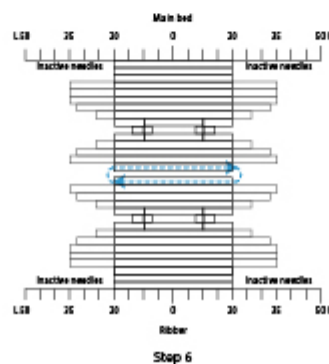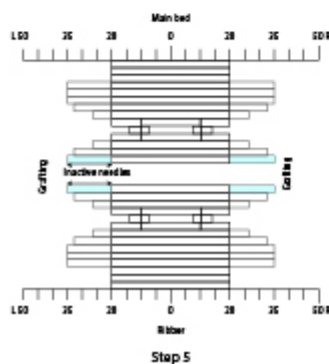
(3) Node

Figure 7: six-directional node geometry created as a seamless knit textile on an electronic Brother KH-970 knitting machine

Irregularities in the textile can be observed on the node. These irregularities, where loops are slightly bigger, are a result of the process described in step 4. The material is still created in one process and seamless.

The approach to creating this complex node could be expanded to create a node with more connections. The limitations in terms of possible angles and number of nodes needs to be further investigated.

6. Conclusion

The case studies presented in this paper illustrate the advantages of using knitting for the creation of seamless, complex shapes. The implications for concrete construction are related to the efficiency of production for fabric formwork, less material waste, the ability to tailor material properties. As patterning and sewing is no longer needed, the production process becomes significantly easier. In terms of scalability, the joining of several pieces of material may still be needed, but with knitting this can be done such that the material becomes seamless. The lack of patterning is of great advantage for reinforcement as fiber continuity is maintained. However, the mechanical properties of knit textiles are the least understood and hardest to model. They are known to have inferior in plane properties, compared to weaving, because of the high degree of curvature in the fibres. Nevertheless, they are superior in terms of energy absorption, impact resistance and drapability. The use of straight fibre inlays can help improve these properties and also ensure specific local properties. Consequently, future research will focus on the development of material models for highly anisotropic spacer fabric and the diversified use of materials within the fabric.

Furthermore, it has become apparent that the fabrication process and sequencing is key for achieving the desired result. The knitting process is cost effective as industrial machines can easily be used with minimal or no mechanical modifications.

Acknowledgements

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