IOP Conf. Series: Materials Science and Engineering **369** (2018) 012041 doi:10.1088/1757-899X/369/1/012041

Development of 3D woven cellular structures for adaptive composites based on thermoplastic hybrid yarns

C Sennewald[1,3], M Vorhof[1], P Schegner[1], G Hoffmann[1], C Cherif[1], J Boblenz[2], M Sinapius[2] and C Hühne[2]

[1]Institute of Textile machinery and High Performance Material Technology, Technische Universität Dresden, D-01062 Dresden, Germany
[2]Institute of Adaptronics and Function Integration, Technische Universität Braunschweig, Langer Kamp 6, D-38106 Braunschweig, Germany

E-mail: Cornelia.sennewald@tu-dresden.de

Abstract. Flexible cellular 3D structures with structure-inherent compliance made of fiber-reinforced composites have repeatedly aroused the interest of international research groups. Such structures offer the possibility to meet the increasing demand for flexible and adaptive structures. The aim of this paper is the development of cellular 3D structures based on weaving technology. Considering the desired geometry of the 3D structure, algorithms are developed for the formation of geometry through tissue sub-areas. Subsequently, these sub-areas are unwound into the weaving level and appropriate weave patterns are developed. A particular challenge is the realization of compliant mechanisms in the woven fabric. This can be achieved either by combining different materials or, in particular, by implementing large stiffness gradients by means of varying the woven fabrics thickness, whereas differences in wall thickness have to be realized with a factor of 1:10. A manufacturing technology based on the weaving process is developed for the realization of the developed 3D cellular structures. To this end, solutions for the processing of hybrid thermoplastic materials (e.g. tapes), solutions for the integration of inlays in the weaving process (thickening of partial areas), and solutions for tissue retraction, as well as for the fabric pull-off (linear pull-off system) are being developed. In this way, woven cellular 3D structures with woven outer layers and woven joint areas (compliance) can be realized in a single process step and are subsequently characterized.

1. Introduction

Flexible, flexible 3D structures made of fiber-reinforced plastic composites (FRP) with defined stiffness have aroused the interest of international research groups. By directly manufacturing such structures, significant advantages can be achieved in terms of weight reduction, increased efficiency and flexibility. The existing limitations in terms of structure design can be significantly extended by implementing flexible 3D structures with variable shapes. In the aerospace sector in particular, the development goals include increasing agility and aerodynamic efficiency. Despite the high potential of adaptive structures, the advantages of flexible structures are often more than compensated for by additional peripheral or system-related efforts. One approach to avoid the contradiction between structural flexibility on the one hand and stiffness and strength on the other hand within the same structure are pressure-activated cell and honeycomb structures. This also includes pressure-actuated cellular structures (PACS, cf. Figure 1), which have so far only been investigated theoretically [1],[2].

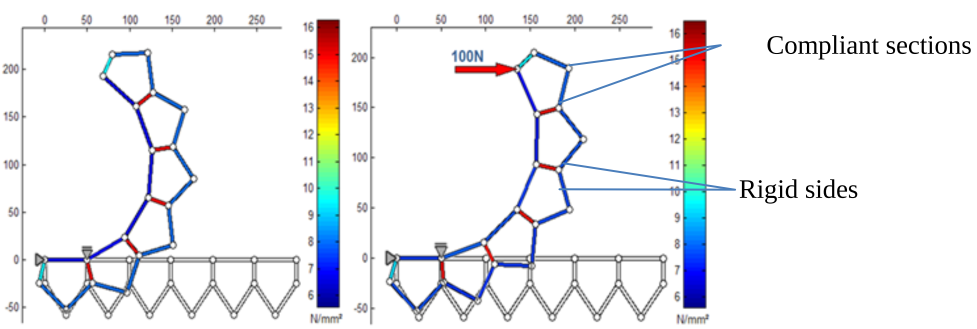

Figure 1. Geometry change of PACS [1].

The aim of this project is to develop theoretical and experimental basics for the development, production and testing of woven PACS. The functionality of the concept is equally guaranteed in the dimensional range between centimeters and meters and can be guaranteed by appropriate geometry and material selection. For the development of the necessary cellular structures as fiber reinforced composite (FRP), textile manufacturing technologies in particular offer numerous solutions for the effective integral production of the necessary 3D semi-finished products [3]-[4]. Since the PACS are characterized by a predominantly biaxial property profile, high stiffness in one direction and low stiffness (flexibility) in the other direction, biaxial structures are particularly advantageous. Weaving is predestined for transverse and longitudinal reinforced biaxial structures and semi-finished products for FRP [5]-[10]. So far, there have been two possible solutions for the integral production of closed-cell woven structures. Several layers of fabric are produced, which are interwoven in line at defined points. The formation of cells between the layers creates a closed-cell honeycomb structure [11],[12]. The main disadvantage of this technology is that no straight yarn layer can be arranged at right angles to the honeycomb direction, which means that the structure has only limited tensile strength and is only suitable to a limited extent for the development of PACS. The second approach uses the woven spacer fabrics developed at the TU Dresden within the framework of Priority Program 639 [13],[14]. This closed-cell structure is integrally woven and possesses biaxial arranged stretched yarn layers. However, the curved structure necessary for PACS is missing. The spacer fabrics have so far been developed for use as lightweight panels that are designed for maximum rigidity and strength throughout the entire structure. For this reason, spacer fabrics were designed homogeneously and with a high thickness, especially in the wall thicknesses. Compliant mechanism integrated in the textile structure, due to very large differences in wall thickness are missing. This does not in any way meet the requirements of PACS. For the development of PACS, integrally produced 3D woven fabrics that combine several characteristics are missing. The production of cellular structures whose wall thicknesses can be adapted to locally variable bending stiffness is not yet known. In addition to the necessary development of the technology and the fabric structures, comprehensive knowledge of theoretical structure development and structure design is also lacking. Closed cellular structures are required for the production of PACS. There are numerous solutions and applications for such structures in which the cells are manufactured and bonded using assembly technology. The almost exclusively used adhesive joints do not meet the requirements of the PACS with regard to strength and reduced bending stiffness, especially at the junctions. Therefore, the focus in the following will be on the consolidation of integrally manufactured cellular semi-finished textile products. Due to their positive matrix properties, thermoplastic FRPs are particularly suitable for the flexible design of the PACS. In addition, the challenge with thermoset FRP is to impregnate the textile semi-finished products in the closed cells. With thermoplastic FRP, the thermoplastic matrix can already be added to the semi-finished product as a thermoplastic fiber in the textile process. These solutions, which were also developed at ITM and are primarily based on the use of hybrid yarns (high-performance and thermoplastic fiber blends), are established. Through the targeted use of hybrid yarns with different blending ratios, which can be adjusted in a defined manner, FRP with graded fiber volume contents and corresponding graded bending properties can also be developed in principle. No investigations have been carried out to date. For the successful implementation of the PACS, solutions are lacking which, above all, can execute the necessary different wall thicknesses with high accuracy and thus ensure a defined bending stiffness. The particular challenge here is to keep the wall thicknesses for bending flexibility to a minimum, especially at the knots. Tried and tested solutions lead to resin accumulation, especially in the knot area.

2. Materials and methods

2.1. Yarn material

As already described, the use of hybrid materials for the weaving of cellular 3D structures is absolutely essential. These hybrid materials consist of a reinforcing component (glass fiber) and a matrix component (thermoplastic fiber). In a thermoforming process, the thermoplastic fiber is melted to form the matrix of the FRP. Only the use of hybrid yarns can ensure even distribution of the matrix material and reliable consolidation of the component in complex structures such as the PACS. In addition, thermoplastic matrices offer the required mechanical properties for the PACS. Two different hybrid yarn materials are used for the development of cellular 3D structures. For a reliable processing of hybrid yarns in the weaving process, it is necessary to either twist or pre-consolidate the hybrid yarns. This is the basis for the selection and development of the yarns. First hybrid yarn was produced with a fineness of 900 tex consisting of glass fiber 2 x 300 tex (GF, 67% content in weight, 46% fiber volume content) and polyamide 1 x 300 tex (PA, 33% content in weight, 54% fiber volume content) with 20 twists per meter. By twisting, the yarn surface is compacted, thus ensuring optimum yarn processing during the weaving process. TecTape with a yarn count of 1800 tex consisting of glass fiber (GF, 67% content in weight, 46% fiber volume content) and polyamide (PA, 33% content in weight, 54% fibre volume content) is used as a further material. The TecTape consists of pre-consolidated spread multifilament yarns, with 2 x Pa with 300 tex fineness on the outer sides and GF Multifilament with 1200 tex in the middle. The TecTape has a tape-like shape with a width of 6-8 mm and a thickness of 0.2 mm and is therefore predestined to produce very thin fabrics.

2.2. Development of algorithms for the geometry formation of cellular 3D structures for PACS

The geometry of the PACS has to be converted into surface elements for the weaving implementation of the cellular 3D structures. This can be done by reshaping 2D layers or by an integral production of the complete 3D geometry in the weaving process. The geometry of the PACS to be achieved is shown in Figure 2.

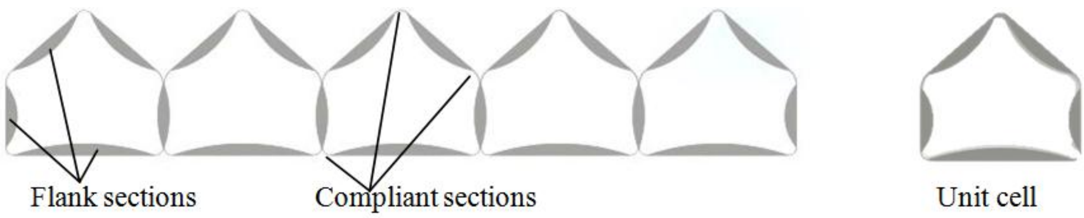

Figure 2. 3D geometry of PACS.

The PACS consist of unit cells which are lined up in the direction of production and which are divided into subareas. In order to generate the overall geometry and for the technical implementation of the weave, the subareas are reassembled periodically. Using combinatorics, the subareas are combined to form unit cells. For the realization of the cellular 3D geometry with a fabric layer, there is exactly one solution. Using 2 layers of fabric, seven different solutions are available. With 3 layers of fabric, 12 different solutions and with 4 layers of fabric 14 solutions can be determined. The solutions for geometry formation are then examined with regard to the fulfilment of the criteria resulting from

IOP Conf. Series: Materials Science and Engineering **369** (2018) 012041 doi:10.1088/1757-899X/369/1/012041

the application. The criteria are: continuous fabric plies, constant wall thicknesses, continuous fabric plies in the flanks, minimum number of plies in the joint area and the minimum number of plies required. Figure 3 shows a selection of different solutions for composing the geometry of the PACS by fabric layers. The colored lines mark the respective fabric layers. At least at the intersection points of the lines, the subareas are connected to each other in a way that makes them compatible with each other. A variant that meets all the evaluation criteria is, for example, the solution consisting of four partial areas in Figure 3 at the bottom right.

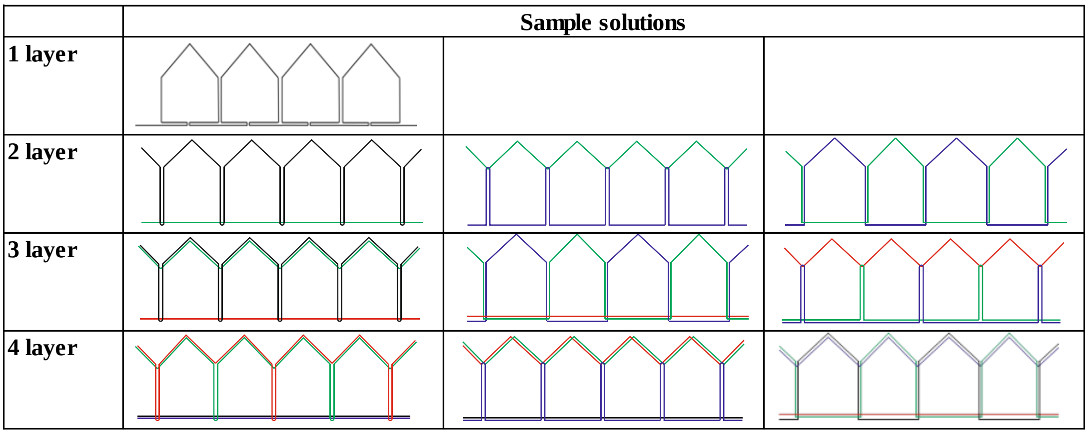

Figure 3. Sample solutions for PACS composed of sub-areas.

3. Results and discussion

3.1. Weave structure development for sections of the PACS

The flanks and compliant sections of the PACS require a separate examination and development. On the one hand, the flanks must be sufficiently rigid (stiffness of the entire PACS) and on the other hand, the compliant sections must be flexible. For this reason, the flanks and the compliant mechanism must show great differences in wall thickness in the individual areas. For this purpose, the technical weaving possibilities (thickening via warp and/or weft threads, inserts) were examined and evaluated. The formation of the compliant sections is achieved by the use of tape yarns and by varying the weave pattern. Without using any trimming the flanks can only be achieved by means of pre-consolidated inserts consisting of several layers used material. The inserts are made by stacking single layers of woven fabric, consolidating them in a thermos press process and cutting into desired size. The processing of inserts has to be taken into account when developing the weaving technology for the whole PACS. The weave pattern design for compliant section and flank section with pre-consolidated inserts is shown in Figure 4.

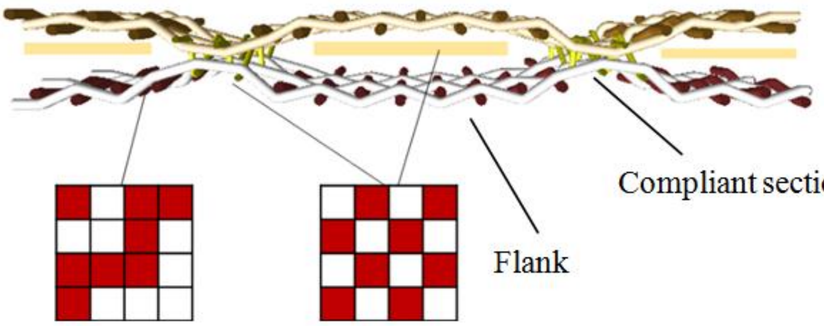

Figure 4. Structure and weave pattern design of compliant and flank section of PACS.

3.2. Methodology for weaving of PACS composed of partial areas

The technical principles of terry and spacer weaving have to be combined for the technical implementation of PACS by means of weaving. Based on the layer arrangement and the resulting connection points, all parts are transferred to a 2D weave arrangement. The gaps resulting from transfer to the plane are filled with floats (see Figure 5).

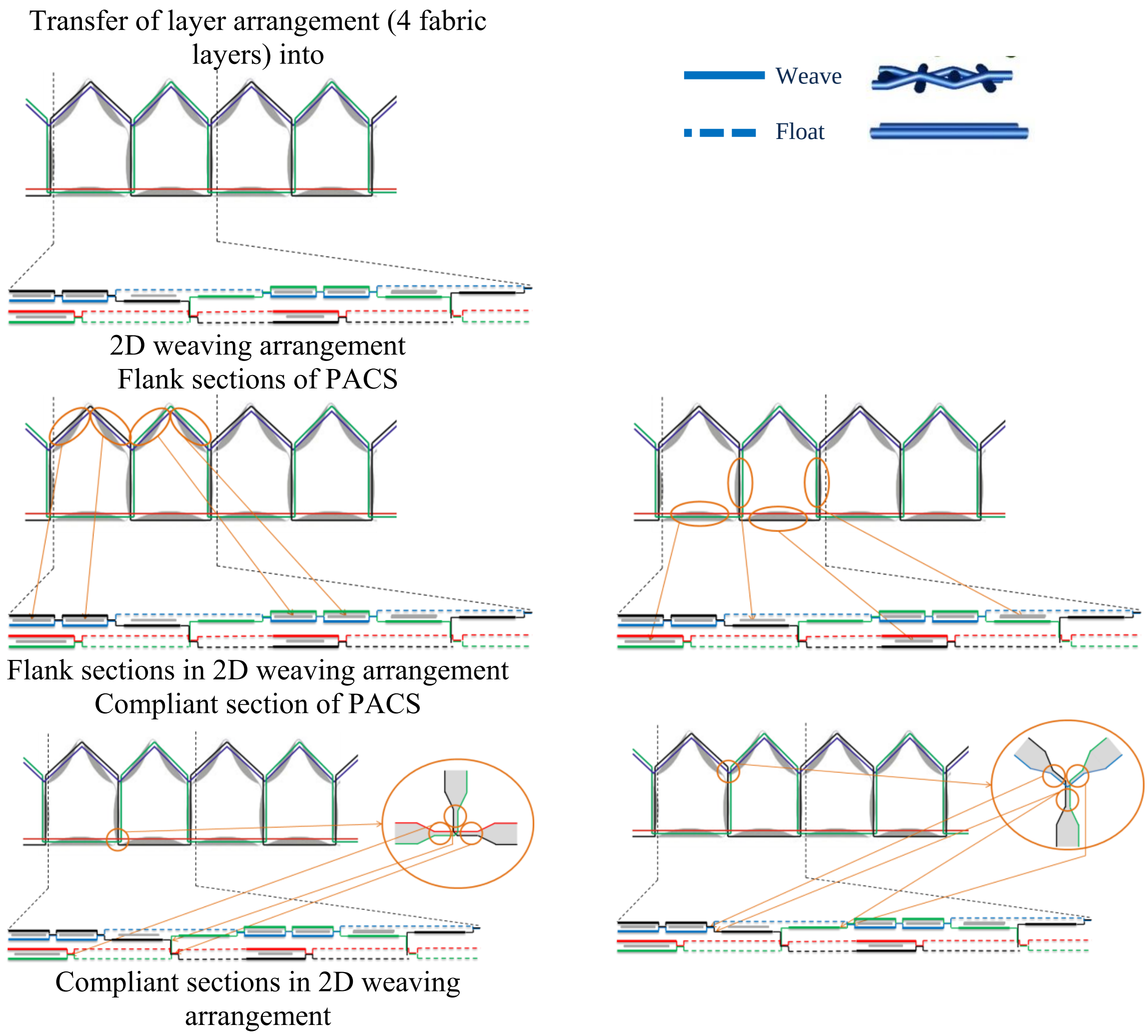

Figure 5. Transfer of layer arrangement into 2D weaving arrangement for weaving of PACS composed of partial sections.

The 2D weaving arrangement again is determined into individual sections, whereas weave patterns for each section must be developed on the basis of the weave patterns developed in 3.1 (Figure 6). In particular, the arrangement of the individual layers on top of each other, their intersection and the position of the floats must be determined. By merging the weave patterns for the individual sections, the total weave pattern for PACS can be developed and the control of the weaving machine can be created.

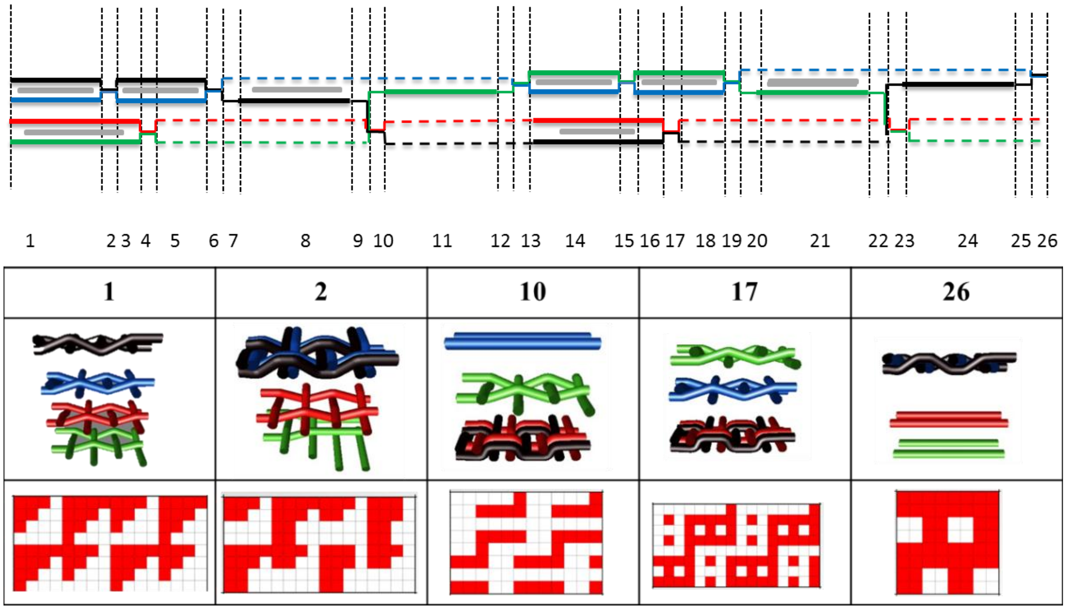

Figure 6. Subareas of 2D weaving arrangement and cross section as well as weave pattern for selected sections.

3.3. *Weave trials*

The process ability of the hybrid yarns in the weaving process and the realization of the sections of the PACS were carried out during practical weaving and consolidation tests (see Figure 7). It was shown that structures with large gradients of wall thickness can be produced in the weaving process. By using suitable tools, and thermos press processes the woven structures can be consolidated into composite compliant structures.

Figure 7. Weaving of compliant and flank sections of PACS using hybrid yarns and consolidated structures with different geometries of compliant section.

4. Summary and outlook

The use of textile reinforced composites in automotive, mechanical and plant engineering sectors is steadily increasing. This is accompanied by an increasing demand for load-adapted, highly flexible and variable structures. In particular, the formation of form-variable structures through selective geometric design in combination with compliant mechanisms shows very great potential for fulfilling the complex requirements. Weaving technology offers outstanding approaches to the implementation of complex 3D geometries. However, there is a lack of methods for the formation of complex 3D geometries such as PACS and for the technical implementation in weaving processes. The first approaches are terry weaving and spacer weaving. However, both methods are not suitable for the technical implementation of PACS. On the one hand the required 3D geometry of the PACS and especially the wall thickness gradients as well as the required different fabric lengths on the outer sides cannot be realized. Therefore, algorithms and methods for the formation of geometry were developed for the realization of PACS by means of weaving. The knowledge gained in the field of geometry formation for the specific arrangement and connection of fabric layers has a generally valid character and can be applied to other 3D geometries. The process chain developed for weaving implementation, i. e. the transfer of layer arrangement into a 2D weaving arrangement and the creation of weave patterns; can also be used for the realization of complex 3D structures in a weaving process. Weave structures have been developed and implemented for the individual sub-areas of PACS. The results obtained serve as a basis for the development of a technology concept and for the constructional and technological work for the development of a weaving machine concept for the realization of the PACS.

Acknowledgments
This article presents selected results of the Collaborative Research Project DFG CH 174/42-1 “Pressure actuated cellular structures (PACS)”. The authors would like to thank the Deutsche Forschungsgemeinschaft (DFG) for the financial support for the project at the Technische Universität Dresden.

References
[1] Gramüller B *et al* 2014 PACS - Realization of an adaptive concept using pressure actuated cellular structures *Smart Materials and Structures* **23.11** 115006
[2] Gramüller B, Hardy K and Christian H 2015 Holistic design and implementation of pressure actuated cellular structures *Smart Materials and Structures* **24** 125027
[3] Cherif C 2015 *Textile Material for Lightweight Constructions* (Springer Berlin)
[4] Bannister M Challenges 2001 for composites into the next millennium-a reinforcement perspective *Composites Part A* **32** doi:10.1016/S1359-835X(01)00008-2
[5] Cherif C *et al* 2012 Development of a process chain for the realization of multilayer weft knitted fabrics showing complex 2D/3D geometries for composite applications *Textile Research Journal* **82** 1195-210
[6] Islam A 2012 3D woven structures and an overview of manufacturing technologies 4th *World Conference on 3D Fabrics and their Applications* (Aachen)
[7] Khokar N 2011 Aligning 3D fabric-forming processes with market requirements *Proceedings of the Third World Conference on 3D Fabrics and Their Applications* (Wuhan, China)
[8] Sharpa K, Bogdanovichb A, Boylec R, Browna J and Mungalov D 2013 Wind blade joints based on non-crimp 3D orthogonal woven Pi shaped preforms *Composites: Part A* **49** 9-17
[9] Khokar N 2014 Development of innovative 2D and 3D fabric-forming processes for manufacturing composite reinforcements *Proceedings of the 8th ADITC* (Dresden, Germany)
[10] Karahan M, *et al* 2012 Low velocity impact characteristic of 3D integrated core sandwich composites *TRJ* **82** doi 10.1177/0040517512436832
[11] Chen X *et al* 2011 An overview on fabrication of three-dimensional woven textile preforms for composites *TRJ* **81.9** 932-44
[12] Chen X *et al* 2008 Design, manufacture, and experimental analysis of 3D honeycomb textile composites Part I: design and manufacture *Textile Research Journal* **78.9** 771-81
[13] Mountasir A *et al* 2015 Competitive manufacturing of 3D thermoplastic composite panels based on multi-layered woven structures for lightweight engineering *Composite Structures* **133** 415-24
[14] Mountasir A *et al* 2016 3D woven near-net-shape preforms for composite structures *Advanced Engineering Materials* **18.3** 391-6