Research Status of Advanced 3D textile technologies and applications for transportation Industry

Dega, Cynthie[1], Habibi, Mohamed[1] and Forcier, Patricia[1]
Groupe CTT, Québec, Canada

Keywords: *Automated braiding, Net shape, Tailored fibre placement (TFP)*

ABSTRACT

Composite materials for technical applications have been on the rise, particularly in the transportation industry. To achieve sustainability while improving performance, comfort and safety, high-performance reinforcements with improved stiffness, strength in the thickness direction and elimination of interlaminar delamination must be developed.

In transportation applications, three-dimensional textile preforms have gained wider acceptance thanks to their flexibility in design and shaping capabilities, due to the complexity of the geometry and some singularities in the loading cases. Also, there are a lot of transportation applications where near-net-shape design and manufacturing can help cut costs.
Much research on 3D textile preform manufacturing uses different technologies, such as TFP embroidery, braiding, and weaving. Thus, this article investigates these technologies opportunities, challenges, and future perspectives in transportation applications.

1 INTRODUCTION

High-specific strength and stiffness make composite materials ideal structural materials in the automobile, aerospace, and other industries. 2D composite laminates offer high stiffness and strength, but they have a long fabric lay-up process and poor out-of-plane properties [1]. In the last few decades, 3D textiles characterized by reinforcing fibres laying in the through-thickness direction have been developed to address these issues [2]. The integrated structure of a 3D textile provides better stiffness and strength in the thickness direction and eliminates interlaminar surfaces. As a major advantage, 3D preforms can fit perfectly into moulds for resin infusion without carefully manipulating the textile structure into the correct shape. The near-net-shape preforms offer more incredible benefits to the industry by enabling the fabrication of larger components as a single woven preform [3].

Textile science has progressed due to improvements in textile machines and production methods. It's also possible to use an enormously broad array of woven or braided patterns, including simple 2D plain weaves, eight-harness satin weaves, and 3D orthogonal weave patterns, all of which can show a useful bias in the orientation of material attributes.
Textile composites are typically produced in three distinct stages. The first step is the selection of fibres. The progress in textile machines makes it possible to use different fibres, i.e. glass, graphite, ceramic or steel fibres, which offer a higher load-bearing capacity for structural composite products. Fibres are bundled together into one continuous strand in the second step of the production process. The third step involves bonding and interlocking the yarns to produce a woven, knitted, braided, and non-woven flat sheet with a specific pattern, depending on the yarns' orientation and the various construction methods used to hold the yarns together. Braiding, Weaving, Stitching, and Knitting are the four primary

manufacturing methods for 3D textile preforms [1]. Depending on the desired characteristics of the final composite part, one of the fibre preform manufacturing methods can be chosen.
Braiding can be used to make cylinders, rods, beams of varied cross-sections, and more complex structures. There are several different track and column braiding procedures available. Traditional solid braiding has been limited to simple cross-sectional geometries since it is made by intertwining three or more thread groups. The ability to produce complicated 3D shapes has recently been improved [4].
Woven preforms are the most common textile manufacturing method, accounting for roughly 70 percent of all textiles produced [5]. High-performance applications requiring a high degree of toughness and rigidity benefit greatly from weaving with straight inlaid yarns. However, too straight threads can make it difficult to produce complex shapes [6].
Stitching is the simplest method of creating 3D textiles. However, the in-plane fibre damage caused by the needle is considerable and have an adverse effect on the composite mechanical properties. As an alternative, using a non-woven through-the-thickness reinforcement allows severe in-plane fibre damage to be avoided.
Knitted constructions have superior elastic behaviour over woven materials because of the interloping features. As a result, knitted structures have become increasingly popular as reinforcements for complex-shaped preforms in composite manufacturing. On the other hand, the loop structure is the primary drawback since it distorts production, resulting in lower strength and stiffness than woven preforms. There are advantages and disadvantages to each fabric-forming process. When it concerns strength and stability, nothing beats woven fabrics. However, knitted fabrics benefit from drapability and extensibility thanks to the ease with which the loop structure can be distorted [7, 8].

This paper addresses technical aspects of TFP embroidery, braiding and weaving that achieve such preforms and explains how they could improve a composite mechanical and physical properties.

2 TEXTILE COMPOSITES APPLICATIONS IN THE TRANSPORTATION INDUSTRY

Composite materials are used for transport vehicle construction. They contribute to the production of high-energy-efficient, lightweight, and durable vehicles without compromising their performance. High strength-to-weight ratios, high flexural and impact strengths, corrosion and weather resistance, durability, dimensional stability, design flexibility, and aesthetics are advantages of composites over metals. These advantages allow composites to meet the transportation industry sustainability requirements, which are overgrowing due to their size and importance. It encompasses all modes of transportation that would enable people or products to move by air, land, or sea, such as aeroplanes, vehicles, ships, and trains.

Composites have anisotropic properties, which means the fibres can be oriented in a specified way (0°, ±45°, or 90°) to offer the optimal mechanical properties in the load direction. Composites can be made from many plies of fibres stacked in various directions to achieve the necessary stiffness and thickness. Transport-related composites applications frequently use thermoplastic and thermosets resins. Many thermoset resins can withstand temperatures up to 500°F and are resistant to solvents and corrosives. They also have excellent finishing and adhesion properties as well as inexpensive costs [9].
In automotive, aerospace, and marine applications, reinforcing fibres are typically made of carbon, glass, and kevlar. Carbon fibre has the advantages of high strength and low density. Still, it also has a high price tag and a brittle behaviour. Glass fibres are excellent thermal and electrical insulators. However, their low modulus and high density make them challenging to replace carbon in some transportation applications. Fibres made from Kevlar are known for their incredible strength, heat resistance, and capacity to absorb

energy, making them ideal for aerospace applications. Even though these fibres are expensive and environmentally harmful to produce, there is an increasing need for more environmentally friendly alternatives like biocomposites [10].

Natural fibre composites are based on polymer matrices derived from renewable or non-renewable resources blended with fibres, including flax, hemp, sisal, bamboo, jute, and kenaf. Among the many benefits they provide are biodegradability, low density, high specific strength, reduced cutaneous and respiratory irritation, low cost, improved insulation, environmental friendliness, etc. When resins are derived from renewable resources such as starch, sugar, vegetable oils and soy oil, they are called bio-based resin and Green composites when reinforced using natural fibres [11-13].

The manufacturing processes used for both synthetic and natural fibres remain the same, despite major concerns about their poor compatibility with polymeric matrices and irregularities in their mechanical properties. Among these techniques, there are open moulding techniques such as spray lay-up, hand lay-up, filament winding, sheet moulding compound, pultrusion, and closed moulding techniques such as resin transfer moulding, injection moulding, compression moulding, etc. [9, 14].

3D reinforced composites are currently gaining traction in producing parts and structures from polymer composite materials. They are made using 3D fibre preforms that have reinforcement in various directions and angles throughout the preform manufacturing process, and they can take on a variety of complicated shapes [15]. Textile composites versatility contributes to their long-term sustainability. Fibre orientations, entanglement, manufacturing techniques, and fabric structures are wildly different from other preform manufacturing methods. In addition to netting and knitting, modern methods of manufacture of 3D reinforced preforms include the Tailored fibre placement technology (TFP), Braiding and Weaving.

Weaving is the most common method for producing 2D preforms fabrics. The rovings or yarns that makeup fibre preforms can be used directly in composites made by the filament winding and pultrusion. Textile processes are characterized by the possibility of interlacing threads in the longitudinal, transverse, and vertical axes, which allows producing 3D textiles. Out-of-plane properties of 3D composites enable optimized design, strong delamination resistance, and improved mechanical properties in all directions. These characteristics are among the criteria for aerospace (such as wing panels, landing gear, rocket nozzles, etc.) and automotive applications.

Composites used in the manufacturing of commercial aircraft, helicopters, and military jets have undergone many developments in the aerospace industry. Up to 20% strength-to-weight ratios, decreased fuel consumption, improved aerodynamics, cheaper production costs and wear and fire resistance are only a few of the advantages of textile composites. In addition to instrument panels, fuselage skin panels and propeller fairings, composites are used in interiors such as baggage compartments and cargo liners. Aramid fibres are utilized in fairings, unloaded bearing components, and radomes, while glass fibres are employed in tiny passenger aircraft parts and heavily loaded parts.
Among the many applications for carbon fibre are satellites, antenna dishes, missiles, and the fundamental structural elements of such vehicles. Glass/phenolic prepreg skin plies cover most of the Nomex honeycomb core in interior sandwich panels, whereas glass/epoxy or carbon/epoxy composite floor panels are commonly employed [16, 17].

Delamination and fissures can develop between layers in composite constructions since they are many ply layers. In light of aeroplanes stringent safety and reliability standards, 3D textile-based composites are a viable option [18].

Compared to conventional metallic materials, glass fibre composites in the automotive sector provided weight savings of up to 25% and up to 40% [19]. An electric vehicle battery range can be increased by up to 10% with a 10% weight decrease in the vehicle frame. In addition, reducing the weight of heavy-duty trucks improves their ability to carry cargo. Military vehicles can also benefit from enhanced performance, survivability and operational support [20].

Automotive composites recycling includes disassembly, debonding, and extracting pieces from the vehicle. It is challenging to separate individual elements with composites while keeping their original features. Recyclable materials can be separated by melting them, using pyrolysis to remove high-value carbon fibres from thermosets, and incinerated to recover the energy in composite materials. Chopped composite materials can also be employed as filler in other applications [9, 21].

3 OVERVIEW OF TEXTILE CONSTRUCTION PROCESSES

3.1 Developments in embroidery technology for three-dimensional preforms

Embroidery is a traditional textile decorative method. The ability to create three-dimensional lightweight constructions and lay threads on the base material in all directions has given embroidery great potential in many innovative functional applications.

In this sphere, Tailored Fiber Placement (TFP) is an embroidery-based processing approach used in 3D preform production. As a result of this technology, a fibre or roving can be placed on the ground to create three-dimensional constructions and vast design possibilities in technological applications, including heating grids, shielding, conductive linkages, and intelligent textile sensors and interfaces (Figure 1). The approach can also use conductive threads, metal wires, layered polymer, and carbon fibres.

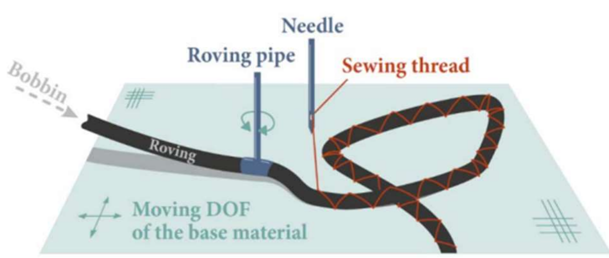

Figure 1: Scheme of the TFP-process [15] left, CTT Group TFP set up (right).

Preform layers are attached to the base material (support layer) using carbon or glass textiles, thermoplastic films, elastomer sheets, and water-soluble substrates. Woven base layer material that extends beyond the fibre blank is either cut or pulled off before being placed in the machine. First, the support layer is included in the fibre blank itself. It does nothing but adds weight to the goods. Fibre blanks that are placed on top of each other are crucial. In addition, the base layers of the finished composite part may separate. When it comes to removing the base material, it is recommended to be used as an auxiliary material. Another issue, however, is that in the event of a base separation, mechanical damage to reinforcing fibres and a violation of the blank's integrity and geometry are very likely occurrences.

An embroidered reinforcement can be applied to a variety of engineering fields. The anisotropic properties of composite reinforcements generated using the TFP technology result from the strong influence of fibre orientation on the stresses in the components. Analytical and numerical methods can be used to model the physical properties of the embroidered structure. When compared to other textile technologies, the

TFP has various advantages. Repetitive placement of fibres on a single region allows local thickness variations in the composite preform. TFP lay-up process allows fibre placement angles ranging from 0° to 360°. This technique minimizes waste and maximizes fibre utilization by enabling near-net-shape manufacturing. In addition, the development of a fibre placement pattern for the embroidery machine takes minimal development time and expenses to implement.
Chemical embroidery, developed initially to manufacture machine-made lace, is another processing method that has found its way into technological applications. The design is often created with water-soluble or heat-destructible materials. Water-soluble substrates have a distinct advantage over woven fabrics, elastomers, and films. The washout of these substrates is economical. When the fibre blank is removed from the water-soluble substrate, there can be a risk of damaging the fibres or changing their shape. This way requires an additional step for solubilizing the substrate (required warm water or other processes), and a drying time is needed.
Another benefit of embroidery is its ability to build structures that are both dimensionally stable and highly repeatable. In addition, rapid prototyping is made possible by using CAD software in pattern design. The chosen fibre course is turned into a software pattern embroidered by an embroidery machine on a base material. However, even though the major part of the embroidery can be automated, it still requires manual intervention.

Because of the limited technical capabilities of embroidery equipment and the limited length of the needle, TFP technology has a fundamental drawback: it can only produce preforms 8-10 mm thick per process operation. Each succeeding patch layer must be connected to the previous one, and the operating principle of embroidery machines dictates that each patch layer must be connected to the initial one as well. Layers add extra needle punches marks to previous preform layers. To the base fibre, the substrate suffers the most damage. This negatively impacts the composite strength because of the numerous fibres being destroyed during the preform manufacturing process, in the case where the substrate is kept in the preform structure, despite their increased shear strength and physical and mechanical qualities which they share with typical polymer materials. Additionally, TFP technology allows for local reinforcements (for example, around the holes), various materials, reinforcing directions and optimizing of material elastic properties [15].

3.2 Developments in braiding technology for three-dimensional preforms

Textile industry methods used to process yarns into the fabric and the specific fibre structures from those operations set braiding apart from weaving and knitting as classical textile processes. Weaved and knitted fabrics are made by orthogonal interlacing of yarns, but interloping yarns form braided fabrics. The main distinction is that the braided produces nonorthogonal multidirectional fabrics without any loops.
When at least three yarn systems are employed, braiding is considered 3D [22]. Complex preforms and components such as tubes with T, I, and J cross-sections can be made using 3D braiding rather than 2D braiding. 3D braiding machines, on the other hand, are slow and pricey. However, they offer the possibility to create multiple layers preforms with no delamination using the multi-axis approach, which uses yarns in numerous orientations and planes [23, 24].

The complexity of 3D braiding processes and machinery is far greater than that of 2D braiding. The primary premise of the braiding process is that two or more sets of yarn carriers (bobbins) move down a track in opposing directions, resulting in yarn interlacing at an angle biassed to the machine axis. The yarns are threaded through the bobbins that travel in a preset direction to create the braided design. Since the diameter of the braiding machine limits the design possibilities, it becomes prohibitively expensive to achieve enormous diameters [3]. On the other hand, braiding has been identified as one of the most

effective techniques in producing low-cost, high-volume composites. In braided constructions, the mechanical characteristics of braiding machines and the intrinsic features of braided fabrics contribute to their total engineering capability.
Braiding is an excellent solution for systems with a mix of materials and quick runs. It is common for braids to be used in various industrial applications, from aerospace and automotive to civil infrastructure and engineered composites. Aerospace propellers, tether struts, inflatable structural beam rocket nozzles, bicycle frames and wheels, and monocoque vehicle chassis are just some of the high-performance commercial uses that may be found in these high-performance products. There will be more and more uses for braids in the future as engineering design and industrial development.

Low cost, manufacturability, higher mechanical performance, absence of corrosion, reparability and recyclability, excellent damping and fuel economy, and low noise level are all requirements for transportation 2D and 3D braided constructions. 3D braided preforms are widely documented for their unique structural properties and performance qualities. Delamination suppression in its entirety, better damage tolerance, impact resistance, fatigue life, outstanding torsional resistance, good bolt bearing strength, superior skin-stiffener pull-off strength, etc., are just a few of the many benefits [25]. As an added benefit, using 3D braided integral, seamless, complex near-net-shape preforms instead of 2D prepreg or fabric plies, tape slitting, or prepregging eliminates many labour-intensive activities from the manufacturing cycle.

Depending on the desired shape, braid-based composite structures can be made by draping the braided sleeve over a mandrel or over braiding the mandrel. This allows for three yarn directions to be implemented when employing radial braiding machines in the performing procedure.
Braided sleeves are made by interlacing many threads together. The yarn is coiled on bobbins and placed on carriers of a braiding machine to automate the braiding operation. In a sinusoidal path, the carriers flow in opposing directions. Biaxial braid is the name given to the fundamental braid that is constructed in this manner. Between 30 degrees and 70 degrees can be achieved depending on how quickly the braid or mandrel exits the machine or is steered through it.
The most prevalent application for biaxial braids (Figure 2(a)) is when the component is subjected to a torsional load. It is possible to create a triaxial braid (Figure 2(b)) by including a fourth yarn direction. A yarn with a zero-degree angle is called a 0° yarn. Their bobbins are located on the outside of the machine and are sandwiched between two braiding strands that cross one other. Using 0° yarns to reinforce the material is a good idea when the component is subjected to a flexural load.

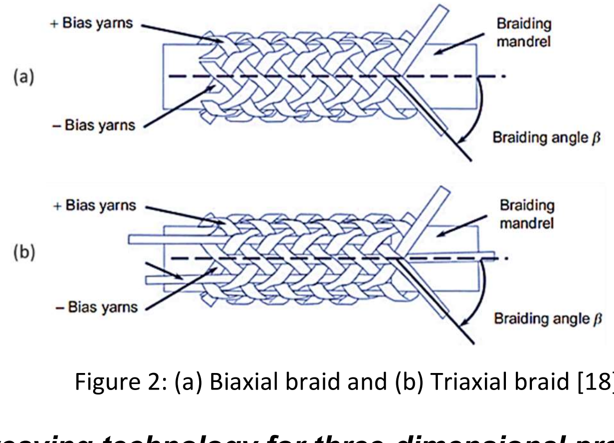

Figure 2: (a) Biaxial braid and (b) Triaxial braid [18].

3.3 Developments in weaving technology for three-dimensional preforms

Weaving is an ancient technology that is remarkable in its ability to intertwine linear materials from perpendicular directions in many different ways to create an integrated structure. For a long time, only materials from the warp and weft directions could be used to make a sheet (i.e. fabric). The woven structures can be categorized as two-dimensional (2D) and three-dimensional (3D) fabrics. Another category of woven fabrics is multilayer fabrics, also called 2.5D fabrics [26].

Two-dimensional (2D) fabric sheets are drapable, flexible, warm, and sturdy, making them useful for clothing and other applications. 2D textiles can be made with high-performance fibres like glass, carbon, and aramid, which can be used for textile composite reinforcements in the aerospace sector [27].
Multilayered constructions (2.5D fabrics/preforms) can also be made using regular looms. The warp yarns are organized in columns (via a single reed tooth), and the weft yarns are inserted using a picking mechanism [26]. The thread counts of different fabric layers are used to bind them together. Multilayer (2.5D) interlock structures are categorized as orthogonal interlock structures and angle interlock structures [26].

Three-dimensional (3D) fabrics can also be created through weaving, using layers of fabrics or yarns to add additional thickness and special looms: creel for warp alimentation, positive rapier or shuttle weft insertion, and specific areas selvages devices. Thick textiles have the immediate advantages of structural integrity, geometric shape satisfaction, and volume for many end-use applications. The weaving process can also leave crimped or straight strands in fabrics depending on the application's requirements. A wide range of 3D fabrics, primarily used in the composites industry, can now be made with custom weaving machines[28]. Many different varieties of 3D weaves exist, and their selection is based on the end-use and performance parameters of the 3D preforms intended for. 3D weaves are created by altering or combining the three fundamental weaves (plain, twill, and satin). Typical examples of a layer-to-layer interlock weave with different methods are shown in Figure 3.

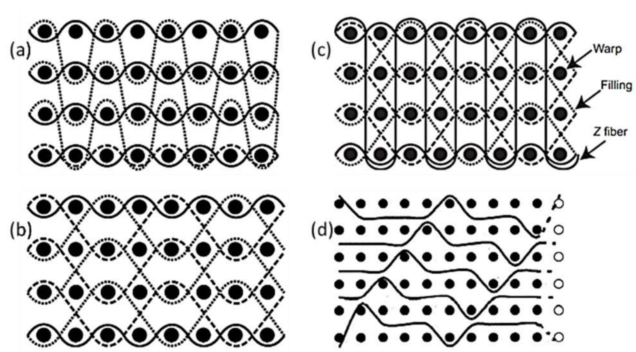

Figure 3: Typical layer-to-layer interlock weave: (a) based on a plain weave, (b) based on twill weave connection, (c) with Z fibres, (d) based on a satin weave [18].

Weave selection is really crucial. In 3D textiles and 3D preforms, the choice of weave architecture is based on the intended use and the performance parameters that must be met. A mixture weave pattern is often chosen based on the end product's performance requirements. It is possible to build thick panels with a mix of interlocking and orthogonal weave and attain optimal performance properties while keeping the layers in place without breaking apart. Figure 3(b) shows a layer-to-layer interlock weave based on the plain weave for multilayer panels or 3D preforms. The warp end or weft is used when two layers are stitched together. Only a section of a layer, not the entire structure, will crumble if the binding threads are damaged. Even though it's one of the most important advantages of interlacement, it also lowers tensile strength since the interlacing compresses fibres.

4 PRODUCTS EXAMPLES AND PROPERTIES

CTT Group is equipped with several 3D preform prototyping machines. Many successful projects have been developed over the years.
In collaboration with Ruiz Aerospace Manufacturing and Bell Helicopter Textron Canada (BHTC), ways to improve the energy efficiency of a vertical lift vehicle were investigated. This study compared blades made with traditional carbon fibre prepreg and a new 3-dimensional (3D) braided fibre reinforcement approach. The carbon fibre braided preform was developed using a Kuka 6-axe robot paired with a Herzog triaxial braiding machine to create 3D geometries. A key challenge for this project was the design of a reusable multi-piece braiding mandrel that could also be used for liquid resin injection and capable of withstanding large production volumes [28].

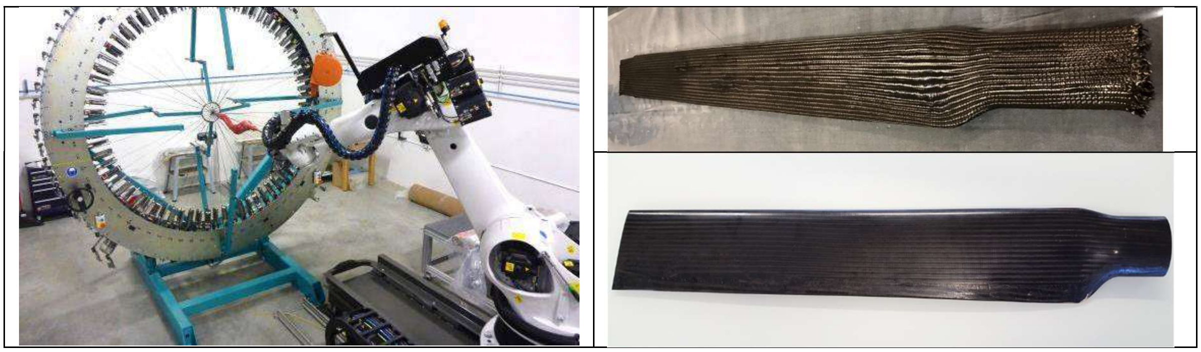

Figure 4: Automated braiding method using a multi-axial braiding ring and a 6-axe robot (left), Finalized braided mandrel before and after moulding (right) [28].

In collaboration with Dimension Composite Inc., ways to improve the efficiency of structural parts of a train were investigated. In that study, a polypropylene non-woven sandwiched between 2 bi-axial glass fabrics was proposed as an alternative to a traditional equilibrated glass mat. The proposed architecture was built up in one piece using the TFP embroidery machine. The 2.5D preform was infused by liquid resin transfer moulding (LRTM), and a comparison was made to the original composite part in 4mm thickness. The conclusion was that in addition to offering a large-scale manufacturing perspective, the 2.5D preform offers a lighter structure which is 25% more resistant to impact.

Table 1: Comparison table between the 2.5D preform and the equivalent traditional composite part.

	Composite: 4 mm (LRTM)	Composite: 4mm (3D preform)	Comparison
Average thickness (mm)	4.50	4.04	90%
Density (g/cm3)	1.54	1.50	97%
Textile reinforcement (%):	25.4	19.15	75%
Mineral charges (%):	15.95	17.3	108%
Tensile strength (Mpa)	100	91	90%
Tensile Modulus (Gpa)	9.24	8.56	93%
Impact strength (J/m):	577.7	714.8	124%

5 Conclusions

Because of its many advantages, such as structural integrity, lightweight, and high performance, 3D textiles have been actively explored as preforms for advanced composites. 3D textile fabrics and their manufacturing processes have been examined in this paper.

In discussing 3D textile preforms, this paper reviewed the embroidery, braiding and weaving technologies used in the 3D textile preforms manufacturing. While these technologies can produce large-scale 3D woven fabrics, their integration is still a challenge in the textile Industry compared to traditional weaving machines.

Depending on the weave geometries, 3D textiles can produce reinforcement preforms for board-shaped and tapered composites and constituent sections in various 3D textiles, such as 3D nodal and shell structures. They also offer undeniable advantages such as large-scale production, weight optimization, cost-effective manufacturing techniques and less part count. Finally, the 2.5 D preform presented as an example and all these advantages showed 25% more impact strength than the equivalent hand lay-up part.

6 REFERENCES

[1] Bilisik, K., Multiaxis three-dimensional weaving for composites: a review. Textile Research Journal, 2012. 82(7): p. 725-743.

[2] Saboktakin, A., 3D textile preforms and composites for aircraft strcutures: A review. International Journal of Aviation, Aeronautics, and Aerospace, 2019. 6(1): p. 2.

[3] Ishmael, N., et al., Textile technologies for the manufacture of three-dimensional textile preforms. Research Journal of Textile and Apparel, 2017.

[4] Potluri, P., et al., Geometrical modelling and control of a triaxial braiding machine for producing 3D preforms. Composites Part A: Applied Science and Manufacturing, 2003. 34(6): p. 481-492.

[5] Gokarneshan, N., et al., Engineering knits for versatile technical applications: some insights on recent researches. Journal of Industrial Textiles, 2012. 42(1): p. 52-75.

[6] Sondhelm, W.S., Technical fabric structures–1. Woven fabrics. Handbook of technical textiles, 2000. 12: p. 62.

[7] Ray, S.C., Fundamentals and advances in knitting technology. 2012: CRC Press.

[8] Aly, N.M. A review on utilization of textile composites in transportation towards sustainability. in IOP Conference Series: Materials Science and Engineering. 2017. IOP Publishing.

[9] Demiral, M., et al., Damage analysis of a CFRP cross-ply laminate subjected to abrasive water jet cutting. Alexandria Engineering Journal, 2022. 61(10): p. 7669-7684.

[10] Habibi, M., G. Lebrun, and L. Laperrière, Experimental characterization of short flax fiber mat composites: tensile and flexural properties and damage analysis using acoustic emission. Journal of Materials Science, 2017. 52(11): p. 6567-6580.

[11] Habibi, M., L. Laperrière, and H. Mahi Hassanabadi, Replacing stitching and weaving in natural fiber reinforcement manufacturing, part 1: mechanical behavior of unidirectional flax fiber composites. Journal of Natural Fibers, 2019. 16(7): p. 1064-1076.

[12] Habibi, M., L. Laperrière, and H.M. Hassanabadi, Replacing stitching and weaving in natural fiber reinforcement manufacturing, part 2: Mechanical behavior of flax fiber composite laminates. Journal of Natural Fibers, 2018.

[13] Habibi, M., et al., Effect of surface density and fiber length on the porosity and permeability of non-woven flax reinforcement. Textile Research Journal, 2018. 88(15): p. 1776-1787.

[14] Khodunov, A., V. Bogachev, and A. Borodulin. Advances in tailored fiber placement technology. in Journal of Physics: Conference Series. 2021. IOP Publishing.

[15] Tanasa, F. and M. Zanoaga. Fiber-reinforced polymer composites as structural materials for aeronautics. in Proceedings of the International Conference of Scientific Paper, Brasov, 23–25 May 2013. 2013.

[16] Yancey, R., How composites are strengthening the aviation industry. Industry Week,[online] Available at: http://www. industryweek. com/none/how-composites-arestrengthening-aviation-industry, 2012.

[17] Islam, M.A., 9 - 3D woven preforms for E-textiles and composites reinforcements, in Advances in 3D Textiles, X. Chen, Editor. 2015, Woodhead Publishing. p. 207-263.
[18] O'Brien-Bernini, F., Composites and sustainability — when green becomes golden. Reinforced Plastics, 2011. 55(6): p. 27-29.
[19] Cresko, J., et al., Innovating clean energy Technologies in advanced manufacturing. Quadrennial Technology, 2015.
[20] Metz, B., et al., Climate change 2007-mitigation of climate change. 2007, Intergovernmental Panel on Climate Change, Geneva (Switzerland). Working ….
[21] Wendland, B., et al., Three-dimensional composite manufacturing processes, in Advances in Composites Manufacturing and Process Design. 2015, Elsevier. p. 131-146.
[22] Bilisik, K., N.S. Karaduman, and N.E. Bilisik, Applications of braided structures in transportation. Braided Structures and Composites: production Properties Mechanics and Technical Applications, Taylor and Francis, Milton Park, 2015.
[23] Bilisik, K., Three-dimensional braiding for composites: A review. Textile Research Journal, 2013. 83(13): p. 1414-1436.
[24] Bogdanovich, A.E., 1 - An overview of three-dimensional braiding technologies, in Advances in Braiding Technology, Y. Kyosev, Editor. 2016, Woodhead Publishing. p. 3-78.
[25] Umair, M., et al., development and characterization of three-dimensional woven-shaped preforms and their associated composites. Journal of Reinforced Plastics and Composites, 2015. 34(24): p. 2018-2028.
[26] Unal, P.G., 3D woven fabrics, in Woven fabrics. 2012, IntechOpen.
[27] Chen, X., L. Taylor, and L.-J. Tsai, Three-dimensional fabric structures. Part 1–An overview on fabrication of three-dimensional woven textile preforms for composites. Handbook of Technical Textiles, 2016: p. 285-304.
[28] Deronde, V., et al., development of a textile process for composite rotor blades, SAMPE Europe 2021