MECH 6521
Manufacturing of Composites

Project Report on

4D Printing from CFRP Composite to Make the Letter "S"

Group II

Yash Chauhan	40156647
Krushil Dharmeshbhai Navadiya	40153144
Sahil Patel	40171642
Aditya Kale	40156585
Smit Jayantilal Kansagara	40184514
Bhargavkumarsinh Chavda	40186919
Jagadeshwar Baskararaja	40198766
Belhafnaoui Mohamed Ali	40224122

Gina Cody School of Engineering and Computer Sciences
Department of Mechanical, Industrial, and Aerospace Engineering
Concordia University

December 2021

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Abstract

This report discusses the manufacturing of a Carbon-Fibre Reinforced Polymer (CFRP) structure in the shape of the letter "S". The method adopted for this project is the 4D printing of composite materials. The structure consisted of 5 layers in total; 1 24-inch-long 0° layer (spine) and 4 90° layers of 13 inches each. The 90° layers are placed in 2 with each pile facing different directions and on opposite ends of the spine.

The final product produced in this experiment was found to adhere with the project guidelines and achieve the design goals that were set beforehand. The structure manufactured accurately portraits the letter "S". It has also been tested against buckling and found that it can support its own weight without distorting the shape too much.

The letter's dimensions are 45.2 cm in height, 11.3 cm in width, and 7.7 cm in depth.

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1 Introduction

A combination of two materials with different properties is known as a composite material. Advanced Composite materials have been used to manufacture different parts and structures across all engineering field applications. Owing to their valuable properties such as light weight, high stiffness, excellent corrosion resistance these materials are abundantly used. Availability of vast fabrication techniques enabling the composite material to form complex shapes is one of the major reasons to select composite materials over the use of conventional metallic surfaces [1].

The technique used to make complex shapes without the use of a mould, 4D printing is a process that combines 3D printing with the application of some activating agent in order to change the shape of the manufactured part after the process. Complex forms can be formed from flat surfaces, but the shape of final component (degree of cure) depends upon the type of manufacturing process used, the material used, orientation of fibre and hand lay-up sequence [2].

The proper usage of 4D printing of composite materials have proven beneficial the following sectors [3]:

- 4D printed materials are used in field of defence and protection which can change their shape according to environmental condition change
- Aerospace industry
- Automobile sector (Composites leaf spring)
- Composites omega stiffeners
- Robotics, Sensors and Flexible Electronics
- Prostheses application in medical field
- Space structures like satellites (PEEK)
- Wind turbine blades and Sport equipment
- Architecture and Civil Infrastructure

The theory used to predict the shape or curvature of final product is known as laminate theory [2]. In order to find out how exactly 4D printing of composites is carried out the layup sequence of the letter 'S' has been developed and explained below.

This paper discusses the 4D printing processes by which the "S" letter was manufactured. It also discusses and analyses the results of this exercise.

2 Composite Configuration

4-D printing is the technique similar to 3-D printing where the successive layer of deposited material gets deformed with time. This characteristic can be exploited to create curved-geometry items without the usage of a complicated mould. Thus, it is also called as "mouldless composites manufacturing". In general, there are 4 mechanisms for formation of the complex shaped products. These are as follows.

2.1 Shape of symmetric laminates

Laminates which possess both material and geometric symmetries with respect to the mid surface of the full laminate are called as symmetric laminates. Alike lamina orientations above and below the mid-surface is geometric symmetry, whereas material symmetry results in all laminae made up of same material or symmetrical opposite laminae having the same material. We all should know that the symmetric laminates with layup sequence of $[0/90]_s$ or $[0_n/90_n]_s$ remains flat after curing and cooling to the room temperature. These kinds of laminates are used as base for the letters.

2.2 Shape of Unidirectional laminates

Laminates in which substantially all of the fibres are parallel are known as unidirectional laminates. Irrespective of any number of layers, these equally oriented laminae remain flat. For example, consider laminate having a combination $[0]_2$ and $[0]_2$ which sums up to $[0]_4$, all along 0° direction, these laminates remain flat after curing and cooling.

2.3 Shape of Cross ply laminates

A cross-ply laminate is made up of an indefinite number of plies, each of which has a fibre orientation of 0° or 90° and can be symmetric or anti-symmetric. The reconfiguration of thermoset matrix composites during curing and cooling can be attributed to two mechanisms: resin shrinkage due to chemical reactions between the molecules in the resin, and mismatch in coefficients of thermal contraction along different directions in different layers in the laminate during cooling from the cure temperature to room temperature. In the reference [2], the principle of altering shape from flat to curved has been demonstrated. Here, the cross-ply laminate is used to obtain the curvatures in letter “S”. The composite layup sequence for letter “S” is shown below in Figure 1.

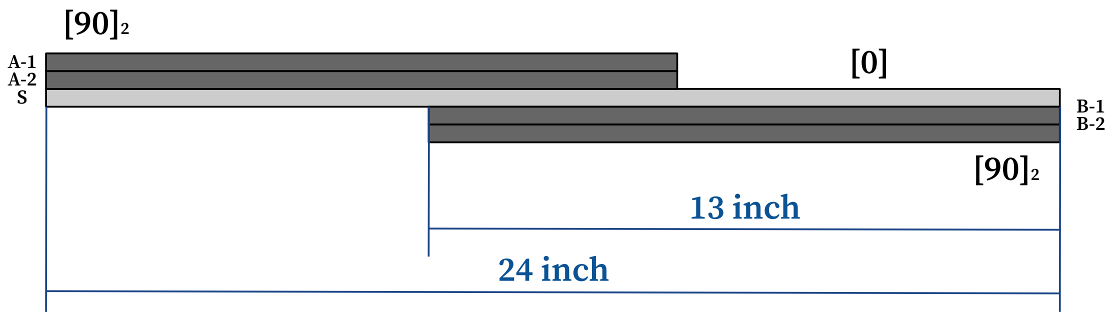


Figure 1: Layup sequence of the letter "S"

The reconfiguration may be evaluated using laminate theory due to the relative thinness of the structure. The approach indicated below can be used to determine the stresses and curvatures owing to shrinkage and thermal effects.

The properties of laminates made up of a number of laminae stacked in a specific order can be derived from the lamina properties.

$$A_{ij} = \int \overline{Q_{ij}} dz \tag{1}$$

$$B_{ij} = \int \overline{Q_{ij}} z dz \tag{2}$$

$$D_{ij} = \int \overline{Q_{ij}} z^2 dz \tag{3}$$

$$i, j = 1, 2, 6$$

And,

$$\overline{Q_{11}} = Q_{11}\cos^4\theta + 2\left(Q_{12} + 2Q_{66}\right)\cos^2\theta\sin^2\theta + Q_{22}\sin^4\theta \tag{4}$$

$$\overline{Q_{12}} = \left(Q_{11} + Q_{22} - 4Q_{66}\right)\cos^2\theta\sin^2\theta + Q_{12}\left(\cos^4\theta + \sin^4\theta\right) \tag{5}$$

$$\overline{Q_{16}} = \left(Q_{11} - Q_{12} - 2Q_{66}\right)\cos^3\theta\sin\theta + \left(Q_{12} - Q_{22} + 2Q_{66}\right)\cos\theta\sin^3\theta \tag{6}$$

$$\overline{Q_{22}} = Q_{11}\sin^4\theta + 2\left(Q_{12} + 2Q_{66}\right)\sin^2\theta\cos^2\theta + Q_{22}\cos^4\theta \tag{7}$$

$$\overline{Q_{26}} = \left(Q_{11} - Q_{12} - 2Q_{66}\right)\cos\theta\sin^3\theta + \left(Q_{12} - Q_{22} + 2Q_{66}\right)\cos^3\theta\sin\theta \tag{8}$$

$$\overline{Q_{66}} = \left(Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66}\right)\sin^2\theta\cos^2\theta + Q_{66}\left(\cos^4\theta + \sin^4\theta\right) \tag{9}$$

Where,

$$n = \sin\theta \tag{10}$$

$$m = \cos\theta \tag{11}$$

And,

$$Q_{11} = \frac{E_1}{1 - \nu_{12}\nu_{21}} \tag{12}$$

$$Q_{12} = \frac{\nu_{21}E_1}{1 - \nu_{12}\nu_{21}} = \frac{\nu_{12}E_2}{1 - \nu_{12}\nu_{21}} \tag{13}$$

$$Q_{22} = \frac{E_2}{1 - \nu_{12}\nu_{21}} \tag{14}$$

$$Q_{66} = G_{12} \tag{15}$$

Where E_1, E_2, G_1, ν_{12} and ν_{21} are the moduli and Poisson ratios of a 21-layer system respectively. Therefore, the stresses and curvatures of a laminate subject to a temperature change ΔT have the following relationships.

$$\begin{bmatrix} N_x^T \\ N_y^T \\ N_{xy}^T \\ M_x^T \\ M_x^T \\ M_{xy}^T \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} \epsilon_x^0 \\ \epsilon_y^0 \\ \gamma_{xy}^0 \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix} \tag{16}$$

Where the column on the left hand side indicates thermal stress and thermal moment resultants, the column on the right side shows in-plane strains and curvatures at the laminate's mid plane, and the square matrix represents laminate stiffness components.

The below are the thermal stress and thermal moment resultants.

$$N_x^T = \int_{-\frac{H}{2}}^{\frac{H}{2}} \left(\overline{Q_{11}}\alpha_x^T + \overline{Q_{12}}\alpha_y^T + \overline{Q_{16}}\alpha_{xy}^T\right) \Delta T dz \tag{17}$$

$$N_y^T = \int_{-\frac{H}{2}}^{\frac{H}{2}} \left(\overline{Q_{12}}\alpha_x^T + \overline{Q_{22}}\alpha_y^T + \overline{Q_{26}}\alpha_{xy}^T\right) \Delta T dz \tag{18}$$

$$N_{xy}^T = \int_{-\frac{H}{2}}^{\frac{H}{2}} \left(\overline{Q_{16}}\alpha_x^T + \overline{Q_{26}}\alpha_y^T + \overline{Q_{66}}\alpha_{xy}^T\right) \Delta T dz \tag{19}$$

$$M_x^T = \int_{-\frac{H}{2}}^{\frac{H}{2}} \left(\overline{Q_{11}}\alpha_x^T + \overline{Q_{12}}\alpha_y^T + \overline{Q_{16}}\alpha_{xy}^T\right) \Delta T z dz \tag{20}$$

$$M_y^T = \int_{-\frac{H}{2}}^{\frac{H}{2}} \left(\overline{Q_{12}}\alpha_x^T + \overline{Q_{22}}\alpha_y^T + \overline{Q_{26}}\alpha_{xy}^T\right) \Delta T z dz \tag{21}$$

$$M_{xy}^T = \int_{-\frac{H}{2}}^{\frac{H}{2}} \left(\overline{Q_{16}}\alpha_x^T + \overline{Q_{26}}\alpha_y^T + \overline{Q_{66}}\alpha_{xy}^T\right) \Delta T z dz \tag{22}$$

Where α_{ij}^T are the thermal expansion coefficients, which are given as follows.

$$\begin{bmatrix} \alpha_x^T \\ \alpha_y^T \\ \alpha_{xy}^T \end{bmatrix} = \begin{bmatrix} m^2 & n^2 & 0 \\ n^2 & m^2 & 0 \\ 0 & 0 & 2mn \end{bmatrix} \begin{bmatrix} \alpha_1^T \\ \alpha_2^T \\ \alpha_1^T - \alpha_2^T \end{bmatrix} \tag{23}$$

As such, the deformation of the laminate owing to shrinkage during curing, or cooling down from either the curing temperature or processing temperature, can be achieved by getting the strains and curvatures using the inverted matrix as follows.

$$\begin{bmatrix} \epsilon_x^0 \\ \epsilon_y^0 \\ \gamma_{xy}^0 \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{16} & b_{11} & b_{12} & b_{16} \\ a_{12} & a_{22} & a_{26} & b_{21} & b_{22} & b_{26} \\ a_{16} & a_{26} & a_{66} & b_{61} & b_{62} & b_{66} \\ b_{11} & b_{21} & b_{61} & d_{11} & d_{12} & d_{16} \\ b_{12} & b_{22} & b_{62} & d_{12} & d_{22} & d_{26} \\ b_{16} & b_{26} & b_{66} & d_{16} & d_{26} & d_{66} \end{bmatrix} \begin{bmatrix} N_x^T \\ N_y^T \\ N_{xy}^T \\ M_x^T \\ M_x^T \\ M_{xy}^T \end{bmatrix} \tag{24}$$

N.B: Equations are from [4].

2.4 Function of non-stick separator

When the deposited layers come into touch with each other at first, they have a tendency to link together following curing and solidification. Therefore, a non stick separator is used to prevent the bonding of two successive layers such as base layer and the laminate. During laying up the letter “S”, thin caul separator was not required as all layers stick together with the middle 0° lamina base.

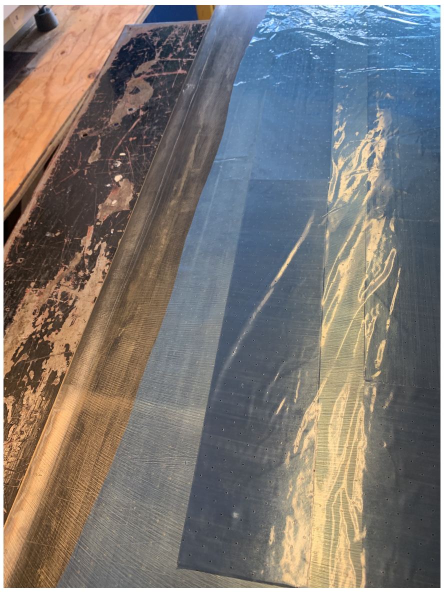
3 Procedure

The principle of mouldless manufacturing of a laminate to form a specific shape is to make it unsymmetrical such that the residual stresses curve the composite to the desired shape.

This project consisted of using prepregged CFRP layers of uniform thickness and a single fibre direction (90° and 0°). The total length of the composite before curing (straight) is of 24 inches. This consists of 1 [0°] of 24 inches, and 4 [90°] layers of 13 inches each. The middle layer [0°] is placed on the dimensioned work mat. Two [90°] layers are sticked to the [0°] layer on top and 2 on the bottom side such that these are in opposite ends of the middle layer [0°]. The length of the [90°] layers is 13 inches such that there is a 1-inch-long overlap area. This serves two purposes in the design; a semi-flat middle section area to emphasise the look of letter “S”, and to avoid a stress concentration point in which only 1 layer is cross-sectionally present.

The prepreg layers are applied such that the protective tape is removed first, and the layer is sticked where it is supposed to go.

The composite is prepared for the autoclave following these steps. First aluminum plate is cleaned using acetone, followed by a release agent [Locktite 44 NC], then a high temperature double-sided silicon tape is placed around the edges of the plate. The composite is then placed on top of the plate. The release material (non-stick film) is then placed on top of the composite, followed by a bleeder layer and a breather layer.



(a) Non-stick Film

(b) Bleeder and Breather

Figure 2: Preparation Layers

The vacuum bag is then placed with holes punched in to install 2 valves for the autoclave and the vacuum pump. The vacuum bag is then sealed using the upper side of the double-sided tape while making sure that air cannot leak from anywhere. The vacuum pump is then engaged before the assembly is placed in the autoclave.

(a) Before Vacuum Engaged

(b) After Vacuum Engaged

Figure 3: Vacuum Sealing

The curing of the composite followed a one-step (linear) increase in the autoclave temperature. The trend of temperatures and pressures is as follows in Figure 4.

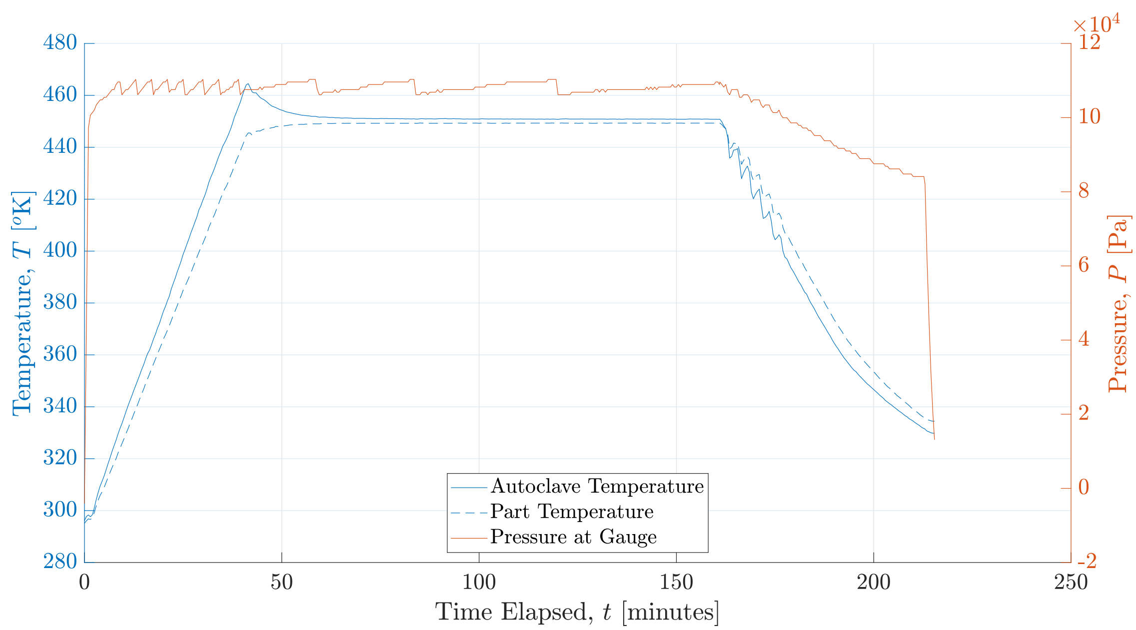


Figure 4: Temperature and Pressure in Autoclave VS Time

The autoclave is programmed to reach a maximum part temperature of 449.3722 °K. This was reached after 85 minutes. The maximum pressure programmed was 110.31 kPa which occurred multiple times during the process, this can be seen through the peaks in Figure 4.

4 Results and Discussion

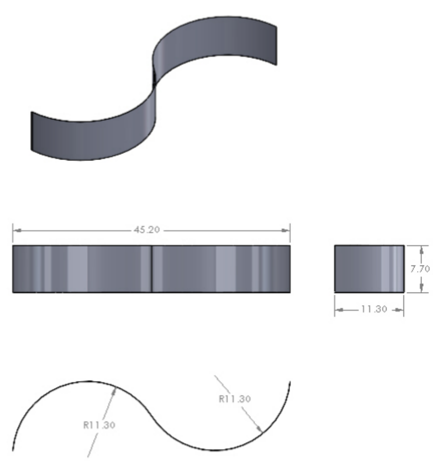
It can be seen from the method of 4D printing of composites can produce composites structures of complex geometry without using the mould. For this project, Prepreg size of 24 inch is given to us so which is suitable for to make exact size and radius letter “S”.After that we arrange 1 layers of 0° and 4 layers of 90°.After the whole process, It is clearly observed from the part that it is like exactly what we expect and did not find any shrinkage and distortion in the part.

By using the CFRP prepreg to make letter “S” by following the steps as mentioned in the procedure section we got the perfect letter “S” which can be seen in Figure 5.

Table 1: Dimensions of the Structure

Specific Dimension	Dimension (cm)
Length	45.20
Radius of Curvature	11.30
Width	11.30
Depth	7.70
Ply Thickness	0.0127

(a) The Final Structure



(b) Generated 3D View

Figure 5: Letter "S"

Factors affecting the final part:

- The amount of curing agent with one particular type of resin can create difference in the amount of shrinkage this can effect on final result.
- The Properties of the constituents is also depend on the resin, type of fibre and volume fraction.
- As there is decrements in the temperature from cure temperature to the room temperature there is change in the modulus of the resin.

Other than the sequence used in this project, different lay-up sequences can be used which would yield similar results to the ones obtained here.

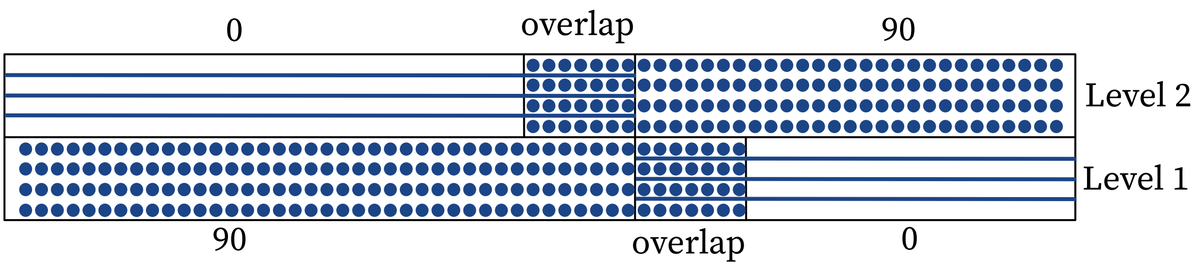


Figure 6: Alternate lay-up sequence for letter "S"

Figure 6 shows the alternate composite lay-up sequence for letter “S”. It shows that the 90° and 0° layers are place at certain length overlapping each other. At second level, the 0° layer is placed on the top of the 90°, and 90° layer is placed on top of 0°.

4D printing is just the beginning of research and development. Therefore, the industry may learn more about it in the near future Ten years. These fabrics are still smart. second-hand Textile and pharmaceutical processes, and the process itself are not unique, but how is this processing implemented? 4D The manufacturing offers the latest products. A business model that meets existing business needs Reduced capital requirements, inventory levels, and time to market Improve the opportunity, and thus the efficiency of the organization.

The main material used in 4D printing is programmable carbon Textile, wood-grain programmable and programmable textiles. The programmable carbon fibre industry is expected to be the largest the entire industry of the 4D printing market.

The advantages of 4D printing are:

- Inexpensive because complex moulds are not required.
- Manufacturing of curved shapes can be fast and economical.
- Increased capabilities of the printed product.
- New application from adaptive materials.
- High manufacturing efficiency.
- Reduced manufacturing cost and less carbon footprint.
- Less space, less volume and lower labour cost.
- Can resist harsh environmental conditions.
- Structures may adapt and change in response to their surroundings.
- Less weight of 4D printed structures cuts a component's mass by 80%.
- Can stimulate and predict the final configuration using Finite element analysis

However, its limitations are found to be:

- Practical experience and knowledge required
- Relatively low modulus as compared to 5D Printing
- Less stable with environmental temperature
- Complex structure and integrated parts manufacturing are complex

5 Future Scope

The concept of the pre-programmed intelligent object will appear to have multiple uses in various industries in the future. The most of apps, on the other hand, are still in the research and development stage as new technologies. The health-care, automotive, aerospace, and consumer industries are expected to be major clients of 4D printing technology. Other industries, such as electronics, manufacturing, and medicine, are likely to have an impact on 4D printing capacity in the near future.

Manufacturers who want to be on the cutting edge of technical advancements and innovations must be aware of technological changes as well as the implications of 4D printing in the future.

Before being widely accepted, 4D printing must overcome numerous technological challenges, including its promising technology. In the future, this technology will be able to support complicated objects, as well as intelligent and long-lasting products.

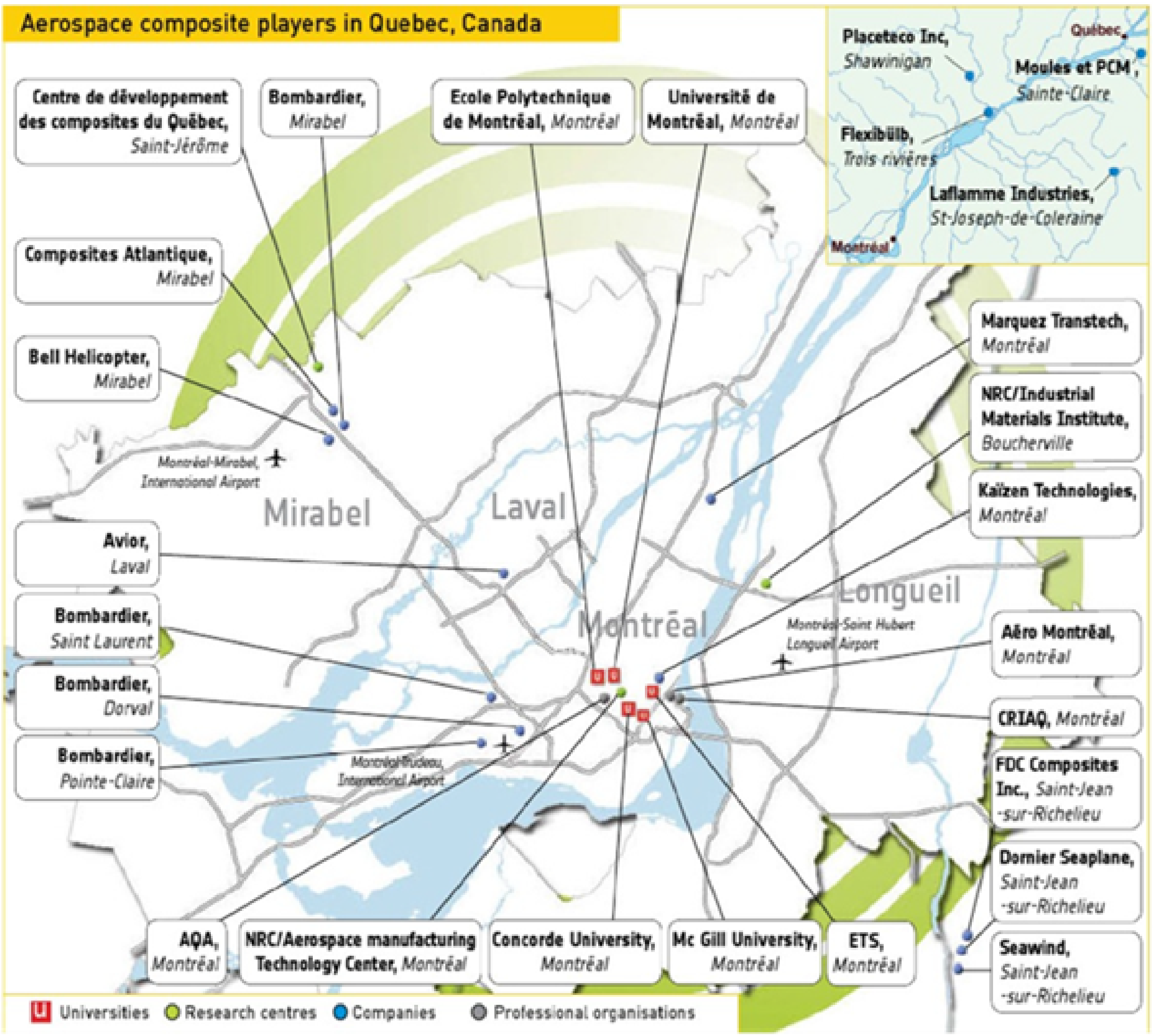


Figure 7: Future Scope in QC, Canada

Industry Analysis and Forecast (2019-2027) for the Global 4D Printing Market – by Material, End User, and Geography: The global 4D printing market has reached \$64.5 million by 2019 and grow at a CAGR of over 33.2% from 2020 to 2025 size is expected to reach \$313.1 million by 2025. This is primarily due to increasing demand in the military and defence, aerospace industry, automotive and healthcare.

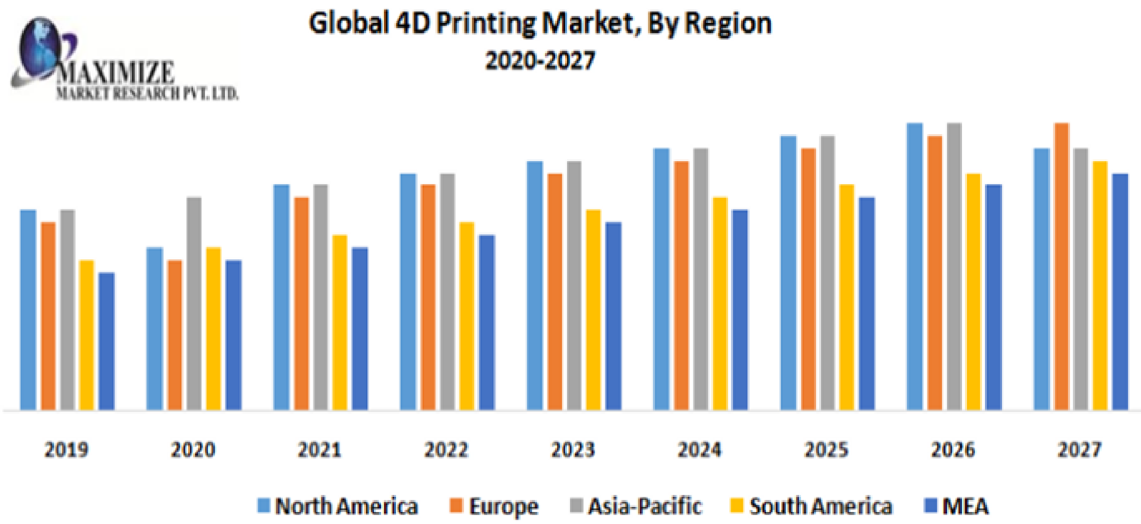


Figure 8: Global market share

Global 4D Printing Market Dynamics [5]:

- The need to reduce manufacturing and process costs and promote a sustainable environment is a major driver of growth in the global 4D printing market. The complexity of intellectual property rights and the high initial costs of development are hampering the growth of the 4D printing market. Compliance with regulatory and performance standards is a challenge for this market
- The global 4D printing market is segmented with the following materials: B. Programmable carbon fibre, programmable wood grain, programmable textiles. The programmable carbon fibre segment is expected to make the largest contribution to the overall market in 2019 with a market share of 62%.
- Early adoption in the aerospace, military and defence, healthcare, and automotive industries. Innovation and product development potential offer many opportunities for the global 4D printing market

Global 4D Printing Market, By Material [5]:

- Programmable Carbon Fibre
- Programmable Wood - Custom Printed Wood Grain

- Programmable Textiles

Global 4D Printing Market, By End User [5]:

- Aerospace
- Automotive
- Clothing
- Construction
- Defence
- Healthcare and Utility

Global 4D Printing Market, By Region [5]:

- North America
- Europe
- Asia Pacific
- Middle East and Africa
- South America

Global 4D Printing Market Key player [5]:

- Autodesk, Inc.
- DassaultSystemes S.A.
- Materialise NV
- Massachusetts Institute of Technology
- Hewlett-Packard, Inc.
- Stratasys, Ltd.
- 3D Systems Corporation
- ExOne Co.

- ARC Centre of Excellence for Electromaterials Science (ACES)
- Organovo Holdings, Inc.
- Organovo Holdings, Inc.
- 4d Printing Inc
- Meta Additive Ltd.
- EnvisionTEC Inc.
- CT CoreTechnologie Group

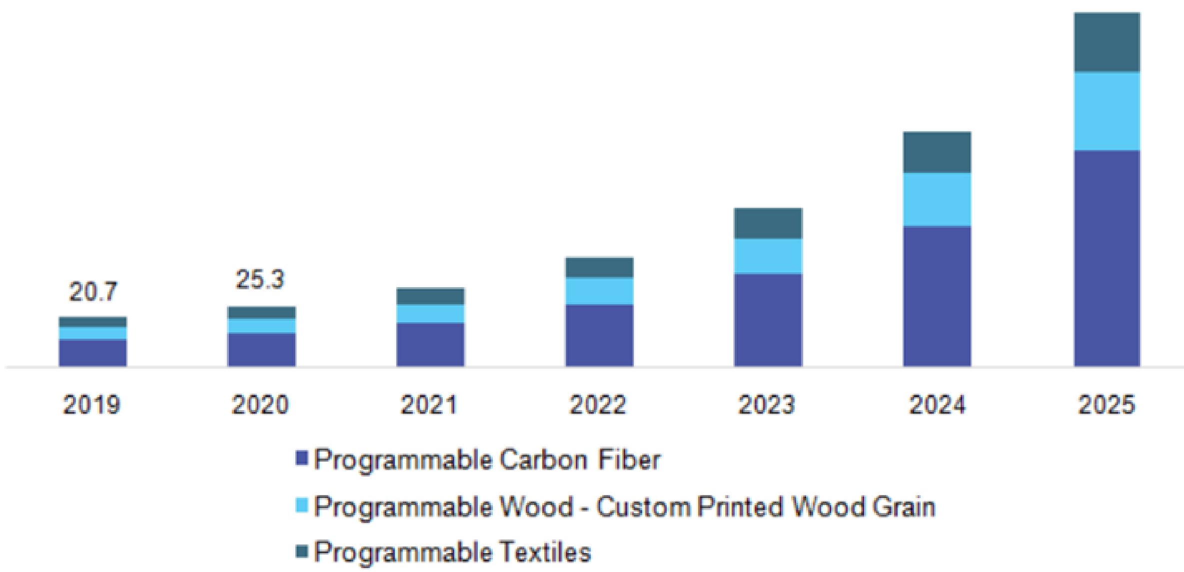


Figure 9: Fiber type use percentile [5]

6 Conclusion

In this report, the layup arrangement for the letter "S" has been described. The 4D printing of the composite material of complex shapes and size is used in such a way that it allows to curve structure without need of any special mould of complex geometry. This has been possible by using prepregs sheets in a flat stack. Upon curing and cooling it to the room temperature, curved laminate has been obtained. The curvature of the composite part mainly be contingent on the asymmetric nature of laminate. The principle of 4D printing can be use successively to manufacture the composite parts with applicable strength and stiffness.

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