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V.I.E.T.N.A.M. by 4D printing of composites

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Abstract:

This paper presents an application of 4D printing of composites (4DPC) to make composite structures of complex geometries without the need for complex moulds. This application is illustrated through the formations of the letters V, i, e, t, n, a, and m, which form the word Vietnam. In the procedure, laminates made of carbon/epoxy prepregs are laid on a flat mould. The deposition of the prepregs on the flat mould is done using an automated fibre placement machine (AFP), which can be considered as a large size 3D printer. For a smaller structure, the prepreg deposition can be accomplished using an AFP machine or by hand lay-up. Upon curing and cooling to room temperature, the laminate transforms itself from a flat configuration to the shape of the intended letter, except for the letter V. The mechanism that enables this transformation relies on the anisotropy of the laminate. This method has many potential applications, particularly in the delivery of bulky three-dimensional structures to remote locations.

Keywords: **alphabet letters, anisotropy, 4D printing of composites.**

Classification number: **2.3**

Introduction

3D printing and 4D printing

3D printing is a well-known manufacturing technique with widespread applications among many areas of society. One of the many 3D printing techniques is fused deposition modelling (FDM). In this technique, melted materials are squeezed through a nozzle of small diameter (fractions of a millimetre). The nozzle is moved by a robotic arm controlled by a computer program. The combination of the motion of the arm, together with controlling of the deposition of the material, provides the ability to produce structures of complex geometries without the need for a complex mould.

In normal 3D printing, the materials remain the same throughout the whole structure. 4D printing is an extension of 3D printing in which the material properties may vary along spatial coordinates [1-4]. Fig. 1 illustrates the concept of 4D printing. For comparison, the figure on the left shows the process of 3D printing where layers of material are deposited to make up a structure. The mandrel used for this deposition is just a simple flat plate. For 4D printing, the materials vary from point to point within the structure. This can be done by changing the materials during the course of the deposition. In Fig. 1, the black colour represents one material and the red colour represents another. Because these materials have different properties, they have different reactions to external stimuli such as the application of heat, electricity, moisture, or light, etc. After a flat stack of material has been deposited, as shown in the left figure, the stack of material is subjected to an external stimulus and this exposure will make the structure change its shape. This process is called self-reconfiguration as shown in the figure on the right. By properly controlling the type of materials and their positions, predetermined complex structures can be obtained.

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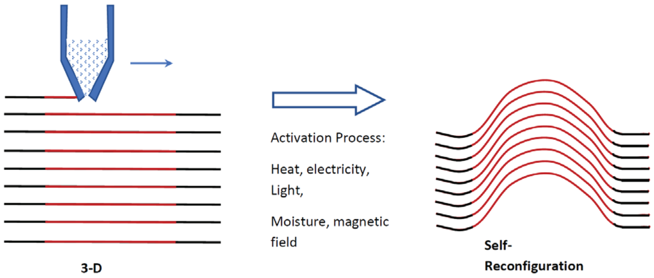

Fig. 1. Concept of regular 4D printing.

4D printing of composites (4DPC)

The 4D printing method described above is usually operated with isotropic materials, such as elastomers and polymers. They have low stiffness (about 1 GPa) and strength (about 10 MPa). Indeed, 4DPC is a method that attempts to utilize long, continuous fibre-reinforced composite materials that have high stiffness (about 180 GPa) and strength (about 100 MPa) along the fibre direction. These materials have been used to construct major engineering structures such as the body of airplanes, automobiles, wind turbine blades, etc. Actually, these are not exotic materials only available in a lab, but are available commercially.

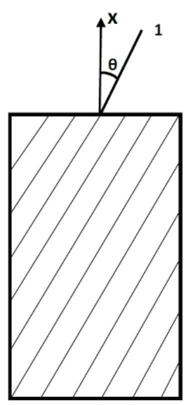

Fig. 2: A typical layer; the fibre direction can be along the length (x direction) of the layer (when θ=0) or off-axis (when θ is different from 0).

The basic element of a laminate is an individual layer (Fig. 2). Each layer has a thickness of about 0.125 mm. For comparison, a hair has a thickness of 0.100 mm. Within each layer, there are many fibres that are made of either carbon or glass. The diameter of each fibre is about 0.007 mm (carbon) or 0.010 mm (glass). The fibres are bonded together with an adhesive that is usually made of epoxy. One way to visualize a layer of composite material is like a piece of tape, except that there are strong, stiff fibres within the tape and that it is sticky on both sides.

The presence of the fibres gives the layer anisotropic behaviour, i.e. the material's properties depend on the direction. For example, the layer is very strong along the fibre direction but relatively weak transverse to the fibre direction. Engineering structures such as airplanes, automobiles, and wind turbine blades are usually subjected to loadings along many directions at the same time. As such, the use of a single layer does not satisfy all loading conditions. In order to address this, a laminate made of multiple layers is usually required. Within a laminate, layers of different orientations are stacked together. One example of a laminate is shown in Fig. 3 where it is made of up of layers at 0^o, 90^o, 45^o and -45^o. The lay-up sequence shown in this figure constitutes a symmetric laminate. What this means is that the laminate has a plane of symmetry at mid thickness as there are identical materials and fibre orientations and at equal distances from the mid plane. The use of symmetric laminates avoids distortion of the laminate due to manufacturing and it simplifies the understanding and design behaviour of the laminates. Symmetric laminates have been used almost exclusively by the worldwide composites community for more than seven decades.

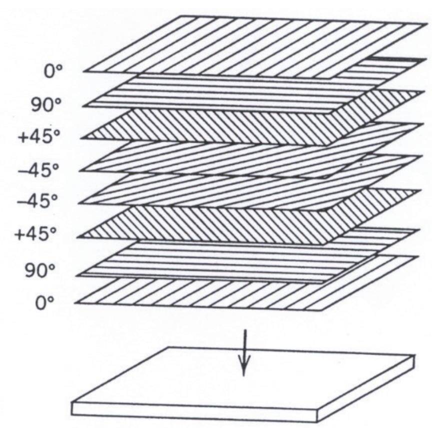

Fig. 3. A laminate made of 0^o, 90^o, 45^o, and -45^o.

The method of 4DPC uses asymmetric laminates, which is not the normal way. Indeed, for most applications of composites so far, asymmetry and anisotropy have been considered as a liability. However, asymmetric laminates are the main mechanism behind 4DPC and this is due to the complex behaviour of the laminate. Actually, asymmetry is considered an asset because it gives rise to the fourth dimension, i.e., the self-reconfiguration of the structure when subjected to the change in temperature. To understand and predict the change in shape of a structure, it is necessary to utilize some theory. Dano and Hyer (2002) [5] and a few other researchers [6, 7] have examined the behaviour of asymmetric laminates upon cooling from cure temperature. It was shown that these laminates can exhibit different shapes at different temperatures and geometrical configurations. Some can take a saddle shape and some can take the shape of circular cylinders. It has also been shown that for plates at room temperature where the length over thickness ratio is significantly large, the radius of curvature obtained using the energy approach by Dano, Hyer and others approximate that obtained using laminate theory. As such, for a situation where the shape at room temperature is concerned, and for thin plates with large length over thickness ratios, the use of laminate theory is sufficient for the prediction of the shape. A few salient features of laminate theory are presented below.

Laminate theory [8]

The main purpose of laminate theory is to obtain the properties of the laminate, which is a stack of individual layers (laminas) each with a specific material, thickness, and fibre orientation, from the properties of the individual layers.

From the lamina's properties, the properties of the laminate, which consists of a number of laminae with a certain stacking sequence, can be obtained as:

$$A_{ij} = \int \overline{Q_{ij}} dz \qquad B_{ij} = \int \overline{Q_{ij}} z dz \qquad D_{ij} = \int \overline{Q_{ij}} z^2 dz \tag{1}$$

where i, j = 1, 2, 6, and z are the structural coordinates along the thickness of the laminate and:

$$\begin{aligned}
\overline{Q_{11}} &= Q_{11}\cos^4\theta + 2(Q_{12}+2Q_{66})\cos^2\theta\sin\theta + Q_{22}\sin^4\theta \\
\overline{Q_{12}} &= (Q_{11}+Q_{22}-4Q_{66})\cos^2\theta\sin^2\theta + Q_{12}(\cos^4\theta+\sin^4\theta) \\
\overline{Q_{16}} &= (Q_{11}-Q_{12}-2Q_{66})\cos^3\theta\sin\theta + (Q_{12}-Q_{22}+2Q_{66})\cos\theta\sin^3\theta \\
\overline{Q_{22}} &= Q_{11}\sin^4\theta + 2(Q_{12}+2Q_{66})\sin^2\theta\cos^2\theta + Q_{22}\cos^4\theta \\
\overline{Q_{26}} &= (Q_{11}-Q_{12}-2Q_{66})\cos\theta\sin^3\theta + (Q_{12}-Q_{22}+2Q_{66})\cos^3\theta\sin\theta \\
\overline{Q_{66}} &= (Q_{11}+Q_{22}-2Q_{12}-2Q_{66})\sin^2\theta\cos\theta + Q_{66}(\cos^4\theta+\sin^4\theta)
\end{aligned} \tag{2}$$

with
$$\begin{aligned}
Q_{11} &= \frac{E_1}{1-\nu_{12}\nu_{21}} \\
Q_{12} &= \frac{\nu_{12}E_2}{1-\nu_{12}\nu_{21}} = \frac{\nu_{21}E_1}{1-\nu_{12}\nu_{21}} \\
Q_{22} &= \frac{E_2}{1-\nu_{12}\nu_{21}} \\
Q_{66} &= G_{12}
\end{aligned} \tag{3}$$

where, θ is the angle between the fibre direction in a layer relative to the x coordinate of the laminate, as shown in Fig. 2, E_1 is modulus along the fibre direction, E_2 is modulus transverse to the fibre direction, G_{12} is in-plane shear modulus, ν_{12} is major Poisson ratio, and ν_{21} is minor Poisson ratio with the relation $E_1\nu_{21}=E_2\nu_{12}$. Typical properties of a carbon/epoxy material are shown in Table 1.

Table 1. Properties of a typical carbon/epoxy unidirectional composite material [8].

Modulus along fibre direction E_1 (GPa)	155 (22.48 msi)
Modulus transverse to fibre direction E_2 (GPa)	12.10 (1.75 msi)
In plane shear modulus G_{12} (GPa)	3.20 (0.464 msi)
Major Poisson ratio ν_{12}	0.248
Coefficient of thermal expansion along fibre direction, α_1 (10^{-6}/°C)	-0.018 (-0.01x10^{-6}/°F)
Coefficient of thermal expansion transverse to fibre direction, α_2 (10^{-6}/°C)	24.3 (13.5 x 10^{-6}/°F)
Moisture expansion coefficient along fibre direction, β_1 (%/%M)	146
Moisture expansion coefficient transverse to the fibre direction, β_2 (%/%M)	4770

For the case of a laminate subjected to a temperature change ΔT, the relations for the strains and curvatures in terms of the stress and moment resultants are given as:

$$\begin{Bmatrix} \varepsilon_x^o \\ \varepsilon_y^o \\ \gamma_{xy}^o \\ \kappa_x^o \\ \kappa_y^o \\ \kappa_{xy}^o \end{Bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{16} & b_{11} & b_{12} & b_{16} \\ a_{12} & a_{22} & a_{26} & b_{21} & b_{22} & b_{26} \\ a_{16} & a_{26} & a_{66} & b_{61} & b_{62} & b_{66} \\ b_{11} & b_{21} & b_{61} & d_{11} & d_{12} & d_{16} \\ b_{12} & b_{22} & b_{62} & d_{12} & d_{22} & d_{26} \\ b_{16} & b_{26} & b_{66} & d_{16} & d_{26} & d_{66} \end{bmatrix} \begin{Bmatrix} N_x^T \\ N_y^T \\ N_{xy}^T \\ M_x^T \\ M_y^T \\ M_{xy}^T \end{Bmatrix} \tag{4}$$

where, the column on the left-hand side represents the in-plane strains and curvatures at the mid plane of the laminate, the square matrix represents components of the compliance, and the column on the right-hand side represents the thermal stress resultants and thermal moment resultants, respectively.

The inverse of the relations in Eq. (4) is:

$$\begin{Bmatrix} N_x^T \\ N_y^T \\ N_{xy}^T \\ M_x^T \\ M_y^T \\ M_{xy}^T \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x^o \\ \varepsilon_y^o \\ \gamma_{xy}^o \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix} \tag{5}$$

where the A_{ij}, B_{ij}, D_{ij} are given by Eq. (1).

The thermal stress resultants and thermal moment resultants are given as:

$$N_x^T = \int_{-\frac{H}{2}}^{\frac{H}{2}} (\overline{Q_{11}}\alpha_x^T + \overline{Q_{12}}\alpha_y^T + \overline{Q_{16}}\alpha_{xy}^T)\Delta T\, dz \tag{6A}$$

$$N_y^T = \int_{-\frac{H}{2}}^{\frac{H}{2}} (\overline{Q_{12}}\alpha_x^T + \overline{Q_{22}}\alpha_y^T + \overline{Q_{26}}\alpha_{xy}^T)\Delta T\, dz \quad (6B)$$

$$N_{xy}^T = \int_{-\frac{H}{2}}^{\frac{H}{2}} (\overline{Q_{16}}\alpha_x^T + \overline{Q_{26}}\alpha_y^T + \overline{Q_{66}}\alpha_{xy}^T)\Delta T\, dz \quad (6C)$$

$$M_x^T = \int_{-\frac{H}{2}}^{\frac{H}{2}} (\overline{Q_{11}}\alpha_x^T + \overline{Q_{12}}\alpha_y^T + \overline{Q_{16}}\alpha_{xy}^T)\Delta T z\, dz \quad (6D)$$

$$M_y^T = \int_{-\frac{H}{2}}^{\frac{H}{2}} (\overline{Q_{12}}\alpha_x^T + \overline{Q_{22}}\alpha_y^T + \overline{Q_{26}}\alpha_{xy}^T)\Delta T z\, dz \quad (6E)$$

$$M_{xy}^T = \int_{-\frac{H}{2}}^{\frac{H}{2}} (\overline{Q_{16}}\alpha_x^T + \overline{Q_{26}}\alpha_y^T + \overline{Q_{66}}\alpha_{xy}^T)\Delta T z\, dz \quad (6F)$$

where the α terms are the off-axis coefficients of thermal expansion and are given as:

$$\alpha_x = \alpha_1 m^2 + \alpha_2 n^2;\ \alpha_y = \alpha_1 n^2 + \alpha_2 m^2;\ \alpha_{xy} = 2(\alpha_1 - \alpha_2)mn \quad (7)$$

and α_1 and α_2 are the on-axis coefficients of thermal expansion of a particular layer, as given in Table 1.

The strains and curvatures due to the effect of cooling can be written as:

$$\begin{bmatrix} \varepsilon_x^o \\ \varepsilon_y^o \\ \gamma_{xy}^o \\ \kappa_x^o \\ \kappa_y^o \\ \kappa_{xy}^o \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{16} & b_{11} & b_{12} & b_{16} \\ a_{12} & a_{22} & a_{26} & b_{21} & b_{22} & b_{26} \\ a_{16} & a_{26} & a_{66} & b_{61} & b_{62} & b_{66} \\ b_{11} & b_{21} & b_{61} & d_{11} & d_{12} & d_{16} \\ b_{12} & b_{22} & b_{62} & d_{12} & d_{22} & d_{26} \\ b_{16} & b_{26} & b_{66} & d_{16} & d_{26} & d_{66} \end{bmatrix} \begin{bmatrix} N_x^T \\ N_y^T \\ N_{xy}^T \\ M_x^T \\ M_y^T \\ M_{xy}^T \end{bmatrix} \quad (8)$$

By obtaining the strains and curvatures as shown in the relations of Eq. (8), the deformation of the laminate due to cooling from either the curing temperature or processing temperature can be obtained.

3D printer for composites

A normal 3D printer is usually small and can sit on a desktop. For the case of long, continuous fibre composites, an automated fibre placement (AFP) machine is used [9]. Actually, AFP machines have been designed to make large structures such as an airplane's body or wings. As such, these machines are huge and costly. The initial intention is not for 3D printing. However, this manufacturing technique is additive and has all features of a 3D printer. Laminates used in 4DPC can be made either by hand lay-up or by the use of an AFP machine.

Potential applications of 4D printing of composites

4DPC have many potential applications and they are given in the following subsections.

Manufacturing of composite structures of complex shape using only a simple flat mould

One example is the manufacturing of an "S" shape structure as shown in Fig. 4 [10]. If one were to use the conventional method of composite manufacturing, S-shaped moulds would need to be made, and this involves time and money.

Another application is the case of a composite flower as shown in Fig. 5. For this structure, 4DPC is the only technique that can accomplish the manufacturing. Indeed, normal composite manufacturing methods cannot make this structure.

Fig. 4. Composite "S" shape made by 4DPC [10].

Fig. 5. Composite flower made by 4DPC.

Another potential application of 4DPC is the manufacturing of composite leaf springs as shown in Fig. 6 [11]. This spring has an elastic constant of 486 N/cm and it was subjected to more than 1 million cycles (from curved to completely flat and back) without any sign of degradation.

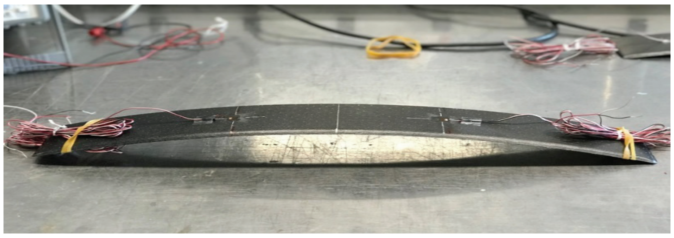

Fig. 6. Composite leaf spring made by 4DPC [11].

Manufacturing of corrugated core for flexible wings

The efficiency of aircraft wings can be significantly improved by changing their shape during flight. This is called "morphing" [12]. Morphing can be accomplished by adjusting the angle between the trailing edge relative to the body of the wing as shown in Fig. 7 (left). By making the core of the trailing edge in the form of corrugation the movement of the trailing edge is facilitated [13]. The use of 4DPC enables efficient and low-cost manufacturing of the corrugated composites.

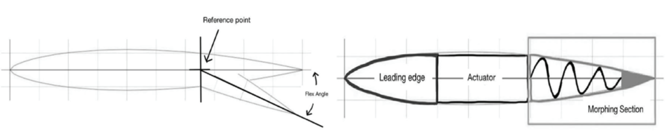

Fig. 7. Morphing of aircraft wings (left: shape changing and right: corrugated composite core).

Efficient packaging

Another potential application of 4DPC is efficient packaging for transportation. In a situation where some structure, such as housing, needs to be installed at a remote location such as outer space or the North or South poles, where access to manufacturing facilities are scarce, the use of 4DPC can offer a solution. The complex structure can be transported in the form of simple flat structures. Upon arrival, the application of the external stimulus can be imposed thereby transforming the flat structure in to a complex 3D structure.

Along the lines of the ability to transform a flat stack of layers into a three-dimensional structure, the idea of trying out the concept on forming letters of the English alphabet were attempted. Indeed, each letter in the English alphabet has different degrees of curvature and complexity. Hopefully, the experience learned during these exercises can be useful for real structures.

Illustrations of capacity of the technique through letters of the alphabet

In an effort to examine the ability of 4D printing of composites, the concept of 4DPC can be examined to see if it can be used to make structures of complex geometries. One example would be for the case of letters of the alphabet. The formation of the letters that make up the word CONCORDIA was made [14]. In this paper, the lay-up sequences for the letters V, e, t, m are developed. These letters, together with the letters already made for the word CONCORDIA can be put together to make up the word Vietnam.

Principles of the procedure

There are basically four guidelines to form complex geometries from flat laminates for the technique of 4DPC. These are:

Symmetric laminates remain flat in both the initial and final configurations

In symmetric laminates such as those with lay-up sequences [0/90]s or [0n/90n]s, the laminate does not change its configuration when its temperature is reduced from curing temperature to room temperature. This reduces complexity in the design of structures using composite materials. As such these laminates have been used for many years in making many engineering structures such as airplane and automotive structures. These types of laminates are used to serve as the base for many letters in this paper.

Unidirectional laminates are flat

Unidirectional laminates are those that contain only fibres along one direction, such laminates with lay-up sequence $[0]_1$, $[0]_3$ etc. A combination of these laminates such as $[0]_1$+$[0]_3$=$[0]_4$ is also a unidirectional laminate. Upon cooling from cure temperature to room temperature, this laminate remains flat.

Un-symmetric cross ply laminates show curvature

Un-symmetric cross-ply laminates are those consisting of layers at 0° orientation and 90° orientation, and are not symmetric. The laminate sequence has the form $[0_m/90_n]$ where m and n are integers. For example, for the letter "a", there are regions where the laminate has the lay-up sequence $[0/90_3]$, where m=1 and n=3. Upon curing and cooling to room temperature, this laminate will change its shape from flat to curved where the 90° layers are on the concave side.

Use of non-stick separator to prevent bonding

In order to facilitate the transformation from flat configuration to curved configuration, it is necessary for some surfaces not to stick together. There are regions in some of the letters that should be separated after curing and cooling. Consider the case of the letter "a" in Fig. 14. The red line shows a non-stick caul plate. Its function is to prevent bonding between the base and the laminate above. At the beginning during the deposition of the layers, all layers are flat and are on top of each other. Since the prepregs are adhesive, they need to be separated such that when they cure and solidify, the layers should not bond to each other. This allows the rise of the majority of the "a" letter above the base plate.

Using the above 4 mechanisms, the lay-up sequences for the letters making up the word VIETNAM are presented below.

Letter V

In the 7 letters making up the word Vietnam, the letter V is the exception where the 4DPC does not work well. The reason is due to the limit of the minimum curvature that can be made using current commercially available composite materials. Using the material properties in Table 1 and the procedure given in equation (1) to (8), the radius of curvature for a [0/90] laminate is 5 cm [10]. Using the lay-up sequence as shown in Fig. 8 would give a structure looking similar to the letter U. This represents the lower limit of the radius of curvature at a corner.

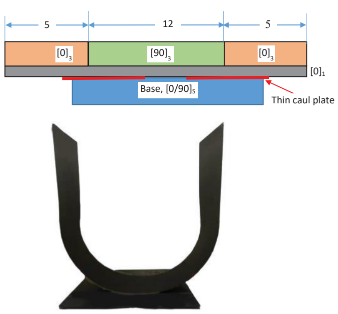

Fig. 8. Lay-up sequence and the letter U.

In order to obtain a sharp corner for the letter V, an alternate procedure (not 4DPC) is used as shown in Fig. 9. In this procedure, two symmetric laminates of lay-up sequence [0/90/0] are bonded onto a thin aluminum piece. The aluminum piece is then bent to the desired radius.

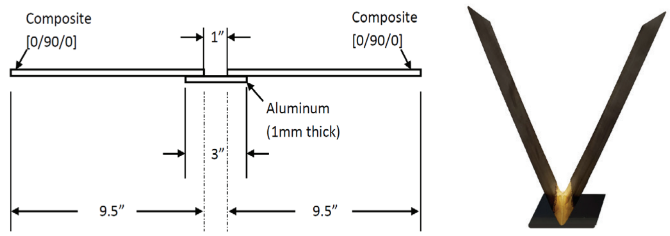

Fig. 9. Lay-up arrangement and letter V.

Letter "i"

The lay-up sequence for the letter "i" was already presented in [14]. It is included here for completeness of the presentation. The lay-up configuration for the letter "i" is shown in Fig. 10.

- First a base laminate of symmetric lay-up [0/90]s is made (blue part).

- A thin layer of metal (7 inch long) is placed from the right side of the base plate (red line). This shim is used to prevent bonding of the upper to the lower part.

- A layer of unidirectional composite [0], with length of 12 inch is laid over.

- From the left side, a laminate of three layers of $[0]_3$ of length 2 inch is laid. This is followed by a laminate of $[90]_3$ of length 6 inch, and finally by another laminate of $[0]_3$ with 4 inch length.

After curing and cooling to room temperature, the assembly changes its shape to a curved shape of the letter "i" as shown in the bottom figure of Fig. 10.

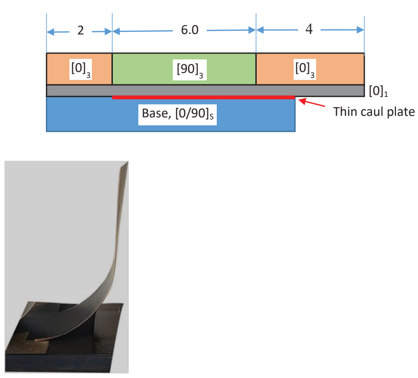

Fig. 10. Lay-up sequence and the letter "i".

Letter e

The lay-up sequence for the letter e is shown in Fig. 11. The letter e can be considered as a double letter "c". Note that there two shim locations (red line) in order to separate the two parts from each other.

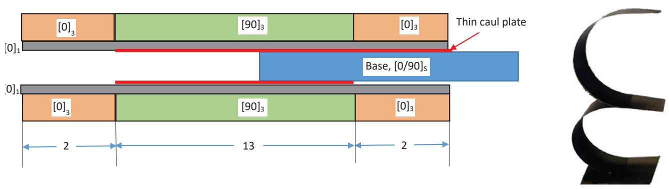

Fig. 11. Lay-up sequence and the letter "e".

Letter t

The lay-up sequence for the letter "t" is as shown in Fig. 12. Note that the red shims are broken at strategic locations in order to allow for bonded regions and non-bonded regions.

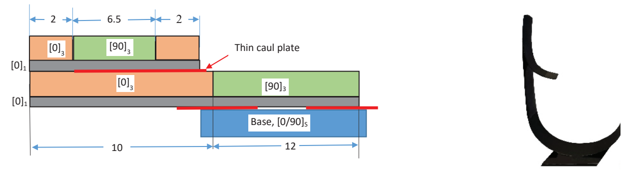

Fig. 12. Lay-up sequence and the letter "t"

Letter n

The lay-up sequence for the letter "n" was already presented in [14]. It is included here for completeness of the presentation.

The configuration of letter "n" is shown in Fig. 13. The configuration looks like a fork with the upper side and lower side separated by a middle portion.

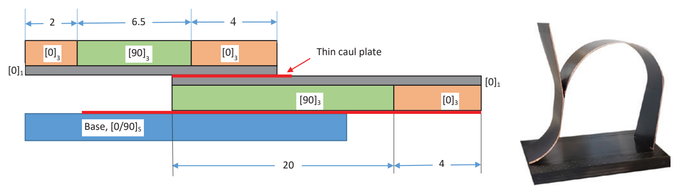

Fig. 13. Lay-up sequence and the letter "n".

Figure 13 (bottom) shows a photograph of the letter "n" after manufacturing. The bond at the lower left side of the letter "n" in Fig. 13 (bottom) corresponds to the bond on the left side in Fig. 13 (top). The right portion of the upper fork in bottom figure corresponds to the right portion of the upper fork in the top figure. It separates from curved portion of the letter "n" due to the non-stick layer as shown by the red line in top figure. The middle part in top figure corresponds to the right portion of the letter "n" in bottom figure.

Letter "a"

The lay-up sequence for the letter "a" was already presented in [14]. It is included here for completeness of the presentation.

The lay-up arrangement for the letter "a" is as shown in Fig. 14. The top figure shows the intended fibre orientations before the lay-up process, which shows an apparent gap between the right sides of the upper fork and lower fork. The middle figure shows the lay-up arrangement after the lay-up process, which shows a bonding region between the right sides of the upper fork and lower fork. Note that in the top figure, the gap between the upper fork and lower fork is exaggerated, since the thickness of 4 layers of 0° would be only 0.6 mm.

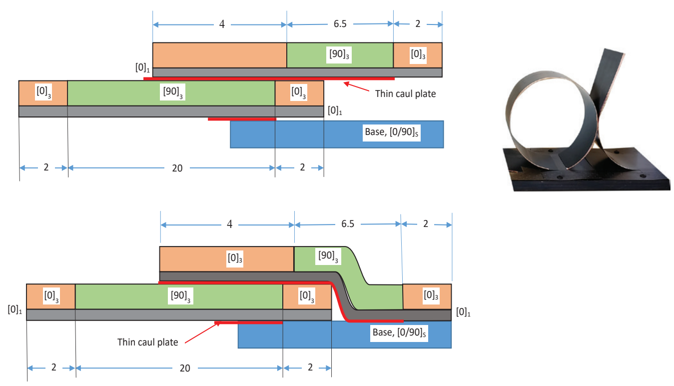

Fig. 14. Lay-up sequence and the letter "a".

The bottom figure 14 shows a photograph of the letter "a" after manufacturing.

Letter m

Figure 15 shows the lay-up sequence and the final letter "m". Note that the bonding between the base plate and the actual letter is over 2 inch of the $[0]_3$ laminate on the right hand side.

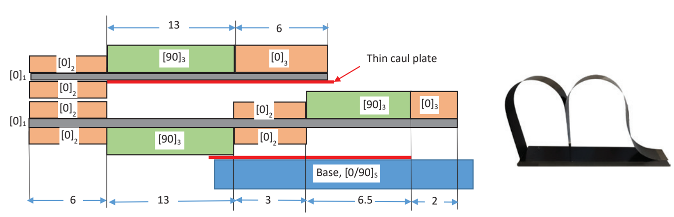

Fig. 15: Lay-up sequence and the letter "m".

The final word "Vietnam"

The above letters were placed together to make the word Vietnam as shown in Fig. 16.

Fig. 16. Final configuration of the word "Vietnam".

Conclusions

In this paper, the lay-up arrangements for the letters "V, i, e, t, n, a, m" have been presented. The principle of 4D printing of composites (4DPC) was used such that no special moulds of complex geometries were required. Instead, the anisotropies of the lay-up sequences allow only flat layers that are laid on flat moulds to begin with. After curing and cooling to room temperature, the flat layers curl up and make the different letter configurations. The principle of 4DPC can be extended to manufacture composite structures of complex geometries without the need for complex moulds and is the basis of the concept of mouldless composite manufacturing. The procedure developed during these exercises can be used to manufacture engineering structures of complex shapes.

COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

REFERENCES

[1] S. Tibbits (2013), "The emergence of 4D printing", *TED Conference*, https://www.ted.com/talks/skylar_tibbits_the_emergence_of_4d_printing.

[2] M. Farhang, M.S.H. Hassani, L. Xun, N. Jun (2017), "A review of 4D printing", *Materials and Design*, **122**, pp.42-79.

[3] M. Rafiee, R.D. Farahani, D. Theriault (2020), "Multi-material 3D and 4D printing", *Advanced Science*, **7**, DOI: 10.1002/advs.201902307.

[4] M.Q. Zafar, H. Zhao (2020), "4D printing: future insight in additive manufacturing", *Metals and Materials International*, **26**, pp.564-585.

[5] M.L. Dano, M.W. Hyer (2002), "Snap through behavior of unsymmetric fibre reinforced composite laminates", *International Journal of Solids and Structures*, **39(1)**, pp.175-198.

[6] M. Schlecht, K. Schulte (1999), "Advanced calculations of the room temperature shapes of unsymmetric laminates", *J. Composite Materials*, **33(16)**, DOI: 10.1177/002199839903301601.

[7] A. Hamamoto, M.W. Hyer (1987), "Non-linear temperature-curvature relationships for unsymmetric graphite-epoxy laminates", *Int. Journal of Solids and Structures*, **23(7)**, pp.919-935.

[8] M. Hyer (2008), *Introduction to the Principles of Composite Materials*, Destech publication.

[9] Van Suong Hoa (2018), "Automated composites manufacturing", *Vietnam Journal of Science, Technology and Engineering*, **60(1)**, pp.28-37.

[10] Hoa Suong Van (2017), "Factors affecting the properties of composites made by 4D printing (mouldless composites manufacturing)", *Advanced Manufacturing: Polymers and Composites Science*, **3(3)**, pp.101-109.

[11] Hoa SuongVan (2019), "Development of composite springs using 4D printing method", *Composite Structures*, **210**, pp.869-876.

[12] T. Yokozeki, S. Takeda, T. Osagawara, T. Ishikawa (2006), "Mechanical properties of corrugated composites for candidate materials of flexible wing structures", *Composites Part A: Applied Science and Manufacturing*, **37(10)**, pp.1578-1586.

[13] D.T. Filipovic, G.R. Kress (2019), "Manufacturing method for high-amplitude corrugated thin- walled laminates", *Composite Structures*, **222**, DOI: 10.1016/j.compstruct.2019.110925.

[14] Suong Van Hoa, Daniel Rosca (2020), "Formation of letters of the alphabet using 4D printing of composites", *Materials Today Communications*, **25**, DOI: 10.1016/j.mtcomm.2020.101115.