CONE STRUCTURES MADE USING 4D PRINTING OF COMPOSITES

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Keywords: 4D Printing of Composites, Moldless Composite Manufacturing, Conical Structures

ABSTRACT

4D Printing of Composites is a new technique for the manufacturing of composite structures of complex shapes without the need to use a mold with complex geometry (this is also called "moldless" manufacturing of composites). By only using a flat mold, a structure with 3D geometry could be obtained after a curing cycle. The main mechanism of the method is the use of unsymmetric laminates, e.g. [0/90]. Due to the difference in coefficient of thermal contraction along different directions in the different layers, there is interaction between deformation of the layers during the cooling cycle from cure temperature to room temperature. This interaction gives rise to the change in shape from flat to curved. In this paper, a novel method for making conical composite structures is presented. The basis of work is on depositing fibers in cylindrical coordinates (principally radial and circumferential directions) for making unsymmetric laminates. The final unsymmetric flat stack of prepreg tapes with the geometry of an annulus sector undergoes a cure cycle to transform into a truncated cone structure. The final structure showed excellent dimensional stability and uniformity. Furthermore, a number of laminates with the same stacking sequence and the same 2D geometry (but different levels of defects) resulted in the same final 3D geometry, which may suggest the repeatability and reliability of this method for manufacturing.

Introduction

The application of composite materials in many engineering applications has become prevalent in recent decades. The union of high strength and stiffness, coupled with lightweight, turn composites into attractive nominees for high-performance applications. However, manufacturing of continuous fiber composites could prove to be costly due to several factors, one of which is expenses associated with tooling. Manufacturing of composite structures typically necessitates using molds. Regardless of whether the final product is a twisted or a curved panel, the requirement for a mold is an omnipresent and demanding part of the manufacturing procedure. Furthermore, the production of suitable molds could be very expensive and laborious for a complex or large structure. Hence, the feasibility of manufacturing without a mold (or with a flat mold) could yield undeniable advantages in terms of saving budget and time. Recent advancements made this feasible only for some parts with simple geometries.

The 4D Printing of Composites [1], abbreviated as 4DPC, is a method that exploits the anisotropy present in laminates composed of unsymmetrically stacked layers. The different coefficients of thermal contraction along and perpendicular to the fiber direction cause interlaminar interaction during the cooling process of cure cycle, transforming the flat shape of panel into curved. Based on this phenomenon, it could be possible to obtain a range of shapes by manipulating the orientation of the fibers in each ply. Similar to 3D Printing, this method is categorized as an additive manufacturing method. The fourth dimension refers to self-transformation of shape from flat to curved or twisted, which mainly depend~~s~~ on temperature for the case of 4DPC. There are other forms of 4D Printing [2,3,4], where usually plastics with low modulus and strength are used. These regular 4D printing techniques could be used for making small and very flexible parts. However, 4DPC opens up the possibilities for manufacturing large structures with high stiffness and strength. This technique has been previously employed to fabricate components with S shape [1], omega stiffeners [6], corrugated core for flexible aircraft wings (Figure 1a) [7], and leaf springs (Figure 1b) [5]. In this work, a method for manufacturing of conical structures using 4DPC is introduced.

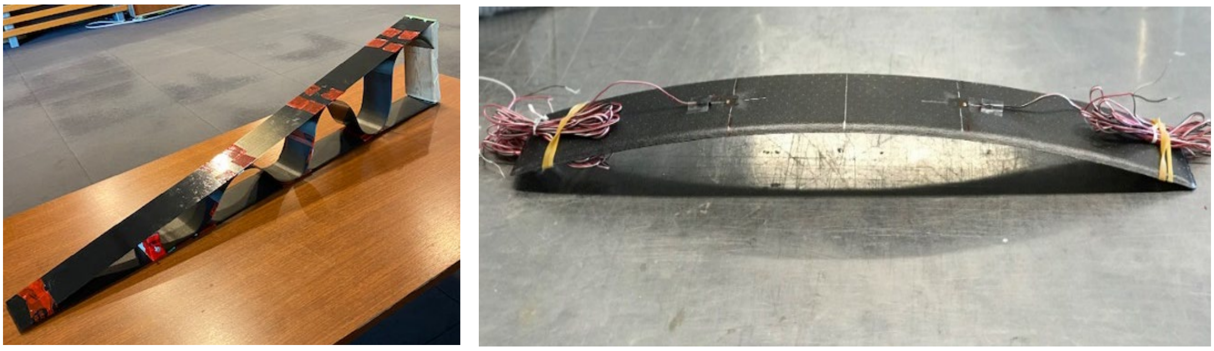

Figure 1: parts made by 4DPC (a) corrugated core for a flexible aircraft wing [7] (b) leaf spring [5]

Cones; Applications, Features and Challenges in Manufacturing

Generally, conical components have variety of engineering applications in automotive, aerospace, HVAC, and construction industries. However, the process for manufacturing of metallic cones usually requires noticeable efforts. Conventional methods involve rolling the sheet metals into a conical shape using special equipment (Figure 2), followed by welding the edges to form a finished part.

Figure 2: Plate Roll Machine for manufacturing metallic cones; R-SMART Planetary hydraulic four roll [8].

Conical composite structures are mainly demanded when high-performance and lightweight required. Conventional methods for manufacturing of composite cones include hand layup and filament winding, both requiring conical molds (Figure 3). In these conventional methods, the placement of fibers along the meridian of cone (to potentially optimize performance under axial load) is usually challenging or sometimes impossible. In the following section, it will be discussed how cones made by 4DPC would overcome this issue.

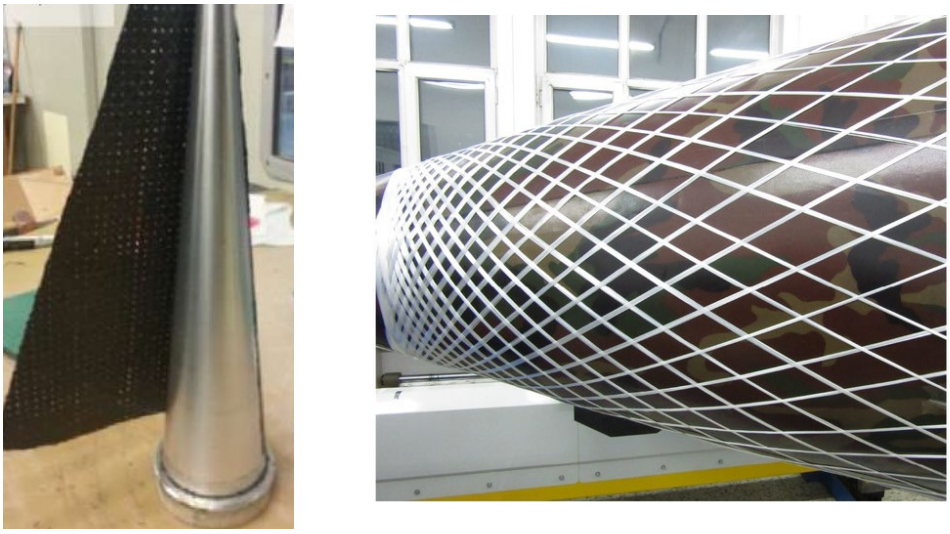

Figure 3: examples of regular methods for manufacturing of composite cones (left) hand layup [9] (right) filament winding [10].

Cones made by 4DPC not only eliminate the need for a conical mold, but they may also offer superior mechanical properties that is the subject of ongoing research. Besides, the dependency of structure's shape on temperature presents unique opportunities for specialized applications. Deployable space structures could encompass one potential application, such as a conical solar panel installed in the nose cone of a spacecraft. Upon arrival at the desired orbit, the closed conical solar pack (Figure 4 (left)) could be deployed. During the daytime when temperature of structure rises to more than 100°C, the panel automatically expands and flattens into the shape of a disk (Figure 4 (right)). This self-reconfiguration of structure maximizes the exposed area to sunlight for optimum energy absorption.

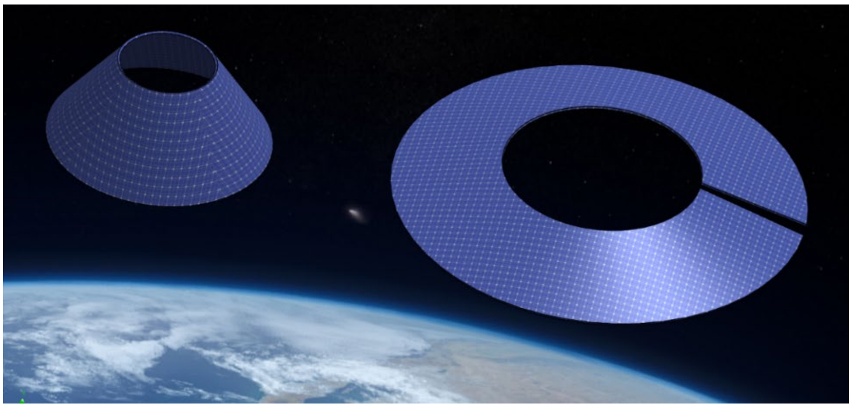

Figure 4: Smart conical solar panel by 4DPC (left) shape during nighttime (right) shape during the daytime.

Manufacturing Procedure by 4DPC

The process for manufacturing of 4D printed cones relies on laying up thermoset prepreg tows onto a flat mandrel with curvilinear fiber paths while maintaining stacking sequence unsymmetric. An annulus sector is the geometry of the flat laminated prepreg strips prior to curing cycle. After performing the curing process, the thermal loads (as a result of cooling down from cure temperature to room temperature) generate distortion required for transforming the 2D annulus shape into 3D conical shape. By simply removing the cured laminate out of vacuum bag, the structure transforms to its stable conical shape spontaneously.

As shown in Figure 5, the geometry of flat pre-cured laminate can be defined by inner radius (R_1), outer radius (R_2), and central angle of arc (2θ). For the case of 4D printing of cones using automated fiber placement, fiber paths could be divided into two categories of radial and circumferential paths as indicated in Figure 5. In this work, two different stacking sequences were employed for manufacturing of two different truncated cone structures. The notation [R_1/C_1] may represent a layup sequence where a radial ply (series of radial tows) is first placed on flat mold, followed by a circumferential layer (series of circumferential tows). The second stacking sequence, [R_2/C_1], denotes an arrangement where two radial plies are placed consecutively, with a circumferential ply placed on top of them.

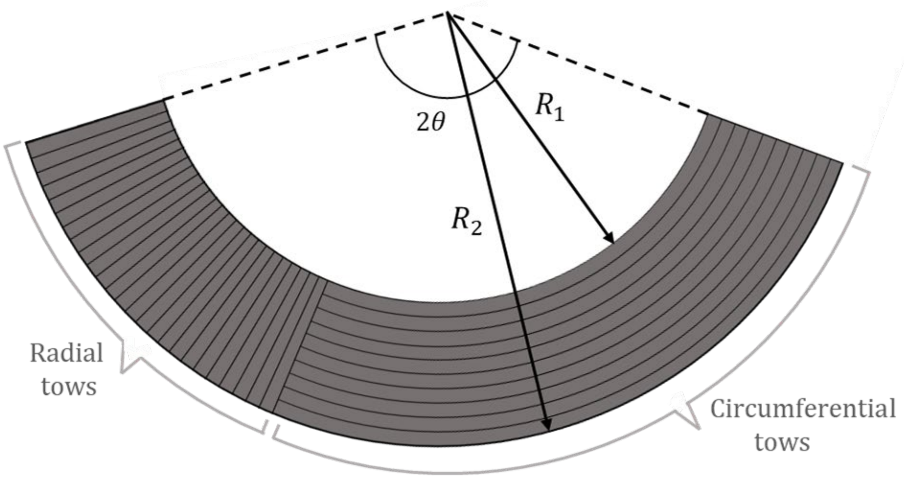

Figure 5: General configuration of pre-cured laminate for 4D printing of composite cones.

The Robotic Fiber Placement Machine developed by Automated Dynamics Corporation (ADC) has been used to carry out lamination of prepreg strips (Figure 6). The 0.25-in wide Tencate prepreg tow is fed into thermoset robotic head for automated deposition. A brass shim is initially placed on the mandrel while its surface is already coated with release agent.

Figure 6: Automated fiber placement machine developed by ADC (Thermoset head).

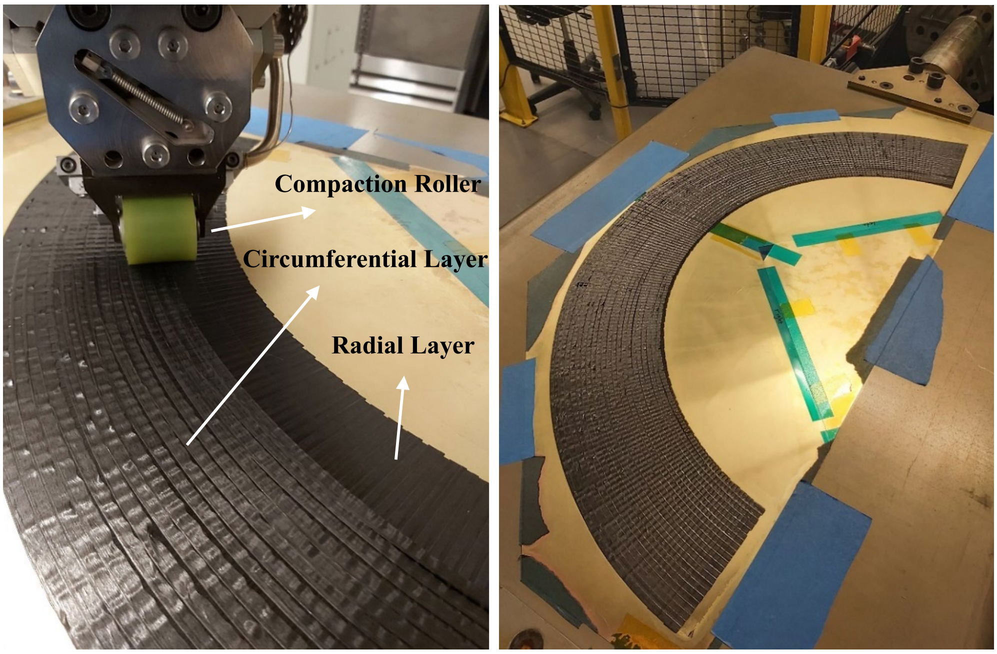

Figure 7: (a) Fiber deposition during the AFP process, (b) Final pre-cured laminate.

Upon completing the fiber placement process (Figure 7a), the final pre-cured flat stack (Figure 7b) is vacuum bagged and undergoes curing cycle in autoclave at cure temperature of 135°C for 90 minutes. The autoclave used for this work is an ASC Econoclave EC2X4. Once the process is finished and laminate is removed from bagging material, it transforms to a truncated cone automatically. There is no need to apply external loads to maintain the conical shape. The internal interaction between radial and circumferential layers holds stable the conical shape. Four cones were manufactured using the discussed method - two cones with [R_1/C_1] and two with [R_2/C_1] stacking sequences. The dimensions of laminates before cure cycle and after the cure cycle are presented in Table 1:

		Pre-cured flat stack dimensions			Measured dimensions of final truncated cone at room temperature		
Cone No.	Stacking Sequence	R_1(cm)	R_2 (cm)	2θ(deg)	r_1 (cm)	r_2 (cm)	α (deg)
1	[R_1/C_1]	29.2	41.9	85	12.8	17.5	21.7
2	[R_1/C_1]	29.2	41.9	85	12.7	17.3	21.2
3	[R_2/C_1]	29.2	41.9	80	9	12.7	16.9
4	[R_2/C_1]	29.2	41.9	80	9	12.6	16.4

Table 1: Dimensions of cones made by 4DPC.

Where r_1, r_2, and α are respectively small radius, large radius, and semivertex angle of free truncated cone at room temperature after cure cycle. The manufacturing process finishes by bonding the free edges of cone. Epoxy resin was used as the adhesive to bond edges, which was cured at room temperature while the edges were kept together under the compaction of two strips of metal (Figure 8a). Subsequently, the adhesive was post-cured in 100 °C for one hour. It was observed that the final structure was in good dimensional stability and had perfectly circular section (Figure 8b).

Figure 8: (a) Process for bonding free edges of cone, (b) Final composite cone.

An important feature about the final cones made by this method is that all the fibers in circumferential layers are concentric and all the fibers in radial layers would intersect at one point on central axis of cone. This feature cannot be achieved by other conventional manufacturing methods, e.g., hand layup, filament winding. For example, making a composite cone with hand layup entails wrapping the fabrics or unidirectional tape around conical tool. The pieces of fabric should be typically cut into the shape of annulus sector (as shown in Figure 9). But inevitably, only a small fraction of fibers could run along the meridian of cone. Once fabric is wrapped over the tool, angle of fibers with respect to the meridian of cone varies along circumference, which is a deviation from desired orientation. In simple terms, the shape of the fabric before layup, as shown in Figure 9, means that the area annotated as A would be the only part of cone with some fibers running along the meridian of cone. But on the other hand, area B would make a part of cone with fibers deviating 45 degrees from meridian of cone. Since even slight deviation of fibers from axis of load remarkably decreases off-axis elastic modulus (E_x), this defect in conventional manufacturing methods of composite cones could result in noticeable reduction in buckling performance under axial load. However, this shortcoming does not exist in 4D printing of composite cones.

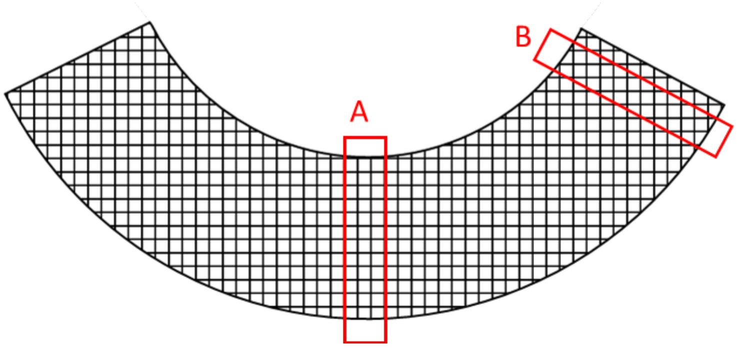

Figure 9: Pattern of fibers in a piece of fabric to be wrapped over conical mold.

However, the automated manufacturing process usually brings along some imperfections, including gaps and overlaps in both radial and circumferential bands, as well as wrinkles and waviness of fibers in circumferential bands (Figure 10). In the radial layer, due to constant width of prepreg tows (0.25 in), naturally overlaps occur close to the inner radius and gaps appear close to the outer radius. By decreasing the distance between radial bands, the defect is limited to overlaps, which is less critical for performance of final structure. On the other hand, in circumferential layer, fibers may buckle and form in-plane waviness or out-of-plane wrinkles. However, under the pressure of autoclave in curing cycle wrinkles were mostly removed.

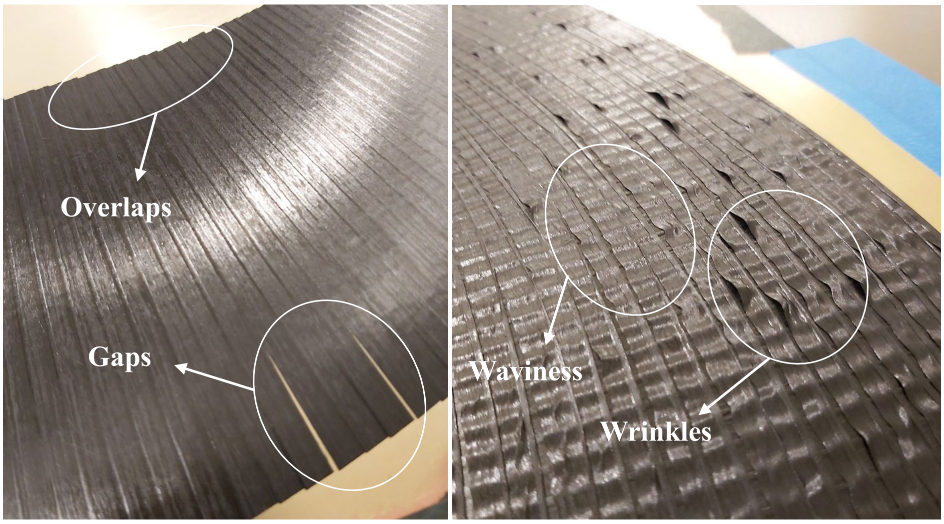

Figure 10: Defects in the process of automated manufacturing of laminate.

Conclusion

This paper shows that cone shaped structures can be made without the need to use a mold with a conical shape. This is done using the technique of 4D printing of composites by using a flat mold only. The final free shape of truncated cone at room temperature is governed by dimensions and stacking sequence of pre-cured flat stack of prepreg strips, and cure temperature. The presence of all strips of radial fibers along the meridian of the cone might offer the potential for enhanced performance under axial mechanical loading. On the other hand, if the edges are left unbonded, the temperature-dependent shape of the structure could suggest specialized applications for morphing conical structures, which could be explored in future studies.

ACKNOWLEDGEMENTS

Financial support from the Natural Sciences and Engineering Research Council of Canada is appreciated.

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