

RESEARCH ARTICLE

Open Access



Vertical Parallel Multi-Material 4D Printing (VPM-4DP): a novel strategy for achieving bio-inspired doubly curved non-planar hygroscopic actuators

Annie Wang^{1*} , Simon Poppinga², Antoine Le Duigou^{3,4}, Elena Vazquez⁵ and David Correa¹

Abstract

Most 4D-printed hygromorphic mechanisms using fibre-polymer composite filaments are thin laminated bilayer composite structures, which are printed flat on the 3D printer bed and shape-change into single or double-curvature geometries in response to moisture uptake. The tendency towards thin laminated 2D-like bilayers might be traced to early research on shape-change laminates, such as bimetals, or to the vertical layering sequencing of most additive manufacturing methods. Recently, actuators with non-planar geometries have been achieved through complex rotational 3D printing, 5 or 6-axis printers, or multi-step repositioning of parts, but these methods require bespoke equipment or intensive post-processing, which greatly limits their application to the ubiquitous 3-axis gantry system. In this paper, we introduce a strategy for vertically printing non-planar shape-changing hygromorphic structures that requires only one print session and minimal post-processing. We demonstrate the novel capability of the presented strategy by creating actuators with double-curvature geometries based on the biological models of the *Bauhinia variegata* seed pod and the *Lilium* 'Casa Blanca' tepals. This novel approach reduces the complexity of manufacturing intricate 4D-printed actuators that have doubly curved geometry. The possibilities in 4D-printed shape parameters are expanded through this method, considering that dimensional curvature and form can now be more easily introduced to structures previously limited by planar printing.

Keywords Multi-material 4D printing, Hygromorphic actuators, Bio-inspired design, Doubly curved structures, Functionally graded structures

1 Introduction

Hydraulically actuated plant movements are driven by water displacement between cells and tissues, which includes changes in hydrostatic (turgor) pressure within living cells (Dumais & Forterre, 2012) and swelling/shrinking of fibrous materials in dead plant tissue (Stahlberg & Taya, 2006). These processes can create reversible (elastic) and irreversible (plastic) material deformations like bending and twisting that are driven either by internal osmotic gradients between cells, which require metabolic energy to set up, or by external humidity gradients, which do not require metabolic energy (Bauer et al., 2021). The latter actuate when water enters inter-fibrillar

*Correspondence:

Annie Wang
ax2999wa@uwaterloo.ca

¹ School of Architecture, University of Waterloo, Cambridge, Canada

² Botanical Garden, Department of Biology, Technical University of Darmstadt, Darmstadt, Germany

³ IRDL UMR CNRS 6027, BIONICS Group, Université de Bretagne Sud, Lorient, France

⁴ Institut Universitaire de France (IUF), Paris, France

⁵ School of Architecture, Umeå University, Umeå, Sweden

spaces and pushes cellulose microfibrils apart, causing moisture absorption and swelling deformation within the structures, and the opposite occurs as water exits to cause shrinking (Stahlberg & Taya, 2006). Since in hygroscopic structures there is no clear differentiation between a triggering stimulus and the actual actuation, we use the term autonomous material response/reactive self-actuation in the following. Examples of this type of movement include seed dispersal mechanisms like those in pinecones (Dawson et al., 1997) and wheat awns (Elbaum et al., 2007). This inert material architecture has inspired much of the current research into shape-change actuators (Gong & Zhang, 2025).

Most shape-change research has been based on Timoshenko's bimetal principles (Timoshenko, 1925), using bilayer structures with differentiated material properties to induce stress-related bending in response to heat. This includes moisture-driven bilayer actuators using hydrogel composites (Erb et al., 2013; Zhang et al., 2016), paper (Mesa, 2020; Poppinga et al., 2021; Reyssat & Mahadevan, 2009), wood (Holstov et al., 2015; Reichert et al., 2015; Rüggeberg & Burgert, 2015), and natural fibre composites (Le Duigou et al., 2020). These mechanisms are designed to start as a planar surface (initial rest-state) and change into a single or doubly curved surface (second rest-state) in response to moisture absorption or desorption. These moisture-driven actuators are composed of an expansion layer made with hygroscopic material (often referred to as the “active layer”) and a less

or non-hygroscopic resistant layer (“constraint layer”), or two active layers with anisotropic properties that give them differing expansion directionality. The relation between the material characteristics of both layers determines the shape-change behavior: if the expansion layer is isotropic, the resulting shape-change is highly dependent on the aspect ratio of the bilayer (Guo et al., 2020; Pezzulla et al., 2016). However, if the expansion layer is anisotropic with direction-dependent properties, then the direction of shape-change is primarily dictated by those properties as seen in Fig. 1. For example, wood veneer and wooden composite bilayers bend perpendicular to the grain direction of the expansion layer (Holstov et al., 2015; Reichert et al., 2015; Rüggeberg & Burgert, 2015).

3D Printing (3DP) allows the mechanical and hygroscopic properties of each layer to be designed through the organization of the print path and the use of different polymers for each layer. The 3DP method for creating structures that autonomously shape-change in response to an external input is called 4D Printing (4DP), in reference to the additional dimension of movement over time (Campbell et al., 2014). In Fused Filament Fabrication (FFF) of hygroscopic filaments, the extrusion process results in direction-dependent behaviour similar to wood grain, where the dominant direction of expansion is perpendicular to the printing direction (Le Duigou et al., 2020). In early bilayer research, wood veneer was selected and cut according to the grain direction and

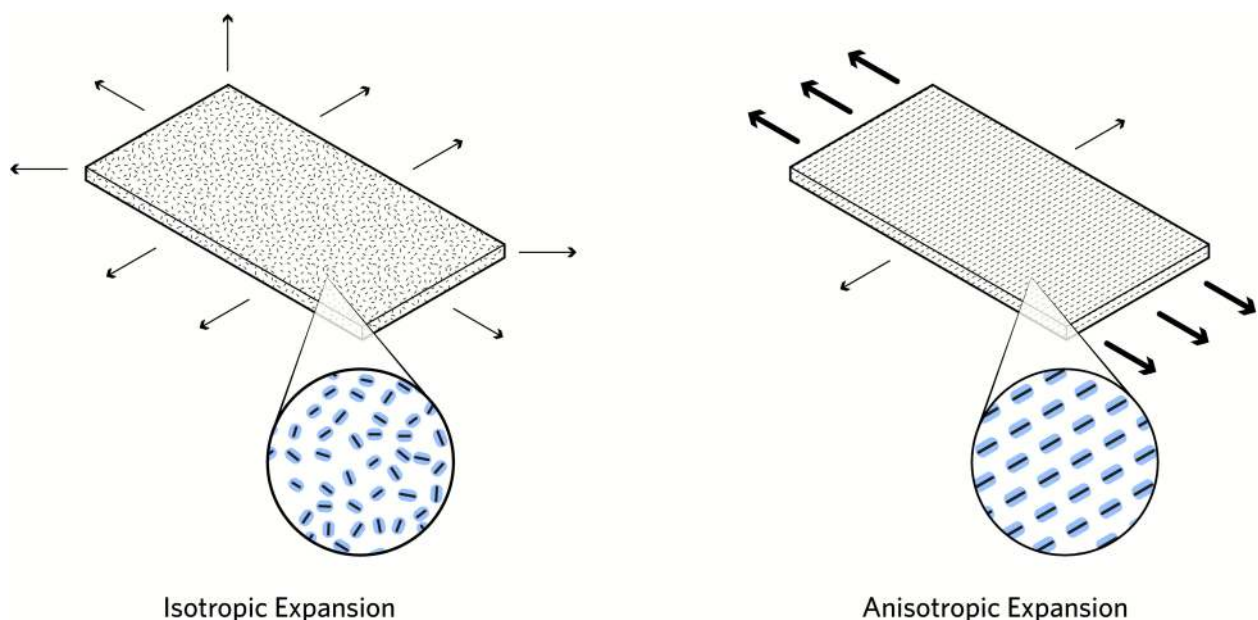


Fig. 1 Fibre arrangement in isotropic expansion compared to anisotropic expansion. Fibres in alignment create a stronger direction of expansion (anisotropy) and these direction-dependent properties affect shape-change in materials such as wood. The anisotropic properties of a material can be defined through the design of the raster patterns in 4D printing (4DP) using Fused Filament Fabrication (FFF) methods

desired expansion direction. This basically follows the same principle as designing raster patterns in 4DP. Hygroscopic actuators made with FFF can use fibre-polymer composite filaments as expansion layers and isotropic filaments like ABS, PLA, or TPU as constraint layers (Correa, 2022); the differential swelling causes stress-induced bending in the bilayer actuator. Examples of 4DP work include the use of hygroscopic natural fibres such as wood fibres (Le Duigou & Correa, 2022; Vazquez et al., 2020), paper pulp fibres (Mulakkal et al., 2018), and continuous flax fibres (De Kergariou et al., 2023; Fruleux et al., 2022; Le Duigou et al., 2017, 2021).

4DP has been used to transfer motion principles from plants, such as distribution of tissue growth or expansion, into the control of residual or internal stress states. However, while most 4DP actuators are printed flat, most plant structures are not (e.g. leaves, stems, or flowers). Many of their intricate motions are uniquely facilitated by their non-planar shapes and complex anatomical features. One of the most well-known plant movements is the prey-capturing mechanism of the Venus Flytrap (*Dionaea muscipula*), whose quick movement is kinetically amplified by the snap-buckling instability of its doubly curved lobes (Fig. 2a) (Forterre et al., 2005; Sachse et al., 2020) and has inspired several studies in materials like hydrogel (Lee et al., 2010), silicon (Holmes & Crosby,

2007), and shape memory polymers (Riley et al., 2020). Other examples of bio-inspired research include propagation mechanisms like the *Pinus wallichiana* scale bending (Fig. 2b) (Correa et al., 2020; Poppinga et al., 2020; Reyssat & Mahadevan, 2009; Tahouni et al., 2021; Zhu et al., 2019), *Dioscorea bulbifera* twisting stabilization (Fig. 2c) (Cheng et al., 2021), and the fast snap trapping of the carnivorous Waterwheel plant (*Aldrovanda vesiculosa*) with its midrib deformation (Fig. 2d and e) (Poppinga et al., 2020; Schleicher et al., 2015). The preceding examples use a variety of fabrication methods and materials, but 4DP is a rapidly developing field with high potential. The 4DP method allows direct transfer of plant geometry and tissue architecture through precise design and modelling of the mechanisms' principles.

Typical 3-axis FFF 3D printers deposit filament vertically, so when printing a bilayer structure, the default orientation is to print the largest surface area flat on the bed (Fig. 3a). This conventional printing method is advantageous due to the simplicity of modelling, designing, and manufacturing, but the structures produced are mostly limited to planar rest-states and z-axis direction shape-change. Early research aimed at achieving non-planar actuators has been completed by printing a cross-section of a plant cell's microstructure (Fig. 3b), resulting in moderately vertical auxetic lattices that move along the

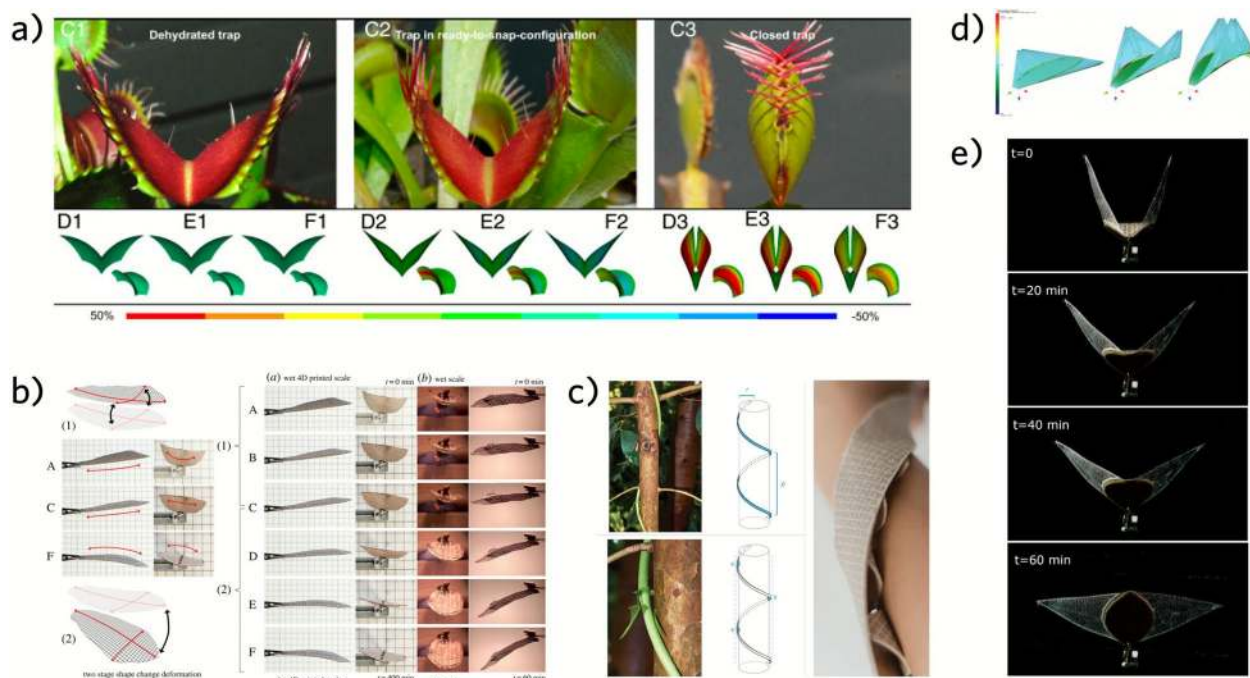


Fig. 2 Existing biomimetic research based on specific plant geometries. **a** Snap-buckling actuation process of the *Dionaea muscipula* (Sachse et al., 2020). **b** 4DP two-phase doubly curved movement based on the Bhutan pine scale (Correa et al., 2020). **c** 4DP coiling actuator based on the stabilization mechanism of the *Dioscorea bulbifera* (Cheng et al., 2021). **d** *Aldrovanda vesiculosa* prey-capturing mechanism (Schleicher et al., 2015) and **e** 4DP curved fold bending (Poppinga et al., 2020). All images adapted with permission

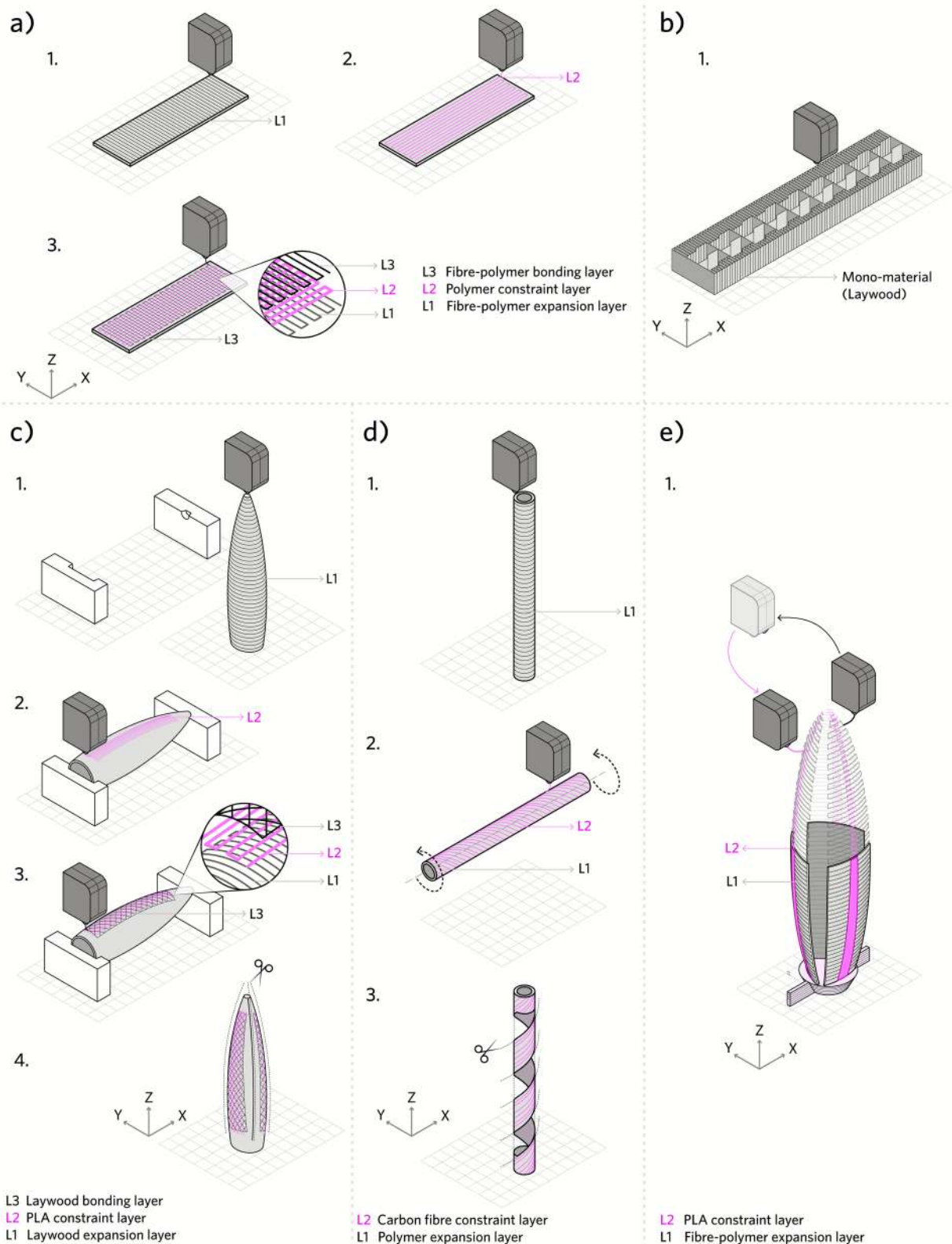


Fig. 3 4DP strategies. **a** Standard planar 4DP method. Expansion and constraint layers are stacked on top of each other. **b** Cross-sectional 4DP research (Sahin et al., 2023). **c** Multi-step non-planar research (Pelliccia et al., 2024). **d** Helicoidal 4DP method (Le Duigou et al., 2024). **e** Novel VPM-4DP method with expansion and constraint filaments printed side-by-side. The dual-extrusion nozzle switches filaments automatically between layers. Expansion layers shown in grey, constraint layers shown in pink

x/y-axis planar direction rather than the typical z-axis direction (Sahin et al., 2023). This approach sets it apart from previous 4DP research but does not address macro-scale curvature. Further work by Pelliccia et al. (2024) successfully addresses a double-curvature rest-state with 4DP hygroscopic actuators (Fig. 3c), however the fabrication process is considerably more complex as it requires multiple print sessions and customized non-planar g-code. Another approach would be to use a bespoke printer with more than 3 axes that can rotate while printing (Le Duigou et al., 2024) as shown in Fig. 3d, but there is still the issue of cost as well as difficulty in fine-tuning and accessing such printers. Considering the complications that may arise with other printing systems, a standard 3-axis printer is still the most accessible and versatile machine for printing non-planar or doubly curved actuators.

Using a 3-axis FFF dual-extrusion 3D printer, this research presents a new methodology of 4D printing hygroscopic actuators with doubly curved rest-state shapes. It requires only one print session as it uses one dedicated extruder each for the expansion and the constraint layer materials, printing the material side-by-side vertically, which then allows the printing of actuators with doubly curved geometries (Fig. 3e). In comparison to the previously described research, this simplifies and improves upon the process of creating non-planar actuators without increasing the need for specialized software or equipment. We propose to call this novel method Vertical Parallel Multi-Material 4D Printing (VPM-4DP). The terms “concurrent”, “parallel”, and “simultaneous” are established terminology when referring to multi-material 3D printing research; these terms refer to multiple filament types being printed at the same time (Al Ali et al., 2024; Bao et al., 2023; Gao et al., 2023). However, there is no previous literature that defines a methodology for multi-material 4DP that focuses on developing actuators with bilayers oriented vertically. Therefore, we propose VPM-4DP as a novel subcategory of 4DP that focusses on non-planar printing and actuation created through printing with multiple filaments side-by-side in this vertical configuration.

We demonstrate the novel capability of the VPM-4DP method by creating double-curvature rest-state structures based on the biological models of the *Bauhinia variegata* seed pod and the *Lilium* ‘Casa Blanca’ tepal. The *Bauhinia* is composed of two pod valves with fibrous layers at opposing 45° angles that bend in opposite directions during shrinkage, which results in twisting and opening as they release seeds (Armon et al., 2011). We expand on existing flat 4DP work based on this twisting mechanism (Cheng et al., 2021; Zeng et al., 2022) and printed double-curvature rest-states that more closely follow the half-ellipsoid shape of the pod. Additionally, we printed a structure based on the flower opening mechanism of the *Lilium* ‘Casa Blanca’. The convex doubly curved tepals of *Lilium* plants bend outward due to strain from differential edge growth, opening the flower for pollination (Liang & Mahadevan, 2011; Schleicher et al., 2015). Initial work by Correa (2022) mimicked the blooming motion from edge-driven growth with wood composite filament as the expansion material, ABS for constraint at the edges, and TPU for the flexible midrib, which was used to store elastic energy (Fig. 4a). Printing and assembling the structure, however, required multiple steps, including manually switching filaments and bending each tepal-like component along the midsection prior to actuation. Recent work by Pelliccia et al. (2024) further developed the *Lilium* blooming motion by using a multi-step printing process to introduce double curvature, eliminating the need for manual bending and assembly (Fig. 4b). Nevertheless, the complex process involves printing the expansion layer as a single shell, adding support for rotation, printing constraints and bonding layers with custom g-code, and finally splitting the shell into three tepals.

In contrast to previous work based on the *Lilium*, the novel VPM-4DP method does not require the same level of manual post-processing but can achieve similar or even improved results. This research continues to build on the previous 4DP *Lilium* models with the VPM-4DP method.

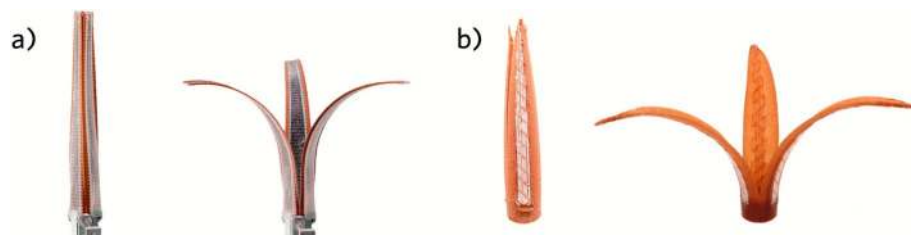


Fig. 4 Existing 4DP research based on the *Lilium* ‘Casa Blanca’. **a** Bio-inspired 4DP based on the lily blooming mechanism using wood composite filament with an initial flat rest-state (Correa, 2022; Poppinga et al., 2020). **b** Bio-inspired lily fabricated using a 4D multi-step printing method (Pelliccia et al., 2024). All images adapted with permission

2 Materials and methods

2.1 Materials used

Natural fibre-polymer composite filament is used for all 4DP tests. Due to the hygroscopic properties of the filament, the resulting printed structure has anisotropic swelling properties in response to water intake. The expansion filament is custom made by CC-Products (Germany) and composed of a TECHNOCEL® cellulose fibre and polyvinyl butyral-polyamide blend at 2.85 mm diameter. The constraint filament is supplied by Forward AM (The Netherlands) under the Ultrafuse® 2.85 mm PLA line. Compared to wood-composite filaments from other works that can range from 10 to 40% fibre content (Le Duigou et al., 2016; Pelliccia et al., 2024; Tahouni et al., 2021), which is standard for most off-the-shelf filaments, the filament used in this research likely has a similar composition to Laywoo-D3 (Laywood) at approximately 30–40% fibre content and therefore is on the higher end of absorbency potential.

2.2 Printing device

A dual-extrusion 3-axis FFF 3D printer (Ultimaker S3, Ultimaker B.V., The Netherlands) was used to print the structures. The dual extruder capability is crucial to this novel one-session approach due to the printer's ability to automatically switch between expansion and constraint filaments within the same layer, whereas previous work completed with single-extrusion printers required

manual changing of filament and limited the ability to print non-planar actuators.

The samples from this new method start as rectangular slabs with a standardized size of 20 mm wide by 100 mm long by 0.6 mm thick and become more complex as new parameters are introduced.

2.3 Printing strategy

The new proposed approach focuses on re-designing the relationship between expansion and constraint regions in the z-axis during printing. The rest-state (before actuation) curvature is defined with single print lines, each forming a curve in plan view, that are stacked onto each other hundreds of times to form a doubly curved surface (Fig. 5a). Both expansion and constraint regions are printed adjacent to each other, which is fundamentally different from the previously established 4DP method of stacking two laminar regions that are homogeneous in the x/y-axis. This new approach allows for multiple samples to be printed at the same time or a complete 4DP mechanism to be printed without the need for additional assembly or extensive post-processing. This is a more straightforward solution for introducing curved rest-states and multi-component structures to hygroscopic bilayered actuators.

The first step of establishing the potential of VPM-4DP is to achieve similar results to planar-printed actuators, whose basic movements are bending and twisting. Preliminary tests using a planar bilayer structure rotated

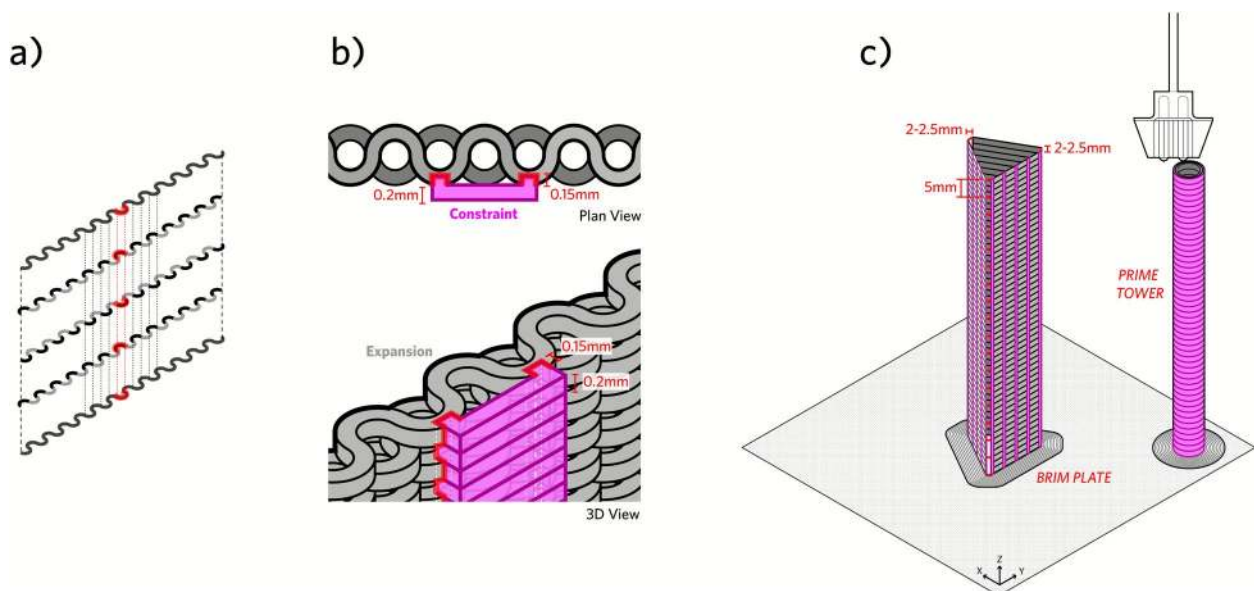


Fig. 5 The three key structural considerations that differentiate VPM-4DP from established 4DP methodology: **a)** alternating waved layers for stability, **b)** mechanical connections created by hooked constraints to strengthen the bond between expansion and constraint layers, and **c)** samples printed in groups with connecting support lines and a brim plate to increase stability of the parts during printing. Additional activation of the prime tower setting for nozzle wiping reduces filament clogging. Expansion layers shown in grey, constraint layers shown in pink

vertically on the print bed resulted in delimitation and delamination between the layers and overall instability. It was concluded that an exact transfer of planar designs would not be realistic due to geometric changes that arise from the vertical orientation, so we developed a method for design unique to vertical actuators.

There are three key structural considerations for vertically printed structures that need to be addressed before actuation occurs:

First, the geometry of the actuator is printed standing upright with the dominant longitudinal axis facing up along the z-axis. This orientation requires hundreds of vertical layers printed on top of each other. To achieve better adhesion and stability between each layer and prevent structural failure, the expansion layers are designed as undulating waves instead of straight lines like in typical 4DP (Fig. 5a). This is adapted from clay 3D printing strategies for improved layer adhesion and stability against buckling (Clarke-Hicks et al., 2023; Shi et al., 2019).

Second, to strengthen the adhesion of the constraint layer to the expansion layer, the constraints are modelled as long, hooked staples that extend into the expansion region approximately 0.15 mm and overlap to create a form of volumetric mechanical anchorage, which is stronger than interfacial bonding between the filament surfaces alone (Fig. 5b). This removes the need for an additional bonding layer as done in previous thin sheet 4DP literature.

Third, high aspect ratio samples (tall and thin) can be easily pushed out of place by the print head. To prevent this, it is best practice to print groups of samples at once and arrange them to form a triangle or a rectangle, with a brim plate connecting them at the bottom for bed adhesion. Single layer connections between the parts are also added, referred to here as lateral support lines. These support lines are 0.2 mm thick (1 layer) and occur approximately every 5 mm vertically. As a group, the optimal spacing between samples is approximately 2 mm to 2.5 mm apart to prevent fusing but allow supporting lines to attach (Fig. 5c). Post-processing of the structure involves trimming the supporting lines and the brim to split each sample apart. The printing of samples as a group with the support lines greatly increases the collective stability.

These three key considerations were implemented in all the samples presented in this paper. Collectively they are fundamental tools in this VPM-4DP methodology.

Print setting considerations for this novel method include the previously mentioned brim plate, and it is also critical to have the prime tower setting enabled, a setting that creates a secondary geometry used to wipe the nozzle after each layer and filament switch. This can

help reduce print failures from nozzle clogging. The print speed of both expansion and constraint filaments was slightly reduced to increase adhesion between layers.

Rhino (Robert McNeel & Associates, USA), Grasshopper (Robert McNeel & Associates, USA), and Cura (Ultimaker B.V., The Netherlands) are used in distinct modelling processes to transfer and adapt current 4DP concepts from planar to non-planar geometries that are printed vertically on the bed.

2.4 Characterization of shape-changing

For each test, the dry sample is submerged in ambient temperature (21° C) water for 5 h, then removed and placed upside down to dry at room temperature (23° C) and humidity (40% RH) for a similar amount of time.

The following tests are named according to curvature, motion type, and test order. The test prefix contains a number, 0 or 1 or 2, to describe the number of axes in which the samples have curvature in their initial rest-state (0 indicates no curvature, planar), plus a letter to represent whether bending (B) or twisting (T) is being tested. The number after the hyphen indicates the test order and multiple samples within the same test are ordered by the letter A, B, C, or D. In the following section, we investigate the design potential of this method with the goal of achieving bending and twisting in non-curved samples with progressively higher complexity and precision, starting with Test 0B-1.

3 Results

3.1 Shape-change in actuator with an initial flat slab-like geometry

3.1.1 Evaluation of moisture-induced bending and effect of constraint line distribution (Test 0B-1)

The strategy for inducing bending in 4DP with a bilayer architecture was transferred to VPM-4DP by adjusting the proportions of constraint and expansion regions, which both became thicker than previous planar bilayers in order to gain stability. Constraint regions, which functioned well as single lines in previous methods, were consolidated and widened to avoid delamination.

In a bilayer structure, the two surfaces are not always completely covered in material; particularly, the constraint layer might have lines or patterns. The more of the surface that is covered, referred to here as "constraint line surface ratio"(CLSR), the stiffer the part will be. If the entire surface is covered, then there will be full stiffness. If only half is, then the stiffness drops accordingly. For the presented CLSR coefficient, a "full constraint layer" refers to if the layer were made of just constraint filament without any voids or gaps.

$$CLSR\% = \frac{\text{Surface area of constraint lines}(ncl * w * l)}{\text{Surface area of full constraint layer}(w * l)}$$

Constraint thickness for all tests remained at 0.2 mm. Each bending test is accompanied by a graph plotting curvature (K) vs time when possible—samples with little movement were not mapped.

Test 0B-1, the first bending test and application of the undulating waved expansion layer and hooked constraint geometry, consists of samples with a thin slab-like geometry 20 mm wide by 100 mm long and 0.6 mm thick each with three variations: 0B-1A (1 constraint, central, CLSR 2%), 0B-1B (3 constraints, equal spacing, CLSR 6%), and 0B-1C (5 constraints, equal spacing, CLSR 10%), all with the same constraint width of 0.4 mm (Fig. 6a). All variants underwent bending with 0B-1C moving the most due to more constraints inducing greater stiffness (Fig. 6b and c) (Online Resource 1). This test demonstrates that the same principles used to create bending in planar 4DP are applicable to VPM-4DP non-curved actuators.

3.1.2 Evaluation of moisture-induced bending and effect of edge-located constraint line distribution (Test 0B-2)

Test 0B-2 investigated the impact of constraint placement along the transversal axis in relation to bending amplitude (range of displacement). Three variations were tested: 0B-2A (1 constraint, 3.6 mm wide, central, CLSR 18%), 0B-2B (1 constraint, 3.6 mm wide, left edge, CLSR 18%), and 0B-2C (2 constraints, 1.8 mm wide, equal spacing, CLSR 18%), one at each edge (Fig. 7a). 0B-2A and 0B-2C had similar amplitudes of bending. 0B-2B, with one edge constraint, bent less likely due to the uneven distribution of the constraint, which caused a corresponding uneven bending and potentially a lower stress gradient (Fig. 7b and c).

3.1.3 Evaluation of moisture-induced twist bending (Test 0T-1)

Previous planar 4DP achieved twisting by changing the angle between the expansion layer and the constraint layer, such as to a 45° diagonal, but this methodology cannot be directly transferred to VPM-4DP due to the way filament is deposited by a standard 3D printer. The new vertical orientation of the samples meant that diagonal directionality in the expansion layer could not be generated without creating breaks within each filament layer, which eliminated any directional impact and compromised collective adhesion. Therefore, if diagonals could not be incorporated into the expansion layer, then the constraint layer geometry would have to be the directional driver of the twisting motion.

Test 0T-1 evaluates the impact of constraint lines arranged diagonally with four variations: 0T-1A (1

constraint, 3.6 mm wide, CLSR 18%) and 0T-1B (1 constraint, 2.2 mm wide, CLSR 11%) with one diagonal constraint spanning across the entire sample, and 0T-1C (4 constraints, 2.2 mm wide, CLSR 12%) and 0T-1D (4 constraints, 1.2 mm wide, CLSR 7%) with 45° diagonal constraints spaced evenly (25 mm spacing) (Fig. 8a). The width of these diagonal constraints was widened from the 0.4 mm used in bending tests to increase surface area and reduce delamination since the angle of the constraints left cantilevering portions between the layers. 0T-1A and 0T-1B bent but did not twist, possibly due to the constraint angle being too small, while 0T-1C saw some limited but inconclusive movement (Fig. 8b). In other 4DP research, 45° appears to be the optimal angle to induce twisting, therefore this value was carried over to the following twisting tests (Cheng et al., 2021; Josselin et al., 2025; Le Duigou et al., 2024). 0T-1D was the most successful variation that achieved clear twisting, demonstrating that constraint angle and frequency play a critical role. Using these results, the tests moved forward to further solidify the geometric requirements of inducing twisting.

3.1.4 Evaluation of moisture-induced twist bending (Test 0T-2)

Test 0T-2 modified the frequency and width of 45° diagonal constraints with three variations: 0T-2A (same as 0T-1D, 4 constraints, 1.2 mm wide, CLSR 7%), 0T-2B (9 constraints, 0.6 mm wide, CLSR 14%), and 0T-2C (19 constraints, 0.6 mm wide, CLSR 27%) (Fig. 9a). All the variations achieved twisting with the most motion from 0T-2A and 0T-2B. Comparing 0T-2B and 0T-2C, 0T-2B was more successful with fewer constraints. However, 0T-2A and 0T-2B achieved a similar amount of twisting, with 0T-2B twisting more, despite the previous comparison noting that fewer constraints were more successful (Fig. 9b) (Online Resource 2). This could be explained by the thinner constraints on 0T-2B reducing the impact of increased frequency but also suggests a relationship between the constraint width, frequency, and spacing to movement. With that knowledge, after twisting was achieved (Fig. 10), actuators were further developed to have single-axis (monoclastic) curvature at their initial rest-state, prior to moisture intake.

3.2 Shape-change in actuator with an initial single-axis curvature (monoclastic)

After demonstrating that this new VPM-4DP method can achieve bending and twisting in non-curved actuators (planar rest-state), these next tests address samples that have single-axis curvature in their initial rest-state. We refer to them as monoclastic actuators.

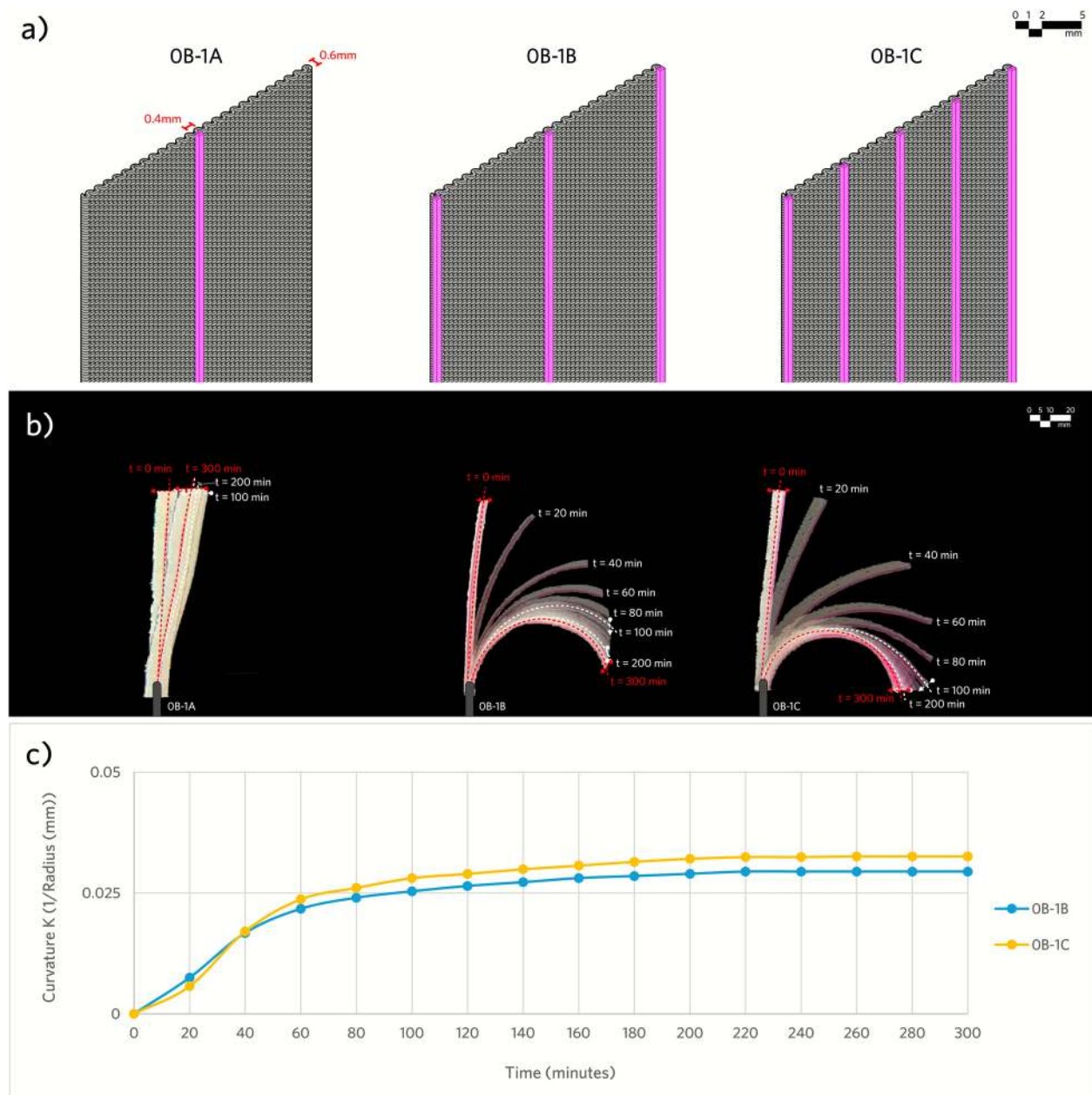


Fig. 6 Images from Test OB-1. **a** The first bending test, OB-1, consists of three 0.4 mm wide constraint variations. OB-1A has one central constraint, OB-1B has three constraints, and OB-1C has five constraints. The constraints are fewer but wider compared to similar existing 4DP research to reduce areas of potential delamination. Expansion layers shown in grey, constraint layers shown in pink. **b** OB-1C, the sample with the most constraints, underwent the most bending. **c** Graph describing curvature (K) vs time. OB-1B and C had a similar amount of curvature with slightly more from OB-1C. The most movement occurs within the first 60 min of submersion, after which it decreases considerably. After application of the previously described structural considerations, this first test achieves bending using the same principles as flat 4DP

3.2.1 Evaluation of moisture-induced bending from monoclastic to anticlastic double curvature (Test 1B-1)

Test 1B-1 used the same five 0.4 mm constraints as the most successful variation from the first non-curved bending test (Test OB-1C), therefore they have the

same CLSR at 10%. These constraints were placed on the outer surface of the samples, i.e. the convex side, to create bending in the direction opposite the curvature. Four variations of initial curvature radius were tested: 1B-1A (25 mm), 1B-1B (20 mm), 1B-1C (15 mm), and 1B-1D (10 mm) (Fig. 11a). Despite the success of these

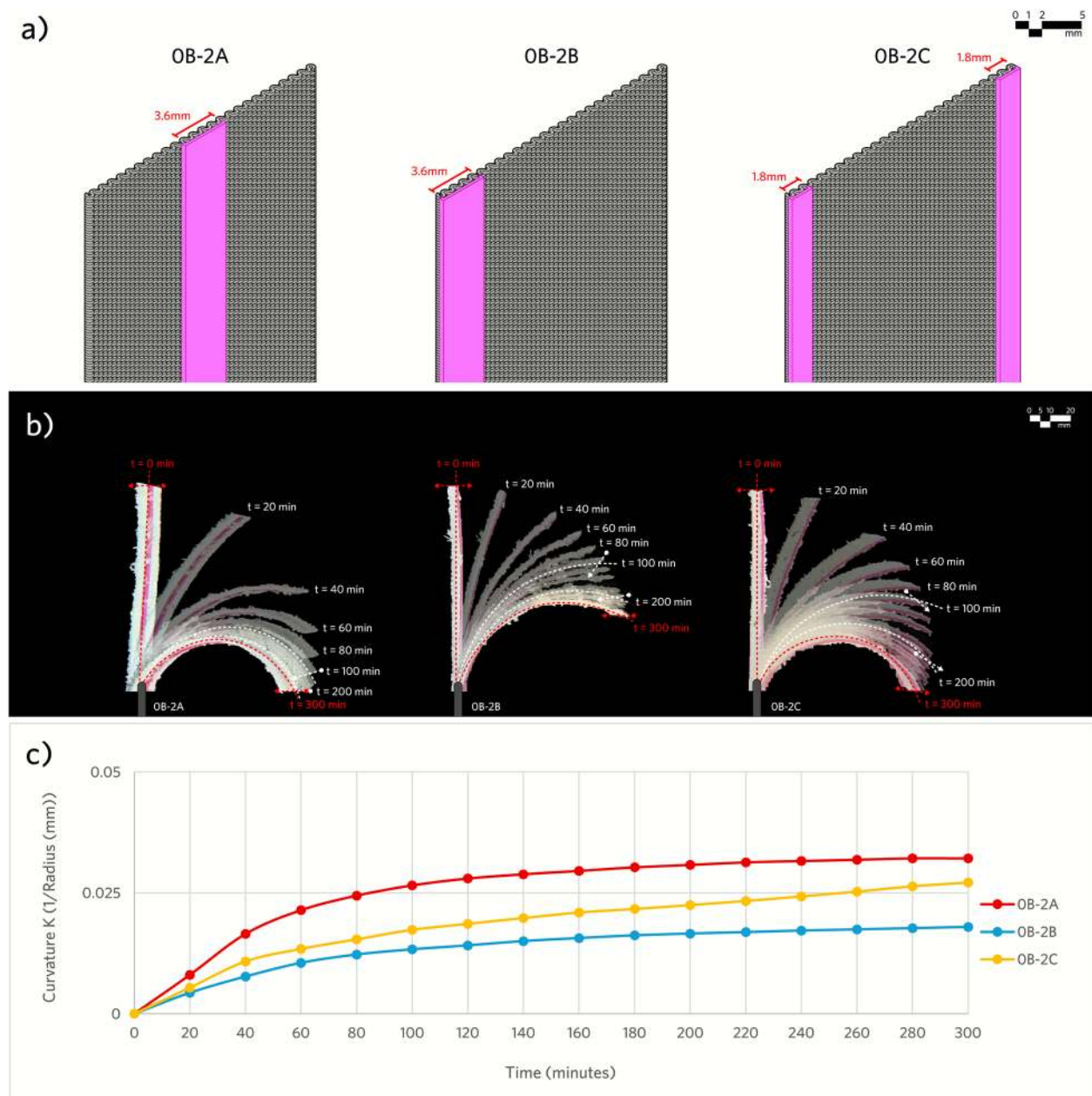


Fig. 7 Images from Test OB-2. **a** Test OB-2 consists of three constraint location variations. OB-2A has one central constraint, OB-2B has one edge constraint, and OB-2C has one constraint at each edge. Expansion layers shown in grey, constraint layers shown in pink. **b** OB-2A and OB-2C bent similarly, while OB-2B did not bend as much likely due to the concentration of the constraint at one edge. **c** Graph describing curvature (K) vs. time. OB-2C continues to increase bending almost consistently after 60 min, compared to the other two samples which decrease in curvature change

constraint parameters on the earlier bending test, none of the single-axis curvature samples had bending in the desired direction other than slight movement from 1B-1A, the variation with the largest radius (Fig. 11b). However, bending in the direction opposite from the constraints was seen in 1B-1B and 1B-1C, indicating

that the constraint parameters were no longer sufficient for constraining the swelling of the expansion layer. There was no significant movement in 1B-1D, but the sample visibly swelled and extended in length. It can be deduced that the initial curvature provides the sample with geometric stiffness (through moment of inertia), acting like a curved beam. In addition, a smaller radius

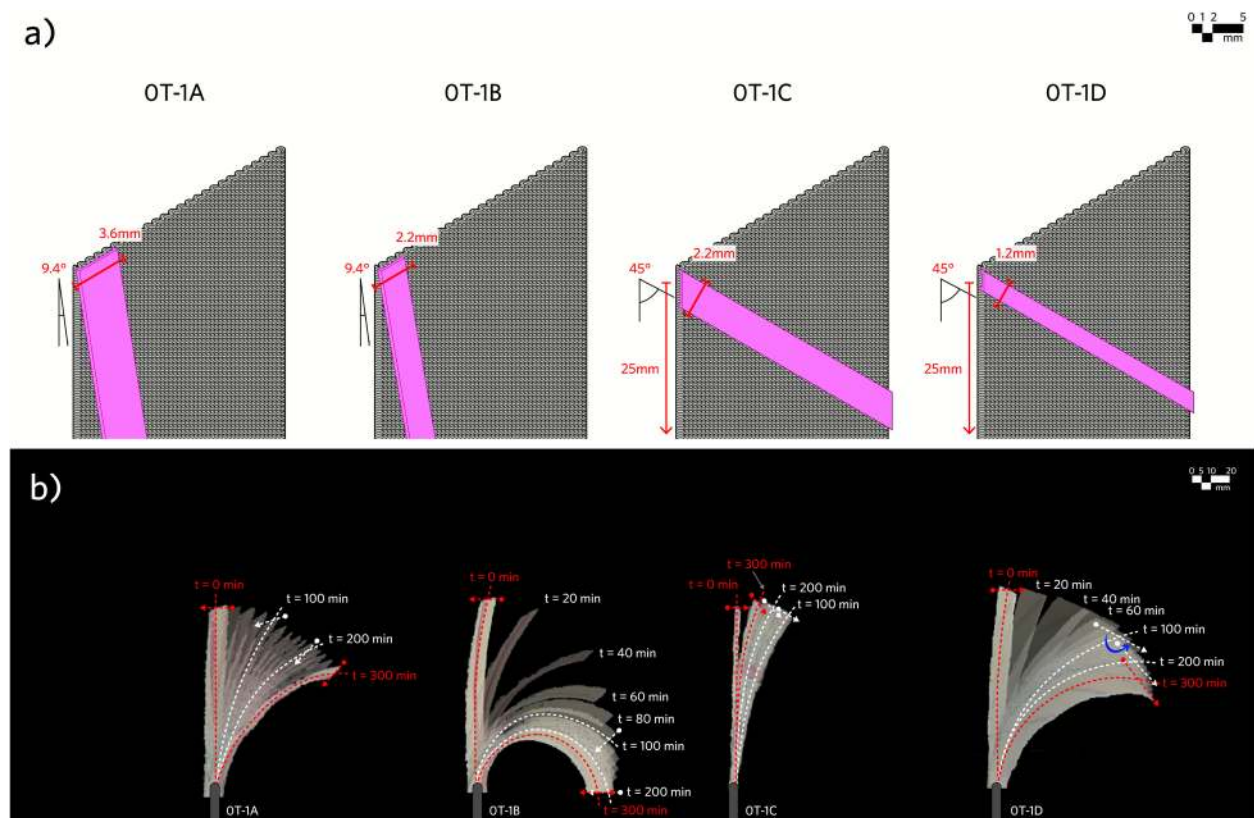


Fig. 8 Images from Test OT-1. **a** The first twisting test OT-1 uses diagonal constraints to induce twisting instead of a diagonal toolpath in the expansion layer, which is how twisting was achieved in previous 4DP research. The vertical orientation of these samples makes a diagonal toolpath generally unachievable with a 3-axis gantry printer due to how filament is deposited. OT-1A and OT-1B have one constraint that spans the entire length of the sample while OT-1C and OT-1D have four distributed evenly along the sample. Expansion layers shown in grey, constraint layers shown in pink. **b** OT-1D was the only sample that clearly twisted, indicating that the angle, width, and distribution of those constraints were sufficient for inducing twisting. Twisting indicated on image with a blue arrow

results in higher geometric stiffness. This stiffness must be overcome to allow bending and shape-change.

3.2.2 Evaluation of moisture-induced bending from monoclastic to anticlastic double curvature (Test 1B-2)

Because results from the variations with smaller radii were farther from the desired motion, the next tests increased the radius of the variations to 30 mm. In addition, because it was considered that the constraint parameters used in Test 1B-1 from Test 0B-1C were not sufficient for constraining the expansion layer, the frequency of constraints was increased to nine and the constraints were widened. Test 1B-2 uses a 30 mm radius for the first two variations, 1B-2A (0.4 mm wide, CLSR 18%) and 1B-2B (1.2 mm wide, CLSR 54%), and 25 mm radius for the other two, 1B-2C (0.8 mm wide, CLSR 36%) and 1B-2D (1.2 mm wide, CLSR 54%) (Fig. 12a). The additional constraints on 1B-2A were still not enough to completely constrain the

expansion layer, as seen from the movement that had only a bit more bending than 1B-1A from the previous test. The wider 0.8 mm constraints on 1B-2C were only marginally more successful. However, 1B-2B was extremely successful in bending and even curled out of the water, so the properties of nine 1.2 mm wide constraints on a radius of 30 mm were ample for creating motion. The same 1.2 mm constraints also did well on a 25 mm radius in Test 1B-2D, though not to the same amplitude of bending (Fig. 12b) (Online Resource 3). Comparing Test 1B-2B and 1B-2D confirms that preserving the same constraints while changing the curvature radius of the expansion layer produces different results (Fig. 12c). As well, it is possible that bending in these single-curvature samples is facilitated by a snap-buckling instability. The single-axis flat bending tests achieve more bending immediately after submersion, whereas these samples have less initial movement because of resistance from the curvature. It may be that continuous bending ultimately causes the curvature to

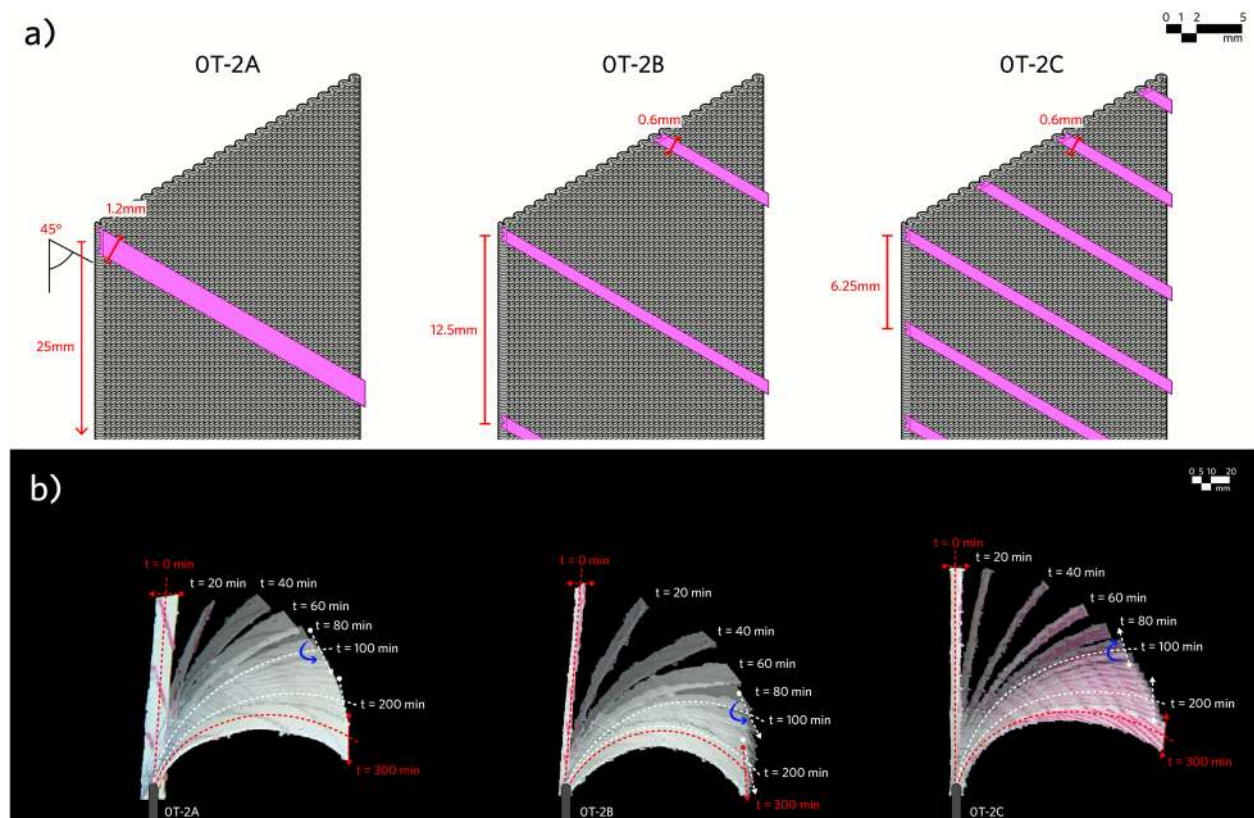


Fig. 9 Images from Test OT-2. **a** Test OT-2 consists of three constraint variations. OT-2A has the same four constraints as OT-1D, while OT-2B and OT-2C increase the number of constraints but reduce the constraint width by half. Expansion layers shown in grey, constraint layers shown in pink. **b** OT-2B was most successful in twisting with fewer constraints than OT-2C. However, OT-2B was also more successful than OT-2A, which had even fewer but wider constraints. Therefore, there must be an ideal ratio of constraint width and distribution to achieve the optimal amount of twisting. Twisting indicated on image with a blue arrow

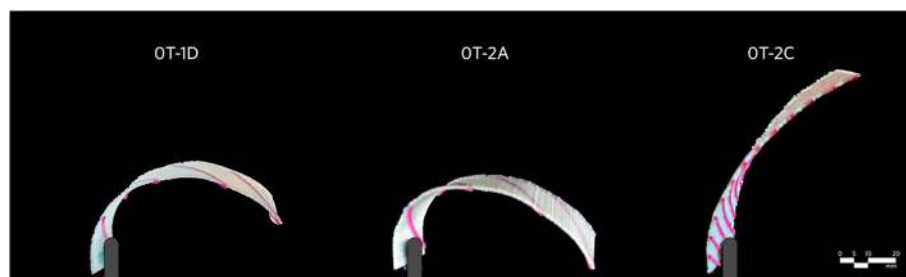


Fig. 10 Final images of OT-1D and OT-2A, which use the same constraints, and OT-2C with thinner and more frequent constraints. Visible twisting can be seen in all three samples, but the increased twisting in the first two samples demonstrates that the ratio of constraint width to frequency to expansion layer has a significant impact on movement

flip outward at the point of deformation and amplifies movement.

3.2.3 Evaluation of constraint distribution in monoclastic actuators (Test 1B-3)

The next set of tests investigated the relationship between constraint width and frequency, and the impact of these

parameters on movement speed or amplitude. The same total amount of constraint (10.8 mm, CLSR 54%) was used for all samples but each sample had this percentage distributed differently in three variations: 1B-3A (same as 1B-2B, 9 constraints, 1.2 mm wide), 1B-3B (5 constraints, 2.2 mm wide), and 1B-3C (3 constraints, 3.6 mm wide) (Fig. 13a). Presumably if the CLSR is equal in

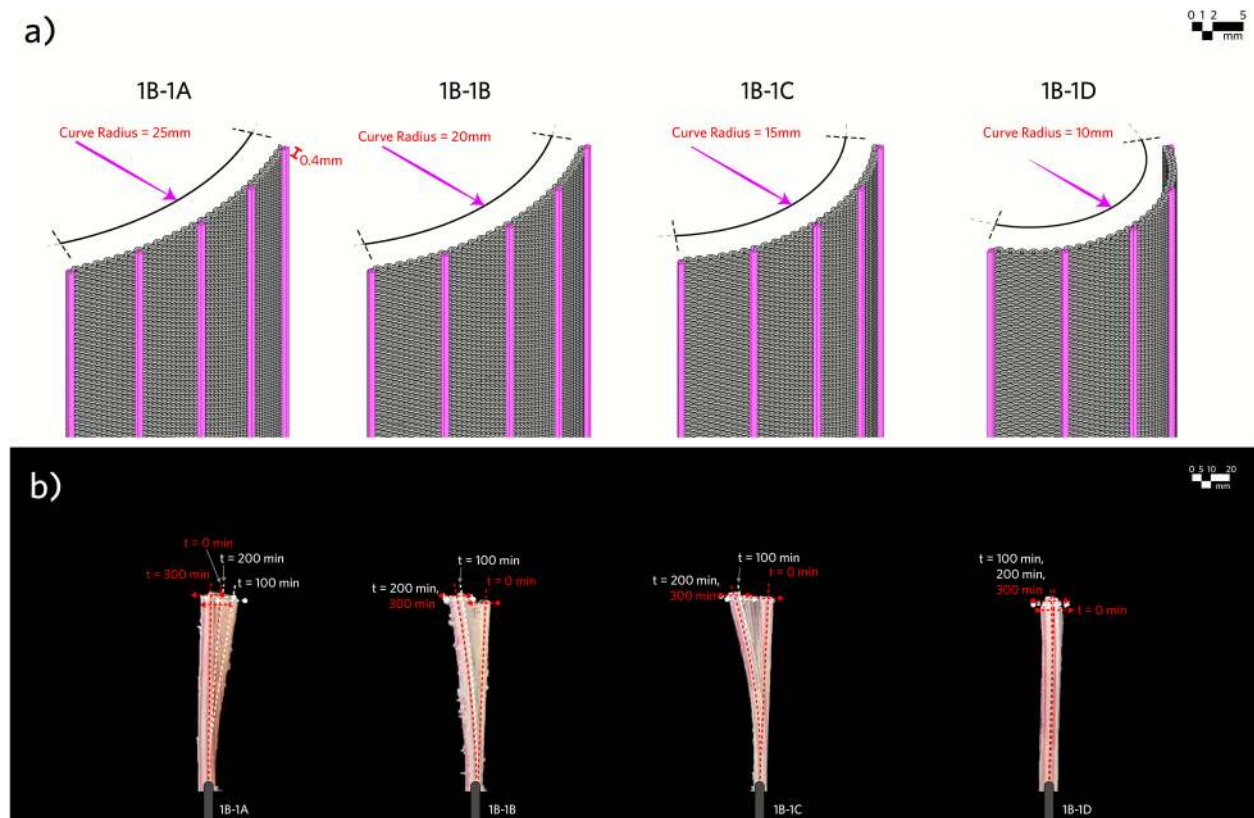


Fig. 11 Images from Test 1B-1. **a** Test 1B-1 introduces curvature to the samples by using the same five constraints as 0B-1C arranged on four different curvature radius variations, with the largest radius at 25 mm on 1B-1A and the smallest at 10 mm on 1B-1D. Expansion layers shown in grey, constraint layers shown in pink. **b** No notable bending in the desired direction was seen from any of the samples. However, the backward bending from 1B-1B and 1B-1C indicates that the previously successful constraints were no longer enough to constrain the swelling of the expansion layer after introducing curvature. 1B-1D with the smallest radius had almost no movement at all

all three samples then the overall stiffness is also equal. The expectation was that they might have a relatively similar amount of bending, but the test showed that sample 1B-3C with the fewest but widest constraints moved the most and fastest (Fig. 13b and c). We speculate that perhaps there is a relationship between constraint distribution and the expansion layer. From completing these single-curvature bending tests, the research has established that introducing curvature changes the geometric properties that were previously successful for inducing bending in planar tests. Furthermore, in curved tests, those parameters must be modified by increasing constraint volume to compensate for additional resistance from curvature radius decreases.

3.2.4 Evaluation of twist bending in monoclastic actuators (Test 1T-1)

This test aims to achieve twisting in a geometry with single-curvature rest-state by combining and adapting the parameters of the successful planar twisting tests (Tests 0T-1D and 0T-2) and last curved bending test (Test

1B-3). Test 1T-1 maintains the 30 mm curvature radius from Test 1B-3 and the four evenly spaced 45° diagonal constraints from Test 0T-1D. However, it increases the width of the expansion layer to 0.8 mm to reduce fragility, as well as the constraint widths to account for the increased curvature resistance. There are four variations: 1T-1A (1.6 mm wide, CLSR 9%), 1T-1B (2.4 mm wide, CLSR 14%), 1T-1C (3.2 mm wide, CLSR 18%), and 1T-1D (3.2 mm wide, CLSR 18%, further increased expansion layer width of 1.0 mm) (Fig. 14a). The results of this test show that all variations had a similar small amount of twisting, though 1T-1D was considered marginally more successful due to the wider constraints and increased expansion layer width that prevented the sample from splitting apart from twisting as much as the others (Fig. 14b).

3.2.5 Evaluation of twist bending in monoclastic actuators (Test 1T-2)

The amount of twisting achieved by tests 0T-1 and 0T-2 was more pronounced than the 1T-1 tests even though

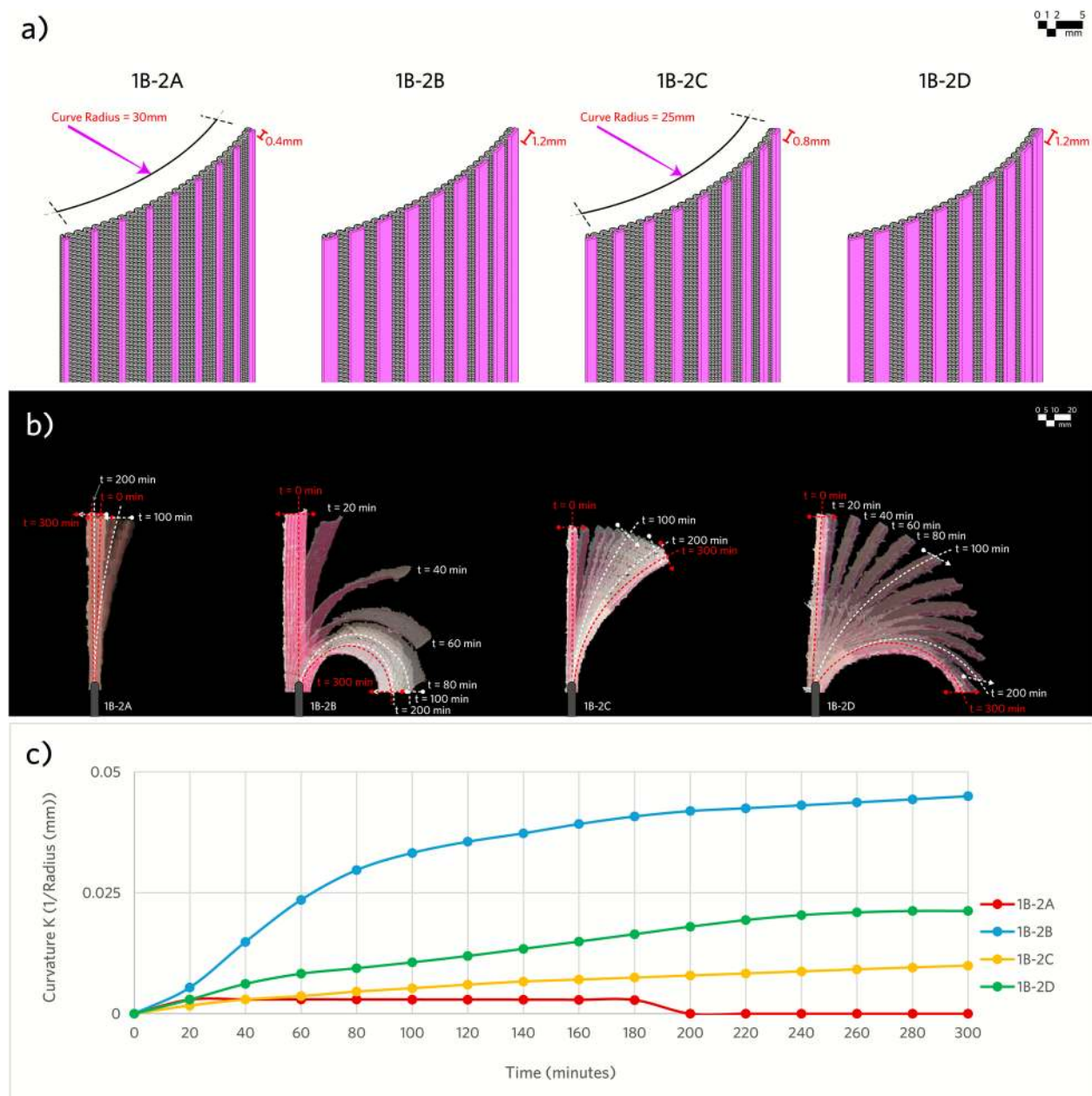


Fig. 12 Images from Test 1B-2. **a** Test 1B-2 consists of four variations with increased curvature radius, either 25 mm or 30 mm, and greater constraint width and frequency. Expansion layers shown in grey, constraint layers shown in pink. **b** 1B-2A and 1B-2C with thinner constraints only had slight bending, but 1B-2B and 1B-2D with wider constraints had significant bending. However, 1B-2D with a smaller radius did not bend as much as 1B-2B despite using the same constraints. This confirms that smaller radii do create more resistance to constraints and therefore movement, so constraint parameters should be adjusted accordingly. **c** Graph describing curvature (K) vs time. 1B-2B achieves much more curvature change between 20 to 80 min. The lower curvature change before 20 min is likely due to initial resistance created by the radius curvature

the latter had wider constraints. Based on these findings, we test two additional parameter variations in test 1T-2. The first option is to increase the overall constraint volume by increasing frequency or width of segments with variations 1T-2A (9 constraints, 2.4 mm wide, CLSR 27%) and 1T-2D (4 constraints, 4.0 mm wide, CLSR 23%)

(Fig. 15a). More constraint volume did result in slightly more twisting from 1T-2A and 1T-2D, but it still did not achieve as much as the planar twisting tests. The second option is to introduce an additional element to strengthen the constraint direction at the edges, similar to some species of plants that have thicker edges on leaves. Variations

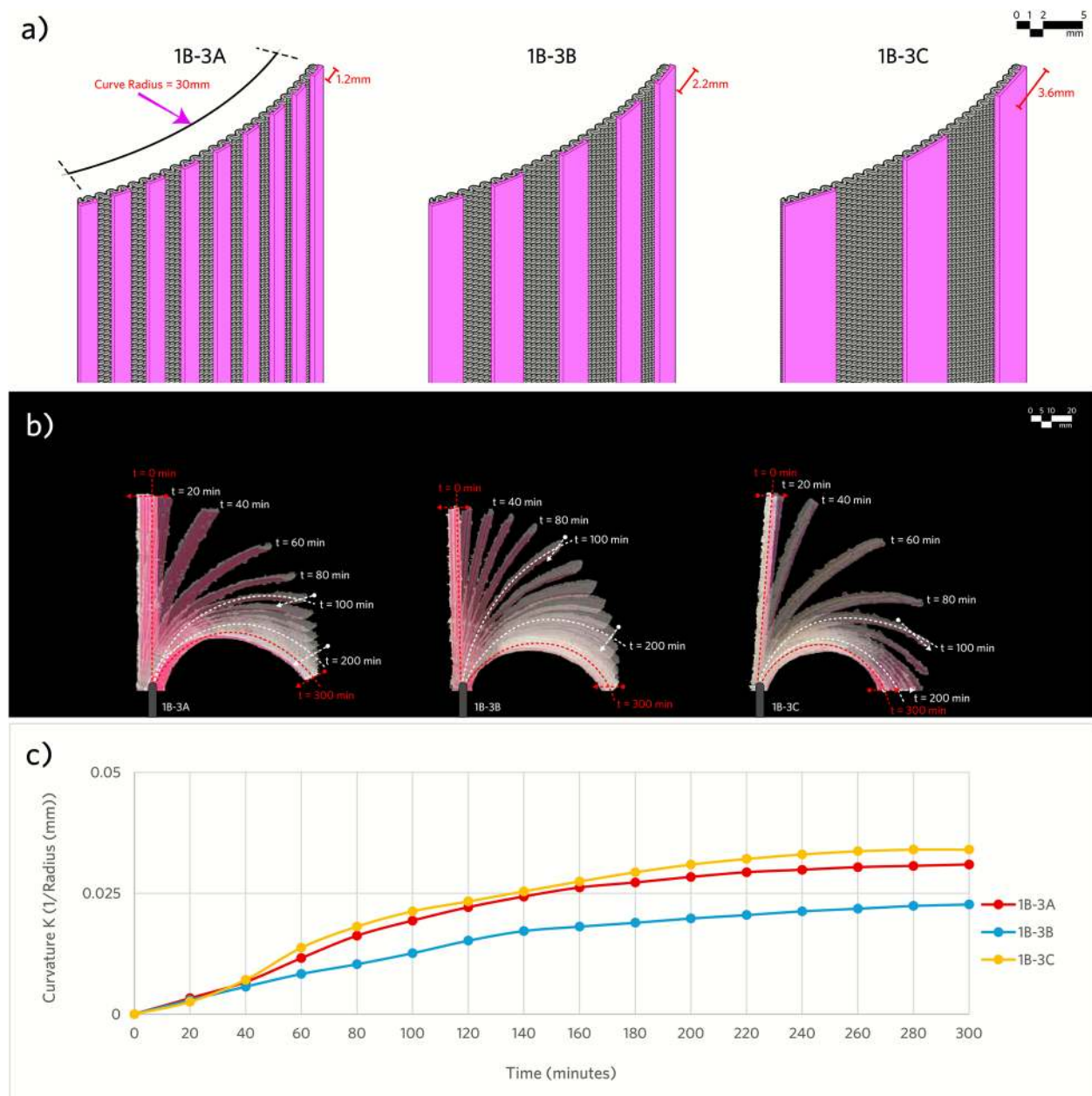


Fig. 13 Images from Test 1B-3. **a** Test 1B-3 consists of three variations using the same total constraint width, 10.8mm (CLSR 54%), divided into smaller segments of differing width and frequency. Expansion layers shown in grey, constraint layers shown in pink. **b** Despite the same total amount of constraints, 1B-3C had the most bending with fewer and wider constraints. This could be due to the relationship between constraint distribution and the expansion layer where there is an optimal distribution pattern. **c** Graph describing curvature (K) vs time. 1B-3C had the fastest curvature change while 1B-3B was slower and more consistent

1T-2B and 1T-2C use the same four 3.2 mm wide diagonal constraints as 1T-1D with an additional vertical edge constraint of 0.6 mm wide in 1T-2B (CLSR 21%), and 1.2 mm wide in 1T-2C (CLSR 23%) (Fig. 15a). The addition of a vertical constraint somewhat reduced the amplitude of twisting in 1T-2B and 1T-2C, which could mean that twisting is affected by edge rotation ability. Initially it was

hypothesized that an additional edge constraint would increase bending while the existing diagonal constraints induced twisting, but 1T-2B and 1T-2C visibly started to twist before stopping at a certain rotation then proceeded to bend, so it may be that the two constraint directions limited each other (Fig. 15b and c).

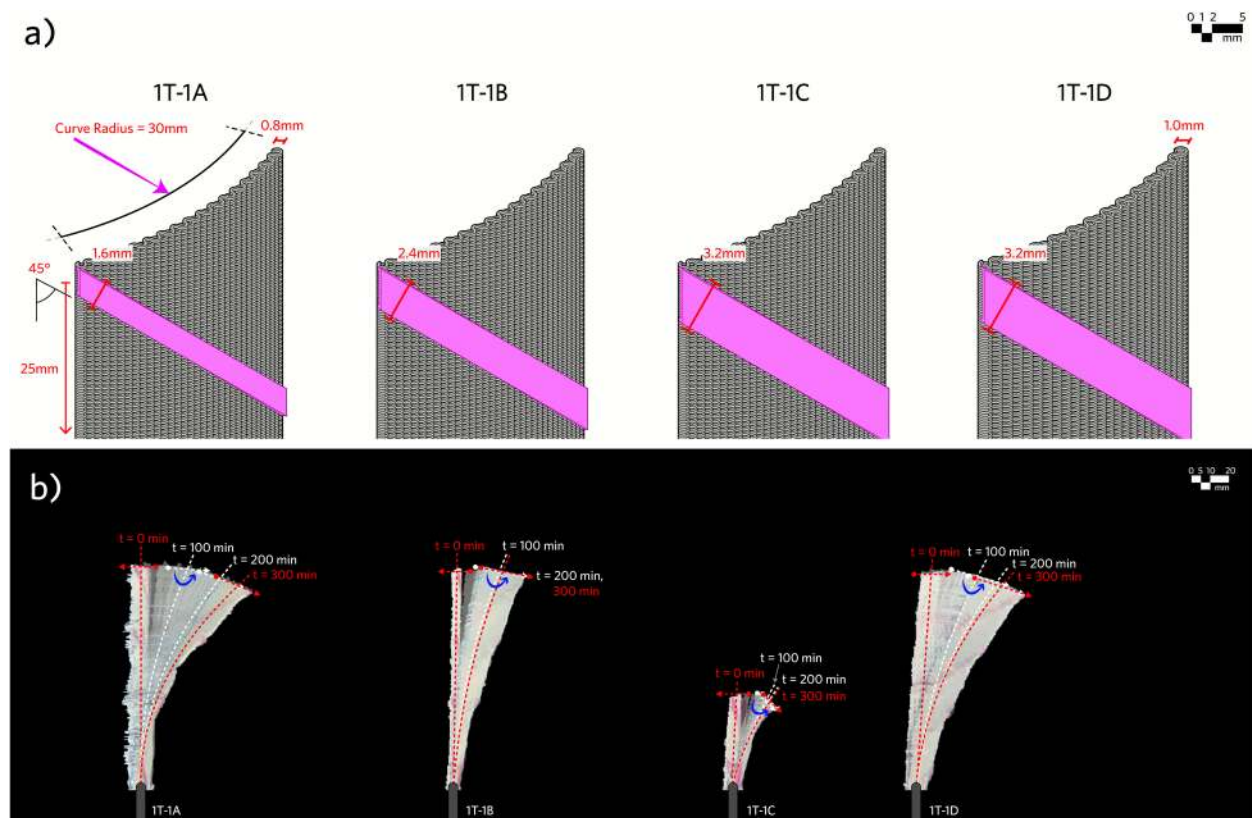


Fig. 14 Images from Test 1T-1. **a** Test 1T-1 consists of four variations each with four diagonal constraints. The widths of the constraints differ across the variations. The constraints are wider than the previous successful non-curved twisting test, OT-1D, to adjust for the added curvature. The expansion layer width was also increased to reduce fragility. Expansion layers shown in grey, constraint layers shown in pink. **b** All samples had some twisting, with 1T-1D being slightly more successful due to wider constraints and thicker expansion layer, but none achieved the same amplitude of twisting seen in Tests OT-1D and OT-2. Twisting indicated on image with a blue arrow

3.2.6 Evaluation of twist bending in monoclastic actuators (Test 1T-3)

An additional test was set up to confirm the effectiveness of the vertical constraint by adjusting its parameters. The same four 3.2 mm wide diagonal constraints from the previous test are used with a vertical edge constraint of 2.2 mm wide in 1T-3A (CLSR 27%) and 3.6 mm wide in 1T-3B (CLSR 33%). The diagonal constraint volumes were also adjusted on a 25 mm radius with variations 1T-3C (9 constraints, 3.2 mm, CLSR 36%) and 1T-3D (9 constraints, 4.0 mm, CLSR 45%), increased from the previous test to account for the smaller radius (Fig. 16a). Increasing the vertical edge constraint width in 1T-3A and 1T-3B did result in more pronounced bending, but it almost completely eliminated twisting and supports the previous observation of the constraint limiting edge movement and twisting. On a 25 mm radius, 1T-3C was successful in achieving a similar amplitude of twisting as previous tests by increasing the constraints from 2.4 mm to 3.2 mm wide (+0.8 mm). With slighter wider constraints, 1T-3D even surpassed the previous amplitude of

twisting (Fig. 16b and c) (Online Resource 4). It could be extrapolated that another 5 mm decrease in radius to 20 mm could be compensated with an increase of 0.8 mm in the constraints to 4.0 mm, as implemented in 1T-3C, to achieve the same twisting.

Overall, the results from these single-curvature tests demonstrate the concept that curved shapes require more constraints to induce the same level of movement as planar shapes; furthermore, the smaller the radius of curvature, the more constraints are necessary due to increased resistance to deformation in the direction of curvature. With this knowledge, the final tests conclude this research by applying these parameter modifications to double curvature.

3.3 Shape-change in actuator with an initial double-axis curvature (synclastic to anticlastic)

Reflecting on the initial goals to transfer non-planar biological shapes into 4DP, this work has demonstrated the ability of VPM-4DP to print curved actuators that shape-change similarly to planar 4DP. Nonetheless,

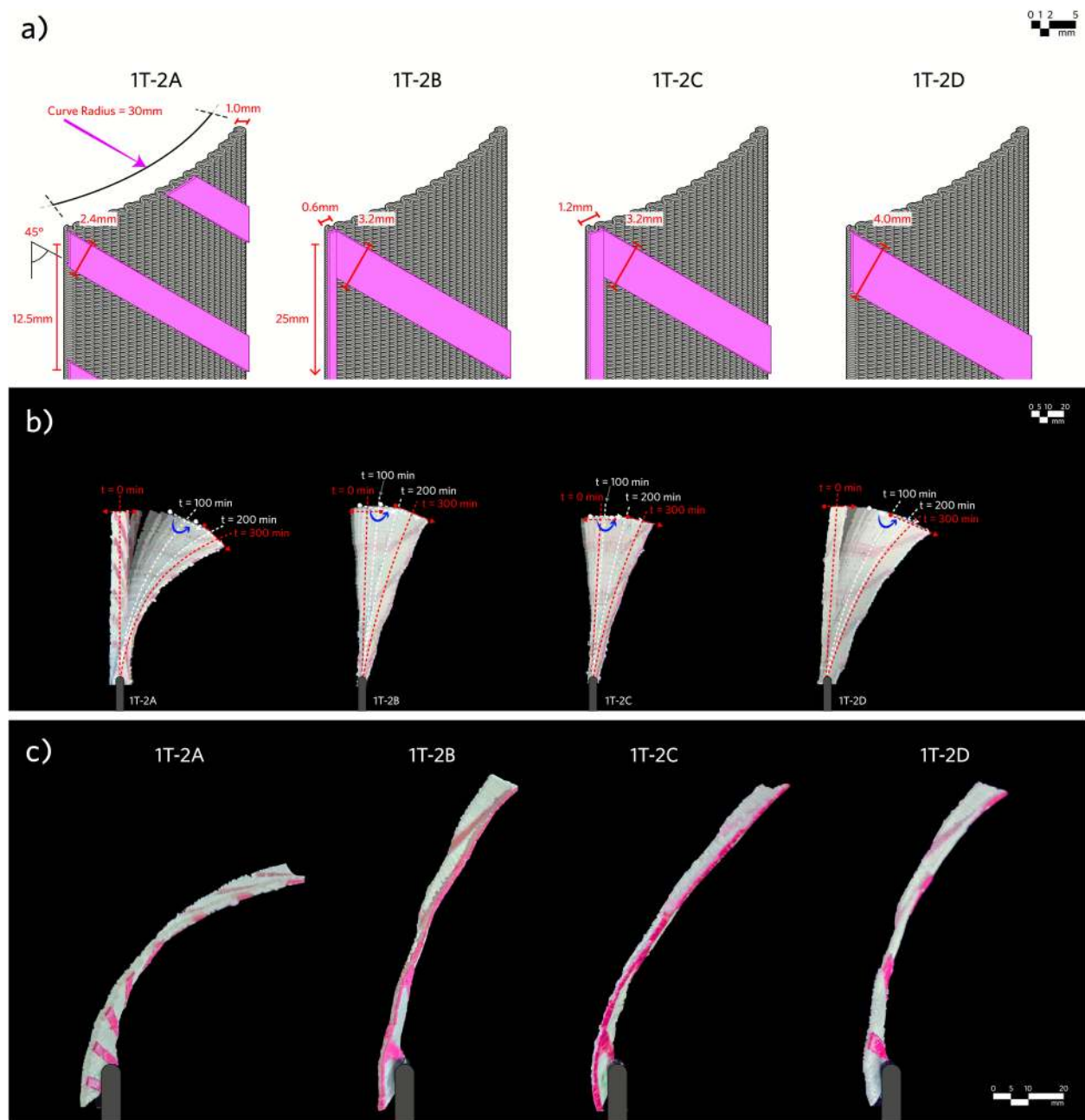


Fig. 15 Images from Test 1T-2. **a** To increase twisting, the existing constraints can be widened or more frequent, or an additional constraint element can be introduced to strengthen the constraint direction. 1T-2A and 1T-2D use the former strategy while 1T-2B and 1T-2C use the latter. Expansion layers shown in grey, constraint layers shown in pink. **b** 1T-2A and 1T-2D have slightly more twisting from increasing previous constraints. The additional edge constraint used on 1T-2B and 1T-2C increased bending but appeared to also somewhat restrict twisting. Twisting indicated on image with a blue arrow. **c** Final images of the samples

its further potential lies in its ability to print a pre-assembled double-curvature structure. With this new method, the two mirrored halves of the twisting *Bauhinia* pod can be printed attached together and with a more accurate surface curvature, as well as the tepals of the *Lilium* flower.

3.3.1 *Bauhinia* pod: Evaluation of moisture-induced twist bending from synclastic to anticlastic (Test 2T-1)

To create a shape more similar to the half-ellipsoid of the pod where the ends of the valves taper together, the radii along the long axis of the pod also taper smaller at the ends and therefore require the constraint widths to be

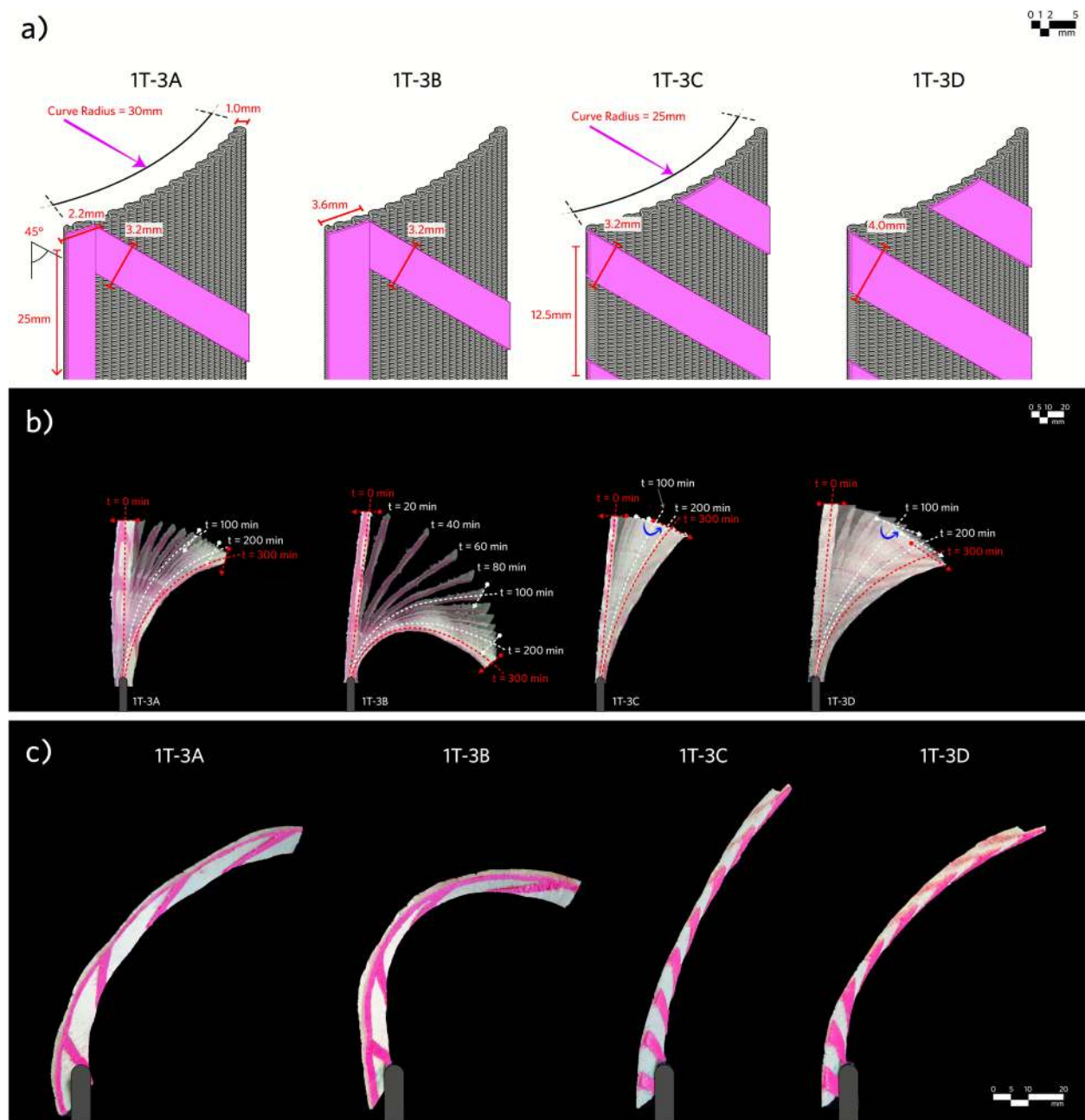


Fig. 16 Images from Test 1T-3. **a** Test 1T-3 consists of four variations that build on the previous strategies of widening existing constraints or introducing an additional constraint element. 1T-3A and 1T-3B widen the additional constraint element while 1T-3C and 1T-3D widen the existing diagonal constraint width. Expansion layers shown in grey, constraint layers shown in pink. **b** Wider constraints on 1T-3C and 1T-3D did result in more twisting. Increasing the edge constraint width on 1T-3A and 1T-3B created more bending, but further restricted twisting. This could imply that edges are involved in twisting, and therefore unrestrained edges are necessary for the twisting motion to occur. Twisting indicated on image with a blue arrow. **c** Final images of the samples

adjusted accordingly, as previously demonstrated. A few geometric changes to the printing methods were made to accommodate the doubly curved form: first, the pods were printed in multiples in a triple-line asterisk following the stability strategy established in the initial tests.

Second, supports were required under the bottom-most curve of each pod, which were manually modelled as thin-walled and hollow for ease of removal during post-processing. Third, each pod had support lines connecting the two halves that break apart once the structure

actuators. Test 2T-1 has pods with expansion layer radius variation from 30 mm in the centre to 10 mm at the ends and a slight vertical curvature. There are eleven constraints with two width variations: 2T-1A changes from 2.8 mm wide in the centre to 3.2 mm to 4.0 mm at the ends (CLSR 36%), and 2T-1B uses 4.0 mm wide constraints throughout the entire structure (CLSR 41%) (Fig. 17a). Each pod half is 20 mm wide at the centre and approximately 133.33 mm in length. 2T-1B had slightly more twisting likely due to the wider constraints used, however both variations were successful and achieved the goal of printing a pre-assembled non-planar hygroscopic actuator inspired by the *Bauhinia* pod (Fig. 17b, c, and d) (Online Resource 5).

3.3.2 *Lilium* flower opening (3 petal design): Evaluation of moisture-induced bending from synclastic to anticlastic (Test 2B-1)

The first test of the *Lilium* model, Test 2B-1, is based on the three tepal designs used by both Correa (2022) and Pelliccia et al. (2024), and the design parameters were based on the doubly curved geometry with one central constraint as developed by Pelliccia et al. (2024). The model was printed in one session and included a base to hold the three tepals, which significantly reduces the amount of manual post-processing and assembly. However, the tepals did require slight splitting with scissors because of the support lines adopted for stability between them. Each tepal is 117 mm at the longest length and 22 mm at the widest width. The curvature of the tepals is 25 mm radius in the x-axis and approximately 260 mm radius in the y-axis, with the parameters of constraint and expansion layers based on previous successful tests of the same x-axis radius (Test 1B-2 and 1B-3). The previous moisture-induced bending actuation tests with curvature indicated that reducing the frequency of constraints required widening of the remaining constraints. However, it should also account for the size of the expansion layer, so the width of the single midrib constraint was 1.8 mm at the top where the tepal was smaller and gradually increased to 5.4 mm at the bottom where the tepal was larger (CLSR 13%) (Fig. 18a). Test 2B-1 achieved similar kinematic behaviour as the model shown in Pelliccia et al. (2024) with a greater amplitude of movement (Fig. 18b and c).

Since emulating the precedent model was successful, the next test looked at the possibility to expand the number of tepals to six in likeness to the biological geometry of the *Lilium*.

3.3.3 *Lilium* flower opening (6 petal design): evaluation of moisture-induced bending from synclastic to anticlastic (Test 2B-2)

Test 2B-2 uses the same parameters for each tepal as Test 2B-1 but arranged with three outer and three inner tepals, as well as a larger base to hold the additional components (Fig. 19a, b, and c).

3.3.4 *Lilium* flower opening (6 petal design): evaluation of multi-stage capacity for chronological shape-change (Test 2B-3)

The final *Lilium* test adds further complexity to the kinematic model and modifies the tepal shape to more closely match the geometric characteristics of the biological model, the *Lilium* flower. Test 2B-3 mimics the faster bending that occurs at the tips and edges of tepals, as well as the slightly earlier opening of the outer tepals, by varying the thickness of the expansion layer and constraint width (Fig. 20a). The expansion layer of the tepals is thicker in the centre and thinner at the tips and edges to increase bending, while the midrib constraint of the outer tepals is widened to create faster bending than the inner tepals. Inner tepal CLSR is 16% and outer tepal CLSR is 21%. These changes alter the stiffness ratio and thus the curvature amplitude and the moisture diffusion time. Though the tepals did not bend as much as previous tests due to the increased thickness of the expansion layer (Fig. 20b, c, and d) (Online Resource 6), overall Test 2B-3 successfully achieves a model more similar in appearance and movement to the biological *Lilium* (Fig. 21a and b) and concludes this research by demonstrating the potential of VPM-4DP for creating doubly curved non-planar hygroscopic actuators (Figs. 22 and 23).

4 Discussion

The proposed VPM-4DP method makes it possible to fabricate structures that shape-change from an initial synclastic curvature (initial rest-state) to anticlastic curvature (moisture-saturated second rest-state) while using an unmodified 3-axis gantry style printer, which is the

(See figure on next page.)

Fig. 17 Images from Test 2T-1. **a** The ends of the pod samples have a smaller radius to taper together while the centre has a larger radius. The first variation, 2T-1A, has constraint widths that increase and decrease according to the radius, and the second, 2T-1B, has the same constraint width throughout that is adjusted for the smallest radius. Expansion layers shown in grey, constraint layers shown in pink. **b** 2T-1A and 2T-1B were similar in twisting, but 2T-1B had slightly more amplitude due to the wider constraints. **c** Samples placed upside down for reversible movement during drying. **d** Final image of samples

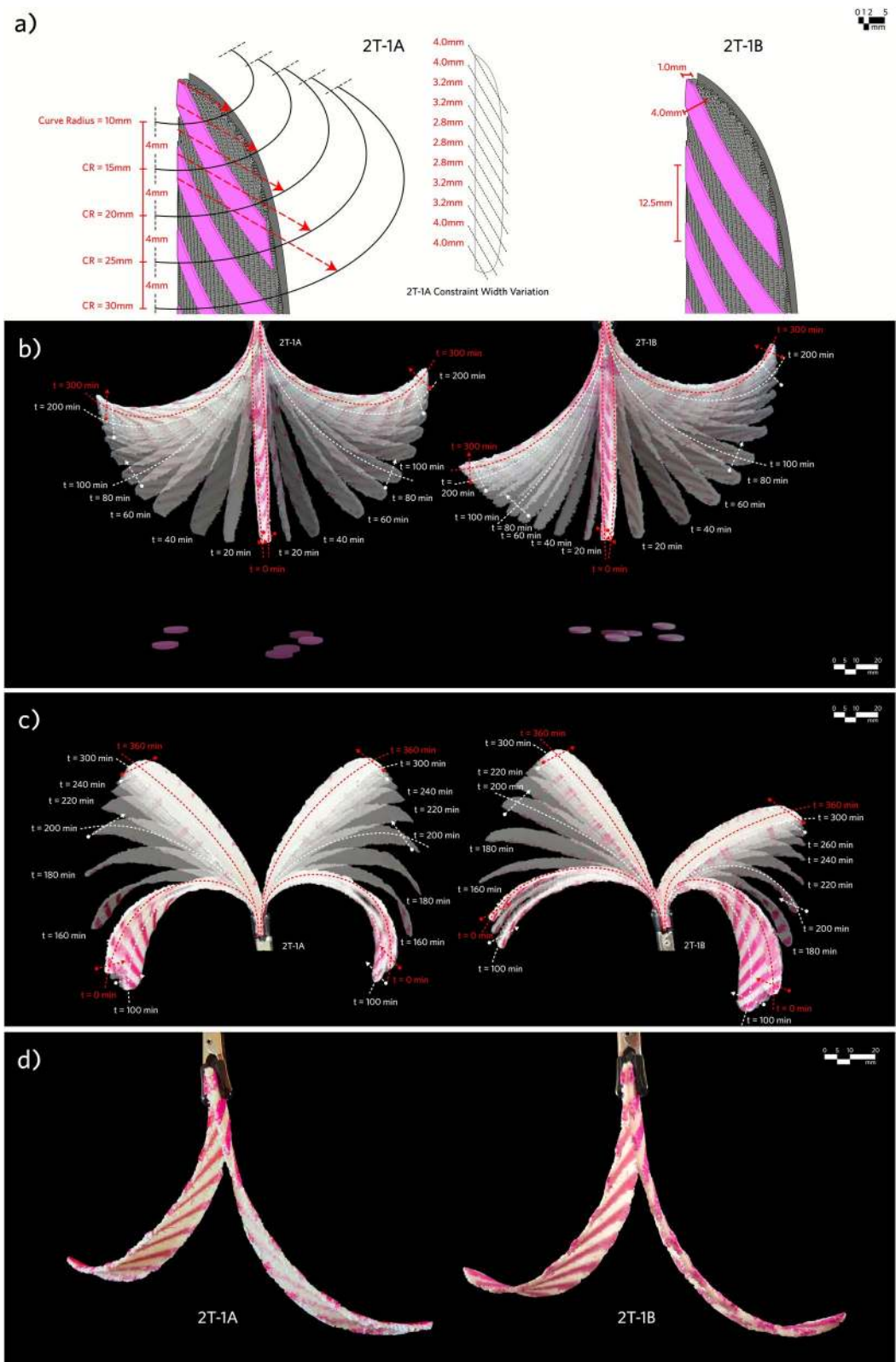


Fig. 17 (See legend on previous page.)

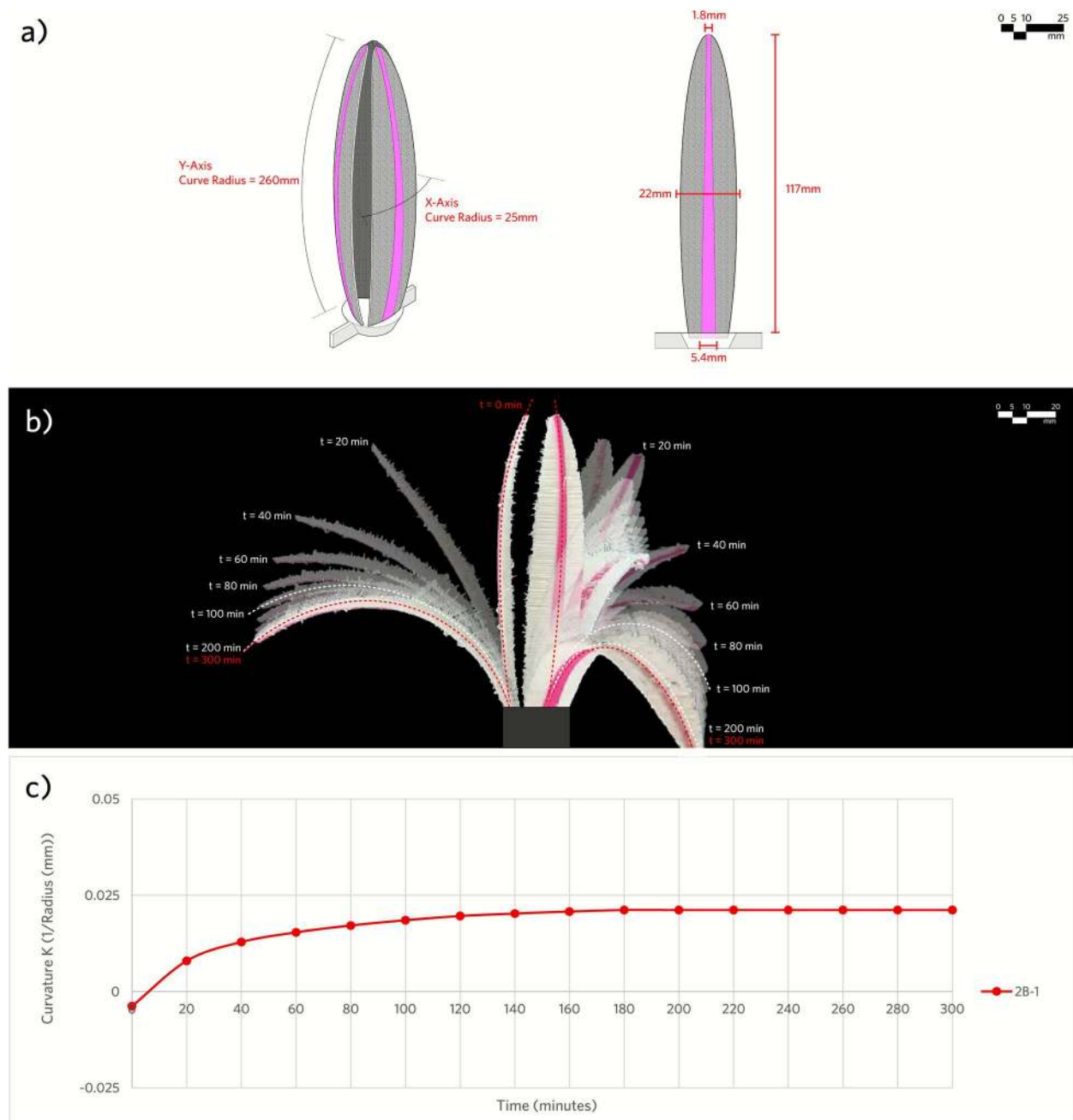


Fig. 18 Images from Test 2B-1. **a** Test 2B-1 uses a three tepal design, which are all fabricated in a single print session and interconnected at the base. There is one single central constraint on each tepal. The constraint width is smaller at the tip of the tepal and wider at the base to account for the expansion layer size. Expansion layers shown in grey, constraint layers shown in pink. **b** This sample is successful in achieving a similar amplitude of bending as the previously mentioned research. **c** Graph describing curvature (K) vs time. The speed and amplitude of tepal bending is comparable to Test 1B-3A and 1B-3C

most conventional type of 3D printer. This is a significant improvement from previous manually laminated and planar 4DP fabrication methods as it allows for the integration of more complex, form-active curved shapes (single or doubly curved), such as those found in the *Lilium*

or the *Bauhinia* pod mechanisms, without increasing the complexity of fabrication methods or equipment required.

The newly introduced curvature of the samples required adaptation of existing 4DP methods, which

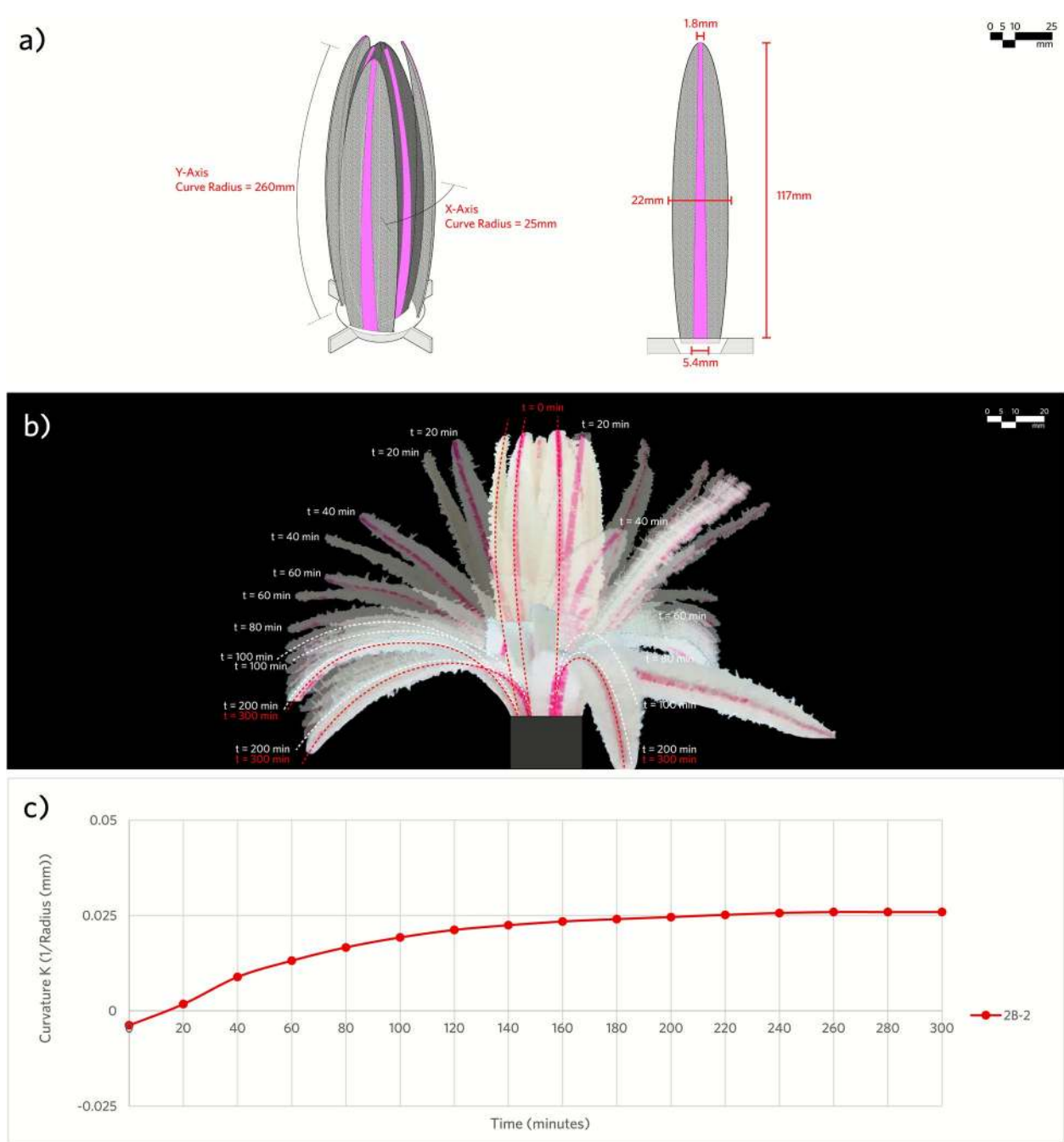


Fig. 19 Images from Test 2B-2. **a** Test 2B-2 places an additional three tepals around the design from the previous test. Expansion layers shown in grey, constraint layers shown in pink. **b** Similar bending can be seen in this sample, with motion from all six tepals to create blooming like the biological model. **c** Graph describing curvature (K) vs time

(See figure on next page.)

Fig. 20 Images from Test 2B-3. **a** Test 2B-3 modifies the tepal shape to more closely match the biological model. To mimic the faster bending of the tips, edges, and outer tepals, the tips and edges of the tepals are thinner and the constraints on the outer tepals are wider. Expansion layers shown in grey, constraint layers shown in pink. **b** The adjustment to the design resulted in more bending in the desired areas, though there was not as much bending as in the previous lily tests. However, this movement is overall more similar to the *Lilium* blooming. **c** Graph describing curvature (K) vs time of the outer tepal. **d** Reversal of bending once the sample is placed in a dry environment

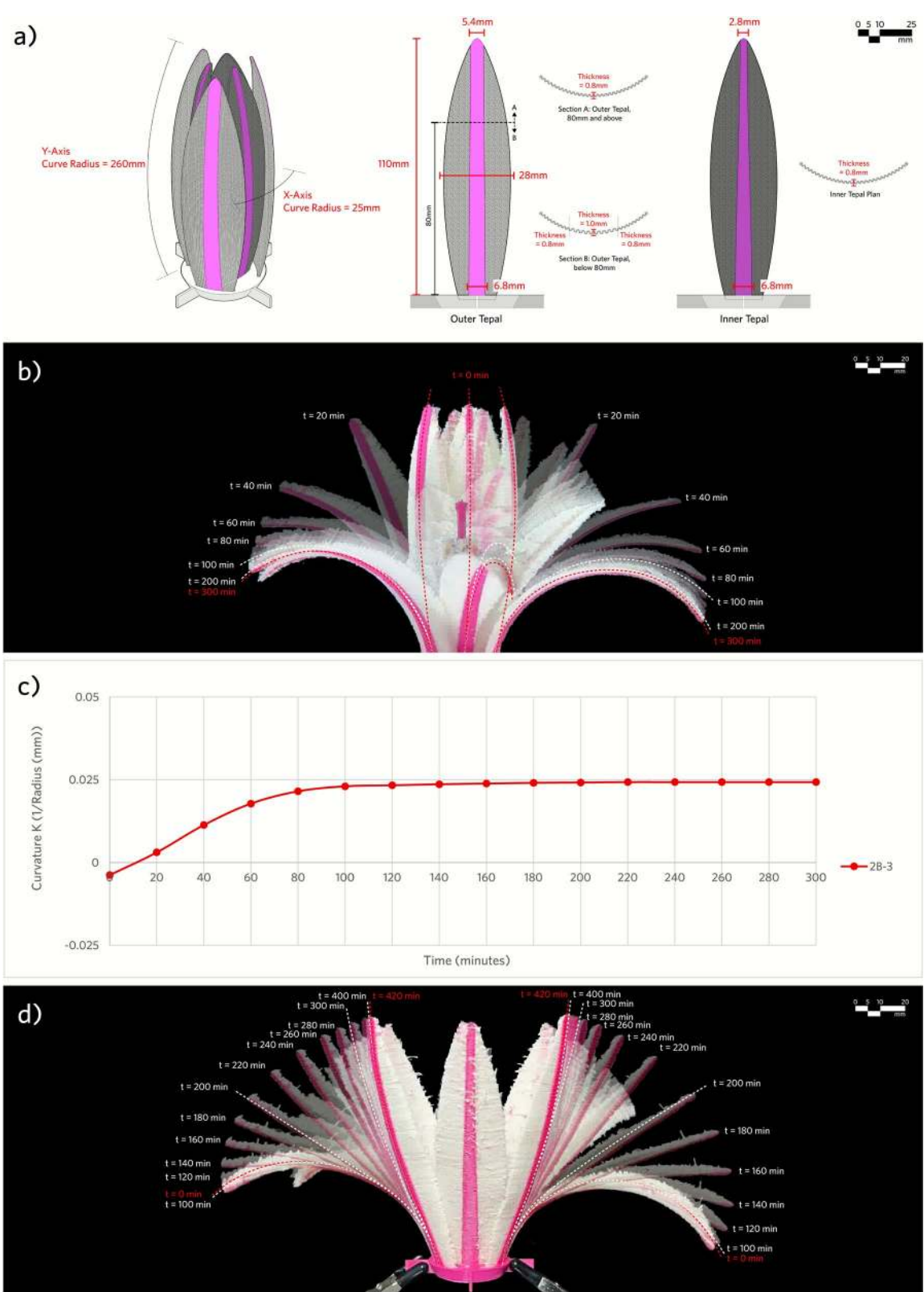


Fig. 20 (See legend on previous page.)

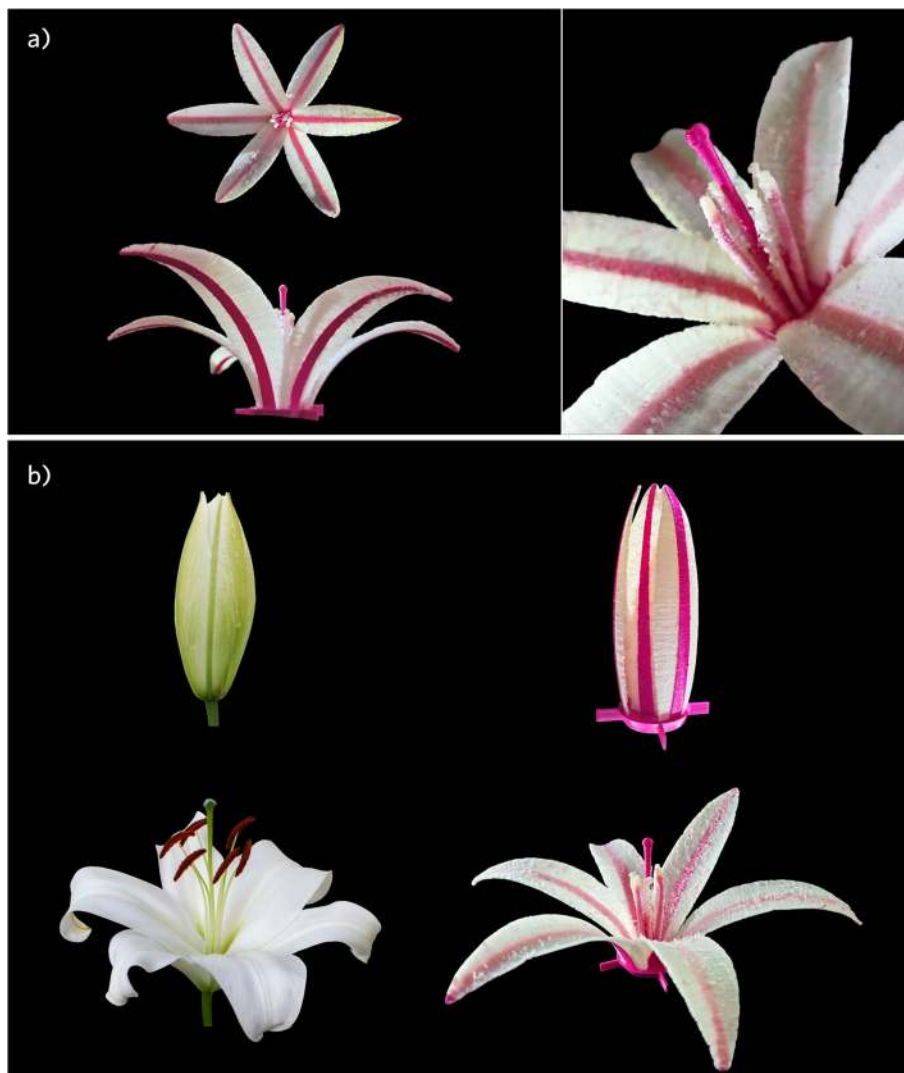


Fig. 21 **a** Final images of the sample from the top, front, and close up, showing the tepal arrangement and double curvature. **b** Comparison of the biological *Lilium* and Test 2B-3. More pronounced bending can be seen at the tips and edges of the *Lilium*, but the creation of this sample using VPM-4DP is a significant step to more printing more complex pre-assembled hygroscopic actuators

revealed several considerations. First, curvature in the expansion layer increases the moment of inertia and thus the geometrical stiffness. This increase in resistance affects the shape-change movement. Curved test structures are observed to have slightly less initial movement than planar test structures because of the resulting increased initial resistance. As well, a decrease in curvature radius (more extreme curvature, more resistance) should be compensated with an increase in constraints.

Twisting test 0T-2 identified that there is an ideal volume and distribution of constraint material across the geometry for movement (which should apply to both bending and twisting). Behaving similarly to bimaterials, the constraint layer should have good tensile strength,

bendability, and be significantly thinner than the expansion layer. There is an optimal ratio of constraint to expansion layer volume, but the constraint width does not need to be spread flat as a single even layer across the expansion as long as the ratio is fulfilled. Throughout the tests, adjustments to width and frequency of constraints still achieve similar movement as existing planar 4DP work; however as seen in Test 0T-1, twisting in VPM-4DP samples is sensitive to further impact by constraint angle and location.

It is speculated that bending and twisting movements in curved tests are facilitated by snap-buckling or elastic instability to some measure. Once the expansion layer is constrained enough and the sample starts to bend, it is

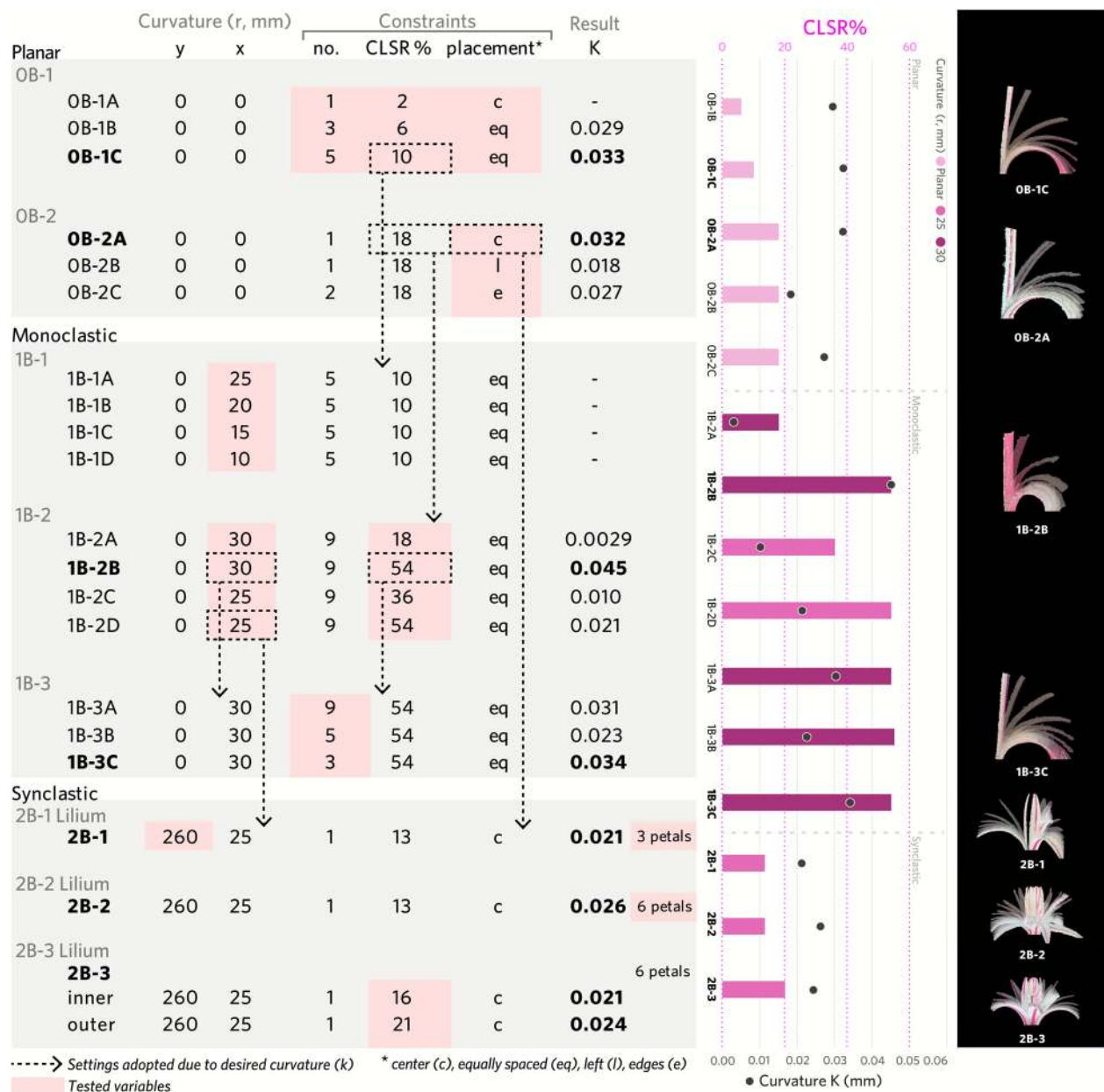


Fig. 22 Summary of results from all bending tests. On the table, pink highlights indicate tested variables while dotted boxes with arrows indicate settings that were adopted between tests. The bar and dot graph shows CLSR and curvature K value for each measured sample. In addition to CLSR, other variables such as constraint frequency, distribution, placement, and radius curvature impact the resulting movement. The most successful tests (OB-1C, OB-2A, 1B-2B, 1B-3C, 2B-1, 2B-2, 2B-3) are bolded and displayed as images on the right

possible that the curvature at the bending point flips outward in the opposite direction. This mechanism appears to work similarly to plants with curved surfaces that harness this instability for movement, such as the doubly curved lobes of a Venus Flytrap (Forterre et al., 2005; Sachse et al., 2020). Like the Venus Flytrap, the movement of these samples is also reversible, though not to the same extent. When placed back under lower moisture

conditions after being submerged in water, the expansion layer shrinks and causes the bending of the samples to straighten out or even achieve a negative curvature. External factors such as gravity and sample orientation may prevent the samples from completely reversing to the original rest-state. Understanding these principles will be helpful for future research using this printing method.

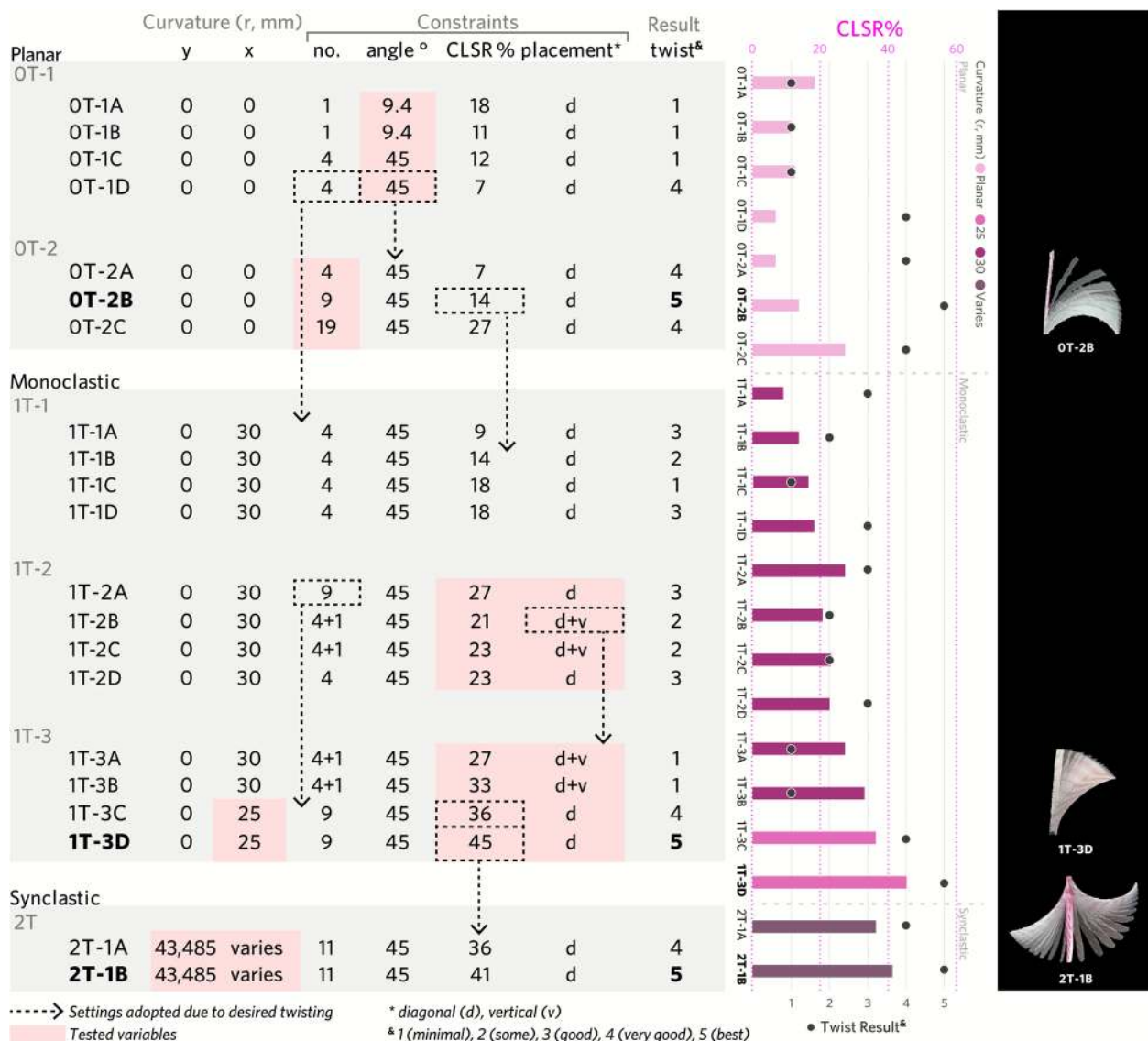


Fig. 23 Summary of results from all twisting tests. On the table, pink highlights indicate tested variables while dotted boxes with arrows indicate settings that were adopted between tests. The bar and dot graph shows CLSR and twist result evaluation for each sample. The most successful tests (OT-2B, 1T-3D, 2T-1B) are bolded and displayed as images on the right

However, the simple 3-axis printing has some limitations. There is a limit to vertical curvature because adhesion between each layer is crucial to the performance of the structure. Generally, the slope of any overhang should not exceed 45° from the vertical axis, otherwise the layers of filament will cantilever too much over each other and delaminate due to insufficient surface contact. In the tests for the pod and lily, an elongated ellipsoidal form was used as a reference shape based on desired height and radius, creating a modest vertical curvature. More extreme curvature could be viable with support structures, but this would require further experimentation

with the new printing method and custom-modelled supports due to the unpredictability of default slicer support generation and difficulty of removal after printing.

In terms of printing time, this novel method of printing takes much longer than previous work with small laminar samples. The structures are larger in size, can include multiple actuators in a single print, and each sample is composed of hundreds of vertical layers, which results in structures that take 6 h or longer to complete compared to approximately 30 min for typical 4DP bilayers. It is also much harder to control the quality of the print since there are many layers that each need to be printed

properly for the structure to actuate. Even once the print is complete, the structures can still fail while actuating due to minute geometric flaws and overall fragility. One such minor print failure can be seen in the case of the lily (Tests 2B-2 and 2B-3), where one of the tepals is faulty and does not bend as much as the others. In addition, because the structures are printed in multiples, the print failure of one structure in the middle of a session means that all of them must be reprinted. However, the most common source of print failure is the fibre-polymer composite filament clogging the nozzle after several hours due to fibre misalignment and polymer stringing or sticking from filament retraction. It is possible that one solution is to increase layer thickness or print speed, but the main complication that can occur with increased print speed is decreased adherence in fibre filament layers since they typically require a slower speed to be pressed together. The deactivation of the prime tower can reduce the print time by an hour or more, but filament clogging, stringing, and possibility of print failure can be exacerbated without this safeguard. Potentially innovation in the fibre-polymer composite filament field can increase the adhesive properties of the material, which would allow more effective and efficient printing. Additionally, the scale of the samples presented in this work has been limited to the size of the printer. Further research regarding the scalability of this method and material would need to be completed to address the wider potential of specific field applications.

We speculate that a similar 4DP geometry with a doubly curved rest-state geometry, like the lily, could be created by a material jetting printer (PolyJet) given its multi-material capability, which includes support material for overhangs and lateral stability. A material jetting method would remove the need to resolve moments of instability in curved samples when the printed layers cantilever over each other, but both the machine and materials required for this approach are significantly more expensive than those used in FFF. Material jetting is also limited to isotropic inks without any type of fibrous fillers. It is curious that no research on double-curvature rest-states that we are aware of has been done with PolyJet equipment, though perhaps cost has been a barrier.

The novelty of this printing method has generated new points for consideration but also addressed existing limitations of 4DP, specifically in biomimetic geometries, that increase the potential of the fabrication method.

5 Conclusion

We introduced a simplified method of vertical 4DP using a dual-extrusion printer that can reduce the process of

creating non-planar fibre-polymer composite bilayer hygroscopic actuators to a single print session. Through this research, we have achieved hydraulically actuated bending and twisting in structures with single and double-curvature rest-states. Reducing the complexity of fabrication in these complex structures lowers the barrier to creating non-planar actuators where less equipment, less custom programming, and less specialized knowledge is needed. With this novel method there are increased opportunities for design in 4DP. Applications that have been of great interest for this field include climate-responsive architectural façades and soft robotics. The number of steps required for the manual assembly of these structures could potentially be reduced by printing multiple samples at once that are interconnected with a base component, like with the *Bauhinia* pod and *Lilium* tests. Overall, VPM-4DP creates new possibilities for complex design in the field of hygroscopically actuated structures.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1007/s44223-025-00103-5>.

Supplementary Material 1.
Supplementary Material 2.
Supplementary Material 3.
Supplementary Material 4.
Supplementary Material 5.
Supplementary Material 6.

Acknowledgements

This research was able to be completed thanks to support from the University of Waterloo School of Architecture.

Authors' contributions

Conceptualisation: Annie Wang, David Correa. Data Analysis: Annie Wang, David Correa, Antoine Le Duigou. Biological Concept Review: Simon Poppinga. Writing – Original Draft: Annie Wang, David Correa. Writing – Review and Editing: Annie Wang, David Correa, Simon Poppinga, Elena Vazquez, Antoine Le Duigou. Figures: Annie Wang, Elena Vazquez, David Correa. Supervision: David Correa.

Funding

The authors did not receive funding for this research.

Data availability

All data and models used in this paper can be made available upon request.

Declarations

Ethics approval and consent to participate

Not applicable. No ethics approval or consent was required for this research since it does not involve human or animal participants, or sensitive data.

Competing interests

The authors declare no potential competing interests of the research, authorship, or publication.

Received: 10 September 2025 Revised: 25 October 2025 Accepted: 6 November 2025
Published online: 17 November 2025

References

- Al Ali, M., Benaissa, B., Khatir, S., Shimoda, M., Kobayashi, M., Vignon, P., Al-Shawh, A., and Lay, B. (2024). Exploring Concurrent Multi-materials and Multiscale Hybrid Topology Optimization for Lightweight Porous Gripping Mechanism. In B. Benaissa, R. Capozucca, S. Khatir, and G. Milani (Eds.), *Proceedings of the International Conference of Steel and Composite for Engineering Structures* (pp. 137–151). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-57224-1_14.
- Armon, S., Efrati, E., Kupferman, R., and Sharon, E. (2011). Geometry and mechanics in the opening of chiral seed pods. *Science*, 333(6050), 1726–1730.
- Bao, C., Moeinina, H., Kim, T.-H., Lee, W., & Kim, W. S. (2023). 3D structural electronics via multi-directional robot 3D printing. *Advanced Materials Technologies*, 8(5), 2201349. <https://doi.org/10.1002/admt.202201349>
- Bauer, U., Müller, U. K., & Poppinga, S. (2021). Complexity and diversity of motion amplification and control strategies in motile carnivorous plant traps. *Proceedings of the Royal Society b: Biological Sciences*, 288(1951), 20210771. <https://doi.org/10.1098/rspb.2021.0771>
- Campbell, T. A., Tibbitts, S., and Garrett, B. (2014). The next wave: 4D printing. *Atlantic Council*. <https://www.atlanticcouncil.org/in-depth-research-reports/report/the-next-wave-4d-printing-and-programming-the-material-world/>.
- Cheng, T., Thielen, M., Poppinga, S., Tahouni, Y., Wood, D., Steinberg, T., Menges, A., & Speck, T. (2021). Bio-inspired motion mechanisms: Computational design and material programming of self-adjusting 4D-printed wearable systems. *Advanced Science*, 8(13), 2100411. <https://doi.org/10.1002/adv.202100411>
- Clarke-Hicks, J., Ochoa, I., & Correa, D. (2023). Harnessing plastic deformation in porous 3D printed ceramic light screens. *Architecture, Structures and Construction*, 3(2), 193–204. <https://doi.org/10.1007/s44150-022-00079-0>
- Correa, D., Poppinga, S., Mylo, M. D., Westermeier, A. S., Bruchmann, B., Menges, A., & Speck, T. (2020). 4D pine scale: Biomimetic 4D printed autonomous scale and flap structures capable of multi-phase movement. *Philosophical Transactions of the Royal Society a: Mathematical, Physical and Engineering Sciences*, 378(2167), 20190445. <https://doi.org/10.1098/rsta.2019.0445>
- Correa, D. (2022). *4D printed hygroscopic programmable material architectures* [Doctoral Thesis, Stuttgart : Institute for Computational Design and Construction, University of Stuttgart]. <http://elib.uni-stuttgart.de/handle/11682/12393>.
- Dawson, C., Vincent, J. F. V., & Rocca, A.-M. (1997). How pine cones open. *Nature*, 390(6661), 668–668. <https://doi.org/10.1038/37745>
- De Kergariou, C., Le Duigou, A., Perriman, A., & Scarpa, F. (2023). Design space and manufacturing of programmable 4D printed continuous flax fibre polylactic acid composite hygromorphs. *Materials & Design*, 225, 111472. <https://doi.org/10.1016/j.matdes.2022.111472>
- Dumais, J., & Forterre, Y. (2012). "Vegetable Dynamics": The Role of Water in Plant Movements. *Annual Review of Fluid Mechanics*, 44(1), 453–478. <https://doi.org/10.1146/annurev-fluid-120710-101200>
- Elbaum, R., Zaltzman, L., Burgert, I., & Fratzl, P. (2007). The role of wheat awns in the seed dispersal unit. *Science (New York, N.Y.)*, 316(5826), 884–886. <https://doi.org/10.1126/science.1140097>
- Erb, R. M., Sander, J. S., Grisch, R., & Studart, A. R. (2013). Self-shaping composites with programmable bioinspired microstructures. *Nature Communications*, 4(1), 1712. <https://doi.org/10.1038/ncomms2666>
- Forterre, Y., Skotheim, J. M., Dumais, J., & Mahadevan, L. (2005). How the Venus flytrap snaps. *Nature*, 433(7024), 421–425. <https://doi.org/10.1038/nature03185>
- Fruloux, T., Castro, M., Sauleau, P., Matsuzaki, R., & Le Duigou, A. (2022). Matrix stiffness: A key parameter to control hydro-elasticity and morphing of 3D printed biocomposite. *Composites Part a, Applied Science and Manufacturing*, 156, 106882. <https://doi.org/10.1016/j.compositesa.2022.106882>
- Gao, Z., Yin, J., Liu, P., Li, Q., Zhang, R., Yang, H., & Zhou, H. (2023). Simultaneous multi-material embedded printing for 3D heterogeneous structures. *International Journal of Extreme Manufacturing*, 5(3), 035001. <https://doi.org/10.1088/2631-7990/acd285>
- Gong, H., & Zhang, Y. (2025). Emerging horizons in hygroscopic actuation: Cellulose and agarose for biomimetic humidity-sensitive systems. *Materials Today Communications*, 46, 112513. <https://doi.org/10.1016/j.mtcomm.2025.112513>
- Guo, Q., Pan, Y., Lin, J., Wan, G., Xu, B., Hua, N., Zheng, C., Huang, Y., Mei, Y., Chen, W., & Chen, Z. (2020). Programmable 3D self-folding structures with strain engineering. *Advanced Intelligent Systems*, 2(12), 2070121. <https://doi.org/10.1002/aisy.202070121>
- Holmes, D. P., & Crosby, A. J. (2007). Snapping surfaces. *Advanced Materials*, 19(21), 3589–3593. <https://doi.org/10.1002/adma.200700584>
- Holstov, A., Bridgens, B., & Farmer, G. (2015). Hygromorphic materials for sustainable responsive architecture. *Construction and Building Materials*, 98, 570–582. <https://doi.org/10.1016/j.conbuildmat.2015.08.136>
- Josselin, M., Castro, M., Di Cesare, N., Scarpa, F., & Le Duigou, A. (2025). Sustainable 4d printed meta biocomposite materials for programmable structural shape changing. *Advanced Materials*, 37(16), 2418656. <https://doi.org/10.1002/adma.202418656>
- Le Duigou, A., Castro, M., Bevan, R., & Martin, N. (2016). 3D printing of wood fibre biocomposites: From mechanical to actuation functionality. *Materials & Design*, 96, 106–114. <https://doi.org/10.1016/j.matdes.2016.02.018>
- Le Duigou, A., Requile, S., Beaugrand, J., Scarpa, F., & Castro, M. (2017). Natural fibres actuators for smart bio-inspired hygromorph biocomposites. *Smart Materials and Structures*, 26(12), 125009. <https://doi.org/10.1088/1361-665X/aa9410>
- Le Duigou, A., Correa, D., Ueda, M., Matsuzaki, R., & Castro, M. (2020). A review of 3D and 4D printing of natural fibre biocomposites. *Materials & Design*, 194, 108911. <https://doi.org/10.1016/j.matdes.2020.108911>
- Le Duigou, A., Fruloux, T., Matsuzaki, R., Chabaud, G., Ueda, M., & Castro, M. (2021). 4D printing of continuous flax-fibre based shape-changing hygromorph biocomposites: Towards sustainable metamaterials. *Materials & Design*, 211, 110158. <https://doi.org/10.1016/j.matdes.2021.110158>
- Le Duigou, A., and Correa, D. (2022). 4D printing of natural fiber composite. In *Smart Materials in Additive Manufacturing, Volume 1: 4D Printing Principles and Fabrication* (pp. 297–333). Elsevier. <https://doi.org/10.1016/B978-0-12-824082-3.00028-3>.
- Le Duigou, A., Grabow, M., Scarpa, F., Deschamps, J., Combescur, C., Labstie, K., Dirrenberger, J., Castro, M., and Lafont, U. (2024). Bioinspired 4D Printed Tubular/Helicoidal Shape Changing Metacomposites for Programmable Structural Morphing. *Advanced Materials Technologies*, 2400237. <https://doi.org/10.1002/admt.202400237>.
- Lee, H., Xia, C., & Fang, N. (2010). First jump of microgel: Actuation speed enhancement by elastic instability. *Soft Matter*. <https://doi.org/10.1039/C0SM00092B>
- Liang, H., & Mahadevan, L. (2011). Growth, geometry, and mechanics of a blooming lily. *Proceedings of the National Academy of Sciences of the United States of America*, 108(14), 5516–5521. <https://doi.org/10.1073/pnas.1007808108>
- Mesa, O. (2020). *Choreographed Matter*. Congreso SIGraDi 2020. <https://doi.org/10.5151/sigradi2020-121>.
- Mulakkal, M. C., Trask, R. S., Ting, V. P., & Seddon, A. M. (2018). Responsive cellulose-hydrogel composite ink for 4D printing. *Materials & Design*, 160, 108–118. <https://doi.org/10.1016/j.matdes.2018.09.009>
- Pelliccia, G., Bianconi, F., Filippucci, M., and Correa, D. (2024). Four-Dimensional Multistep Vertical Printing for Hygroresponsive Shape Change with Nonplanar Rest-State Geometries. *3D Printing and Additive Manufacturing*. <https://doi.org/10.1089/3dp.2023.0337>.
- Pezzulla, M., Smith, G. P., Nardinocchi, P., & Holmes, D. P. (2016). Geometry and mechanics of thin growing bilayers. *Soft Matter*, 12(19), 4435–4442. <https://doi.org/10.1039/C6SM00246C>
- Poppinga, S., Correa, D., Bruchmann, B., Menges, A., & Speck, T. (2020). Plant movements as concept generators for the development of biomimetic compliant mechanisms. *Integrative and Comparative Biology*, 60(4), 886–895. <https://doi.org/10.1093/icb/icaa028>
- Poppinga, S., Schenck, P., Speck, O., Speck, T., Bruchmann, B., & Masselter, T. (2021). Self-actuated paper and wood models: Low-cost handcrafted biomimetic compliant systems for research and teaching. *Biomimetics*, 6(3), 42. <https://doi.org/10.3390/biomimetics6030042>
- Reichert, S., Menges, A., & Correa, D. (2015). Meteorosensitive architecture: Biomimetic building skins based on materially embedded and hygroscopically enabled responsiveness. *Computer-Aided Design*, 60, 50–69. <https://doi.org/10.1016/j.cad.2014.02.010>

- Reyssat, E., & Mahadevan, L. (2009). Hygromorphs: From pine cones to biomimetic bilayers. *Journal of the Royal Society Interface*, 6(39), 951–957. <https://doi.org/10.1098/rsif.2009.0184>
- Riley, K. S., Ang, K. J., Martin, K. A., Chan, W. K., Faber, J. A., & Arrieta, A. F. (2020). Encoding multiple permanent shapes in 3D printed structures. *Materials & Design*, 194, 108888. <https://doi.org/10.1016/j.matdes.2020.108888>
- Rüggeberg, M., & Burgert, I. (2015). Bio-inspired wooden actuators for large scale applications. *PLoS ONE*, 10(4), e0120718. <https://doi.org/10.1371/journal.pone.0120718>
- Sachse, R., Westermeier, A., Mylo, M., Nadasdi, J., Bischoff, M., Speck, T., & Poppinga, S. (2020). Snapping mechanics of the Venus flytrap (*Dionaea muscipula*). *Proceedings of the National Academy of Sciences of the United States of America*, 117(27), 16035–16042. <https://doi.org/10.1073/pnas.2002707117>
- Sahin, E. S., Cheng, T., Wood, D., Tahouni, Y., Poppinga, S., Thielen, M., Speck, T., & Menges, A. (2023). Cross-sectional 4D-printing: Upscaling self-shaping structures with differentiated material properties inspired by the Large-Flowered Butterwort (*Pinguicula grandiflora*). *Biomimetics*, 8(2), 2. <https://doi.org/10.3390/biomimetics8020233>
- Schleicher, S., Lienhard, J., Poppinga, S., Speck, T., & Knippers, J. (2015). A methodology for transferring principles of plant movements to elastic systems in architecture. *Computer-Aided Design*, 60, 105–117. <https://doi.org/10.1016/j.cad.2014.01.005>
- Shi, J., Cho, Y., Taylor, M., and Correa Zuluaga, D. (2019). *Guiding Instability—A craft-based approach for modular 3D clay printed masonry screen units*. https://doi.org/10.5151/proceedings-ecaadesigradi2019_522
- Stahlberg, R., and Taya, M. (2006). *What can we learn from nastic plant structures? The phytomimetic potentiality of nastic structures* (Y. Bar-Cohen, Ed.; p. 616802). <https://doi.org/10.1117/12.658924>
- Tahouni, Y., Krüger, F., Poppinga, S., Wood, D., Pfaff, M., Rühle, J., Speck, T., & Menges, A. (2021). Programming sequential motion steps in 4d-printed hygromorphs by architected mesostructure and differential hygro-responsiveness. *Bioinspiration & Biomimetics*, 16(5), 055002. <https://doi.org/10.1088/1748-3190/ac0c8e>
- Timoshenko, S. (1925). Analysis of bi-metal thermostats. *Journal of the Optical Society of America*, 11(3), 233. <https://doi.org/10.1364/JOSA.11.000233>
- Vazquez, E., Gürsoy, B., & Duarte, J. P. (2020). Formalizing shape-change: Three-dimensional printed shapes and hygroscopic material transformations. *International Journal of Architectural Computing*, 18(1), 67–83. <https://doi.org/10.1177/1478077119895216>
- Zeng, S., Gao, Y., Qiu, H., Xu, J., & Tan, J. (2022). Design, fabrication and application of self-spiraling pattern-driven 4D-printed actuator. *Scientific Reports*, 12(1), 18874. <https://doi.org/10.1038/s41598-022-23425-0>
- Zhang, L., Chizhik, S., Wen, Y., & Naumov, P. (2016). Directed motility of hygro-responsive biomimetic actuators. *Advanced Functional Materials*, 26(7), 1040–1053. <https://doi.org/10.1002/adfm.201503922>
- Zhu, Q., Jin, Y., Wang, W., Sun, G., & Wang, D. (2019). Bioinspired smart moisture actuators based on nanoscale cellulose materials and porous, hydrophilic EVOH nanofibrous membranes. *ACS Applied Materials & Interfaces*, 11(1), 1440–1448. <https://doi.org/10.1021/acsami.8b17538>

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.