# Programmable Assemblies

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under the direction of
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# 1. Table of contents

## 2. Abstract

This research is an extension of the Self-Assembly Lab's research on programmable material. The first research module deals with integrating multi-material fused deposition modeling (FDM) technologies to program a fully cured carbon fiber sheet by printing material with a high shrinkage value on its surface, resulting in the emergence of novel forms, functions, and behaviors.

This research on self-transforming carbon fiber involves examining its material behavior the designed anisotropic properties, in reference to manipulating the printed grain direction of the active material—a technology developed by the Self-Assembly Lab—in addition to a digital and computational approach for designing the structure. These are contextualized within a design proposal to develop a large-scale, "light-activated" carbon fiber installation for BSA Space in Boston. A thermally active polymer with a high-shrinkage value is 3D-printed onto a fully cured, continuous, flat carbon fiber sheet that is light-activated, transforming its shape into a helix structure.

## 3. Introduction

Four-dimensional (4D) printing technologies have been introduced recently, exploiting materials' properties to alter their shape, resulting in the emergence of novel forms, functions, and behaviors. 4D printing exhibits exceptional capabilities, in which actuation, sensing, and programmability are embedded into the material and are activated via passive energy sources such as heat, light, and water.[1]

The research internship at the Self-Assembly Lab is aimed at exploring programmable material compositions by utilizing the unique capabilities of 4D printing technology toward improving scalability and higher functionality [2]. The fourth section investigates the properties of the cured carbon fiber material developed by Carbitex, alongside the printing of active material on its surface. This technology was developed by the Self-Assembly lab, which, depending on the directionality of the printing, folding, and twisting of carbon fiber, are controlled and can be tailored to obtain certain geometries[4]. The goal for the project is to create a large-scale 4' carbon fiber sheet activated by a light source to transform from a flat surface into a helix structure, for exhibition at the Boston Society of Architecture. The helix is designed parametrically to attain variation in its width, frequency, radius, and overall length. The design problem that challenged the team was how to optimize the helix geometry so that the longest helix would be achieved on a 4'x2' multi-material FDM printer, which meant maximizing the length of the helix but minimizing the number of intersections with the print base. Genetic algorithm tools were utilized to find the fittest individual with the desired parameters.

# 4. Self-Evolving Helix

A self-evolving helix exploits the flexible properties of the carbon fiber material by depositing active material onto its surface, in order to transform its shape into 3D geometrical states and introduce new functions and behaviors. Due to the shrinkage of the deposited active material after cooling and bonding on the carbon fiber surface, the carbon fiber sheet begins to transform and change its behavior in reference to the pattern printed on its surface. The research explores evolutionary computation techniques to optimize the form of the helix structure.

## 4.1 Objectives

The team aims to create a large-scale, light-activated carbon fiber helix structure on a multi-material FDM printer for the BSA Space exhibit titled Bigger than a Breadbox, Smaller than a Building, in Boston. Non-electrical material activation media such as heat or light sources will be employed to test a cured carbon fiber material's behavior in performing certain actions, such as folding or spiraling, while targeting the self-assembly of a helix form. The team intends to parametrically model the helix structure in order to achieve variation in its width and radius, as well as control the frequency of its turns and the distance between them. These parameters will inform the team in obtaining a helix with maximum height from a flat 4'x2' cured carbon fiber sheet, by means of genetic algorithm tests for multi-criteria optimization.

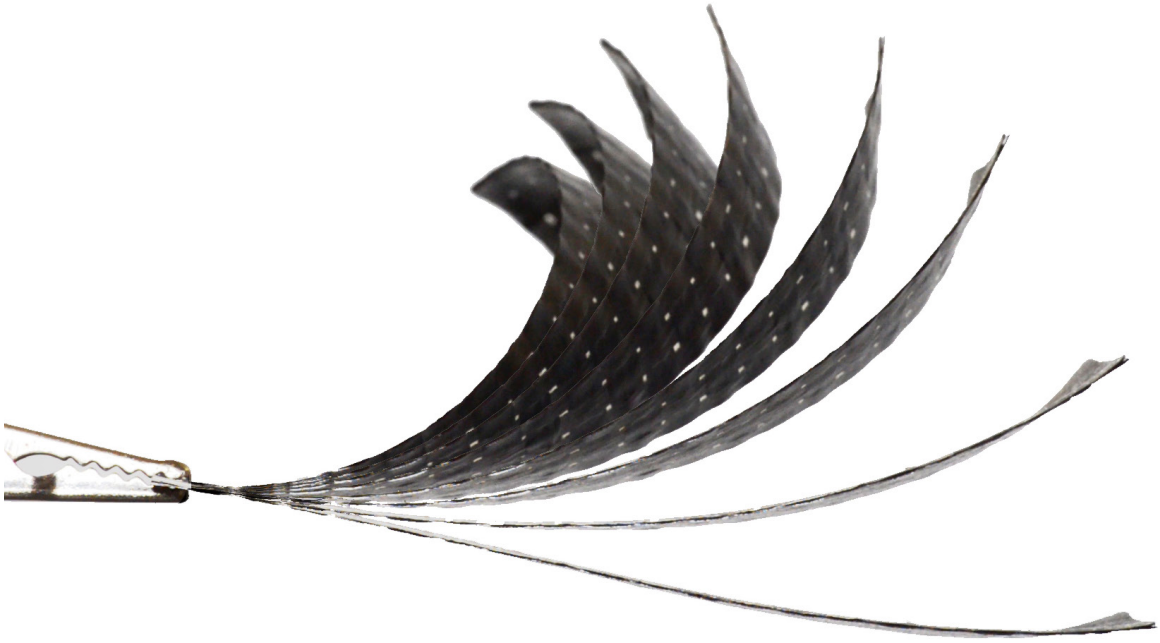


Fig.4.1.1 Carbon fiber sheet with printed active material. After directing IR light on the carbon fiber surface, the active material flattens the carbon fiber, and the shrinkage of the active material after cooling down causes the carbon fiber sheet to fold back to its original state. Source. www.selfassemblylab.net

## 4.2 Carbon Fiber

Carbon fiber is a composite material characterized by high tensile strength and stiffness, light weight, and anisotropic properties; therefore, it is used in a variety of industrial fields, particularly in aerospace applications and architectural construction. In collaboration with Carbitex, we have provided a  0.35-mm thick, fully cured carbon fiber material with CX6 technology, which allows the carbon fiber to be flexible once cured. The carbon fiber sheet is composed of a 2 mm x 4 mm grid pattern and is coated with a resin layer on one side. The goal is to exploit the superior properties of carbon fiber, with its extremely light weight, in combination with active materials to perform specific functions.

## 4.3 4D Printing

4D printing is a new technique that enables the material to transform its shape or change its function after printing another material on its surface [3]. A custom FDM multi-material printer is used to print active material onto the carbon fiber surface. A polyamide polymer that possesses a high shrinkage value, is deposited onto the surface of the cured carbon fiber to transform its shape and change its behavior. Depending on the orientation of the printed pattern on the carbon fiber's surface, different behaviors and actions have been experimentally investigated and developed, such as folding and spiraling. The Self-Assembly Lab found that a folding behavior emerges when a pattern is deposited parallel to the grain orientation of the carbon fiber. In contrast, printing a pattern perpendicular to the grain orientation of the carbon fiber results in a twisting behavior (Fig. 4.3.1). After experimenting with different printing settings, we found that printing two layers of nylon with a 0.2 mm space between them is best for programming the carbon fiber sheet to perform the required actions. Further, depositing active material with an initial height of 0.25 mm above the surface of the carbon fiber sheet helps in bonding the deposited layer.

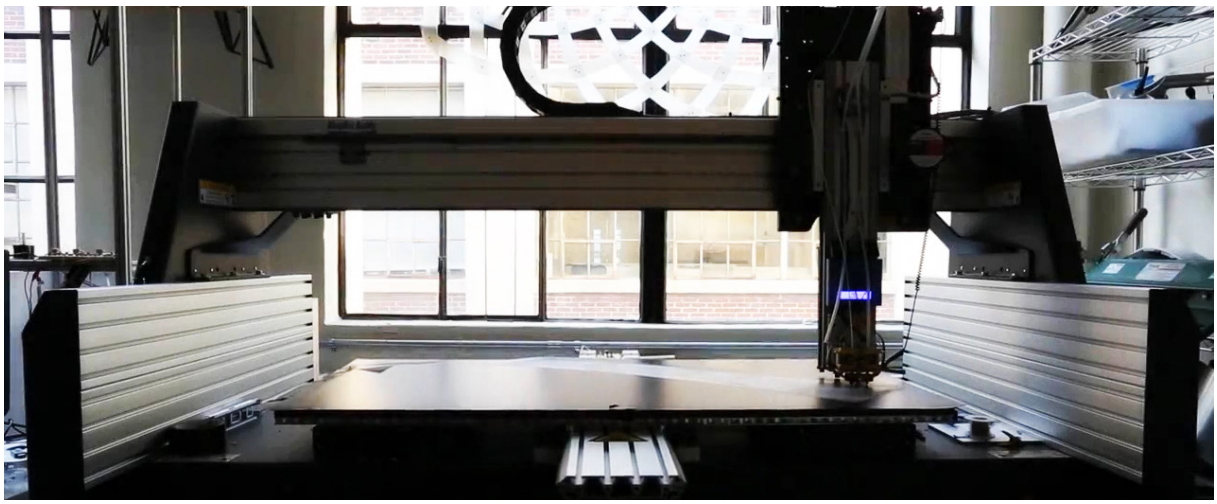


Fig.4.3.1 Shopbot multi-material 3D printer with a printing area of 4' x 2' is used to deposit active material on the carbon fiber surface to transform its shape.  Source. www.selfassemblylab.com

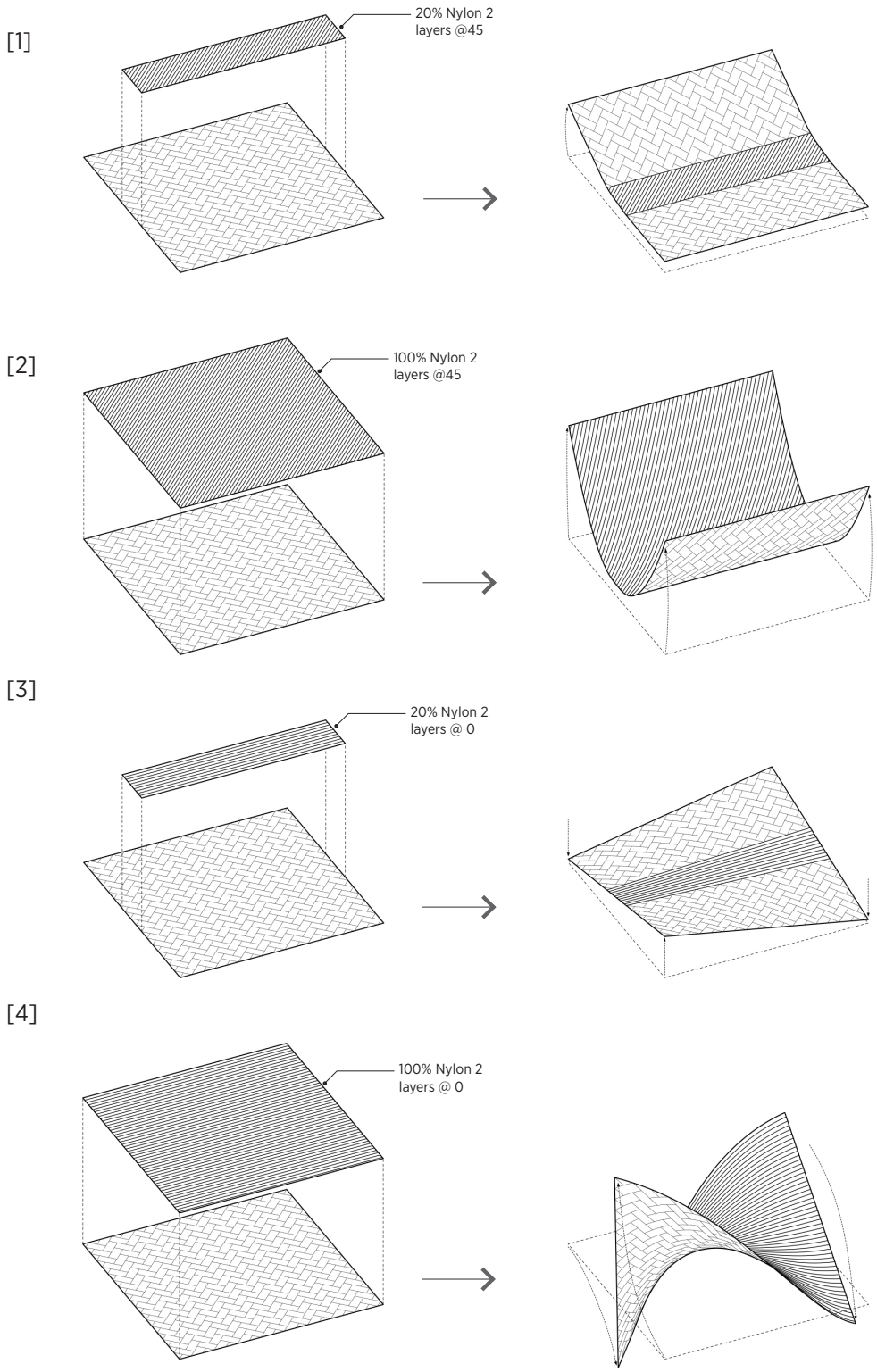



Fig.4.3.2. 1.local folding is achieved by printing active material parallel to the grain directionality of the carbon fiber. 2. Global fold/curve results from printing on the whole surface of the carbon fiber at 45 degrees. 3. Local twisting is achieved by printing active material perpendicular to the carbon fiber grain. 4. Global twisting/spiral emerges from printing on the whole surface of the carbon fiber at 0 degree.

## 4.4 Parametric Helix

The ambition of the project was to develop a large-scale light-activated helix structure from a 4’ x 2’ carbon fiber sheet that will fit onto the large-format FDM printer’s bed with the same dimensions. The team developed a digital parametric helix with different controllable parameters to find the best-fit iteration that would fulfill the team’s ambition. The helix’s defined parameters include the number of oscillations (turns), the radius value, and the height between each oscillation (Fig. 4.4.1). Furthermore, the variation in the helix width, radius of the consecutive turns, and vertical separation between each oscillation were controlled to improve structural and functional performance, as well as reduce material waste (Fig. 4.4.1).

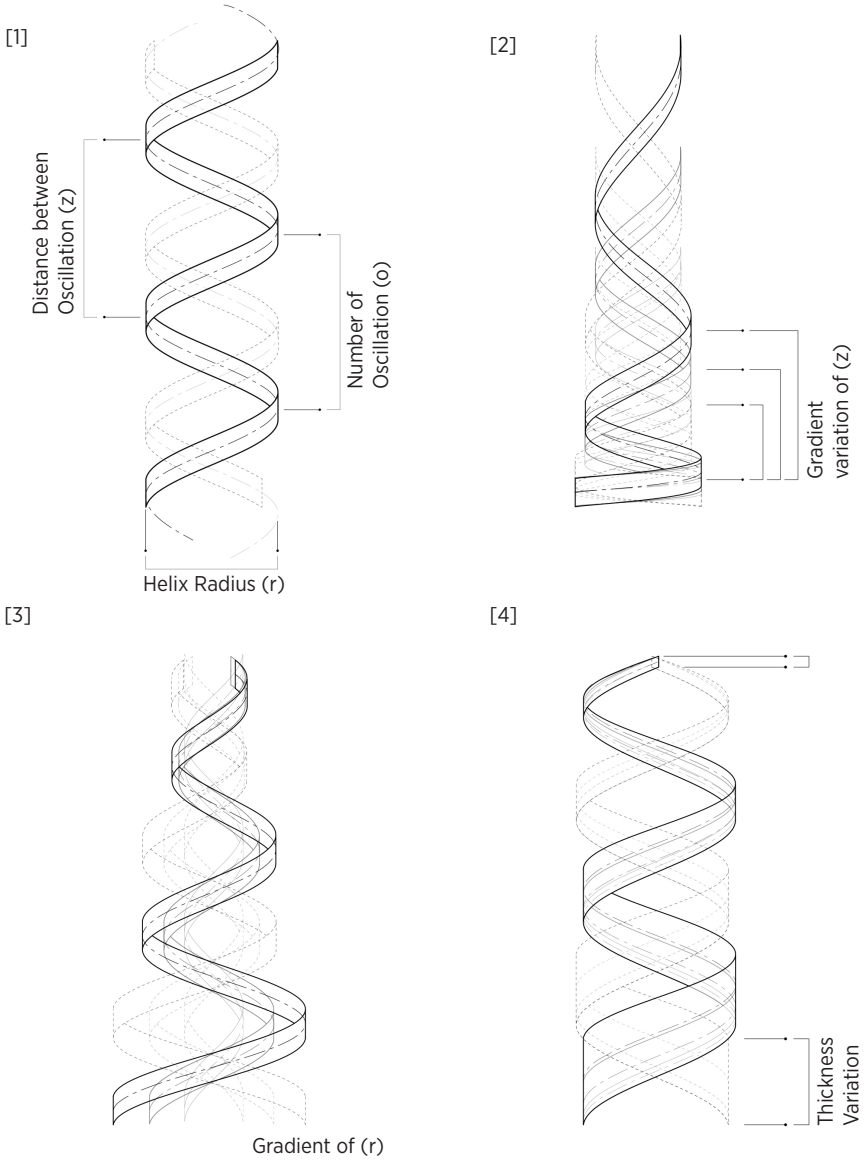
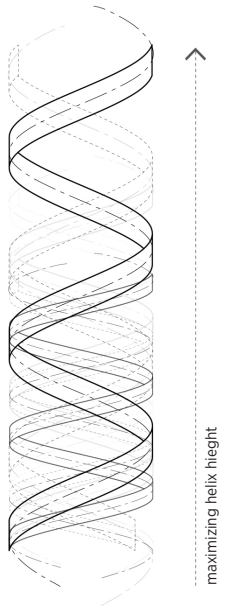



Fig.4.4.1 1.Defined parameters of the helix includes, radius (r), number of oscillation (o), and distance between oscillations (z). 2. Gradient range between 1” to 8” is defined for (z) value. 3. Gradient range between 1” to 8” is defined for (r) value. 4. Gradient range between 1” to 8” is defined to control the width of the helix structure.

## 4.5 Multi-Optimization Criteria

The team has begun to explore evolutionary computation by using the Octopus plug-in (multi-optimization engine) to generate optimized solutions for the helix structure, in response to defined fitness criteria. The first fitness criterion is to maximize the height of the helix form; the second is to minimize the distance between the end points of the unrolled helix surface and the diagonal end points of a 4' x 2' rectangle, which represents the size of the given carbon fiber sheet. Initially, the team proposed a structure suspended from the ceiling; thus, the total length of the helix is calculated as the sum of the original helix's height resulting from the parametric model, along with its vertical displacement imposed by gravity force, which is calculated with Karamba3D. The second fitness criterion evaluates the relationship between the unrolled surface and the Shopbot printer's bed; in other words, it confirms the viability of any proposed helix's height. The parameters defined in Section 4.4 will act as the genes in the Octopus engine.

[1]




[2]

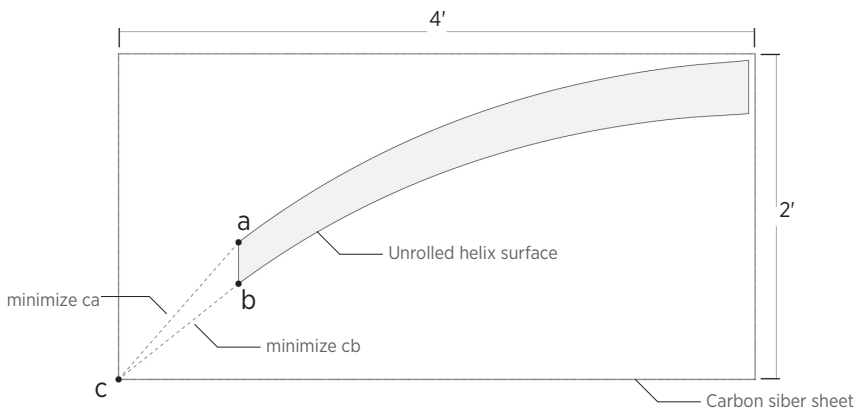



Fig.4.5.1 1. The first fitness criteria aims to maximize the overall height of the helix structure. 2. The second fitness criteria targets minimizing the average distance between the end points of the unrolled helix surface in reference to a 4'x2' rectangle

### 4.5.1 Displacement

The first option proposed for the installation was a suspended double-helix structure that is light activated, which would be subjected to deformation by gravity force, resulting in increased overall height. This was calculated with the Karamba 3D structural plug-in for grasshopper3d, which transforms the center line of the resulting helix form into a beam component for analyzing and visualizing the deformations. Data from the carbon fiber material were collected, including its Young's modulus of 23000 kg/cm2 and its specific weight of 0.03 Kn/m3. These values are not specific to the given carbon fiber; they represent a carbon fiber with resin coating cured at 120 °C. Furthermore, the results were based on one anchor point per helix (support point) (Fig. 4.5.1.1).

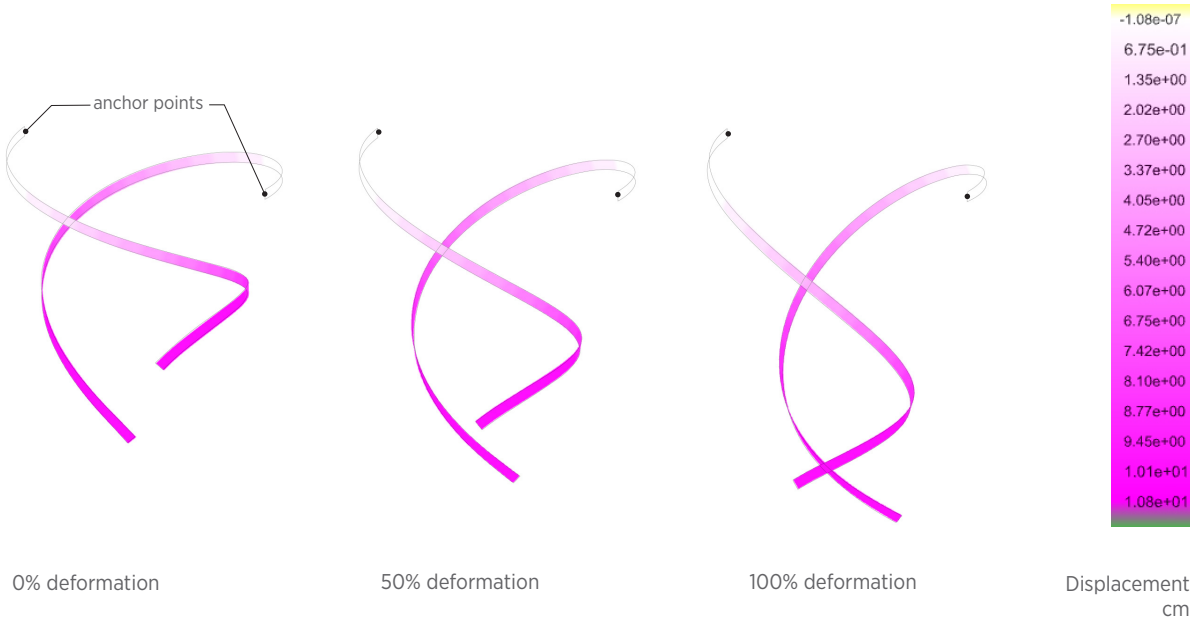



Fig.4.5.1.1 Karamba 3D displacement analysis.

### 4.5.2 Genes/Genepool

In biology, genes are a set of instructions made from DNA and are responsible for creating proteins. Similarly, in Octopus , a series of actions signifies the "genes," which are applied to the helix model to produce distinct forms or "individuals." In this experiment, eight genes were defined as representing the "genepool," and two fitness criteria were evaluated.

### 4.5.3 Experiment Set-up

In the Octopus interface, “elitism”—the percentage of population solutions that will breed the next generation—was set to 50%. “Mutation probability”—the likelihood of the genes mutating within the individuals in the population—was set to 20%. “Mutation rate,” which implies the amount of change in the value of the mutated gene, was set to 80%. Finally, the “crossover” was set to 100%, indicating that all of the population would be killed and not carried to the next generation. The Octopus engine was run for a population of 30 individuals and 50 generations.

### 4.5.4 Results and Findings

- The average distance between points a and b to point c was greater than 10 cm in almost 90% of the population in generation 50 (Fig. 4.5.3.1).
- In the process of setting up the experiment, a Boolean operation that eliminates and kills any individual with a height less than 3’ was set; therefore, all of the double helixes were  greater than 3’ in height.
- Variation in helix height, radius, and its oscillation patterns and frequencies were evident throughout the populations (Fig. 4.5.3.2).
- Individual 24 from generation 50 had a height of 3.89’, with an average distance of 9.9 cm from points a and b to point c, in which the unrolled surface was modified to fit the cutting bed for the fabrication process.

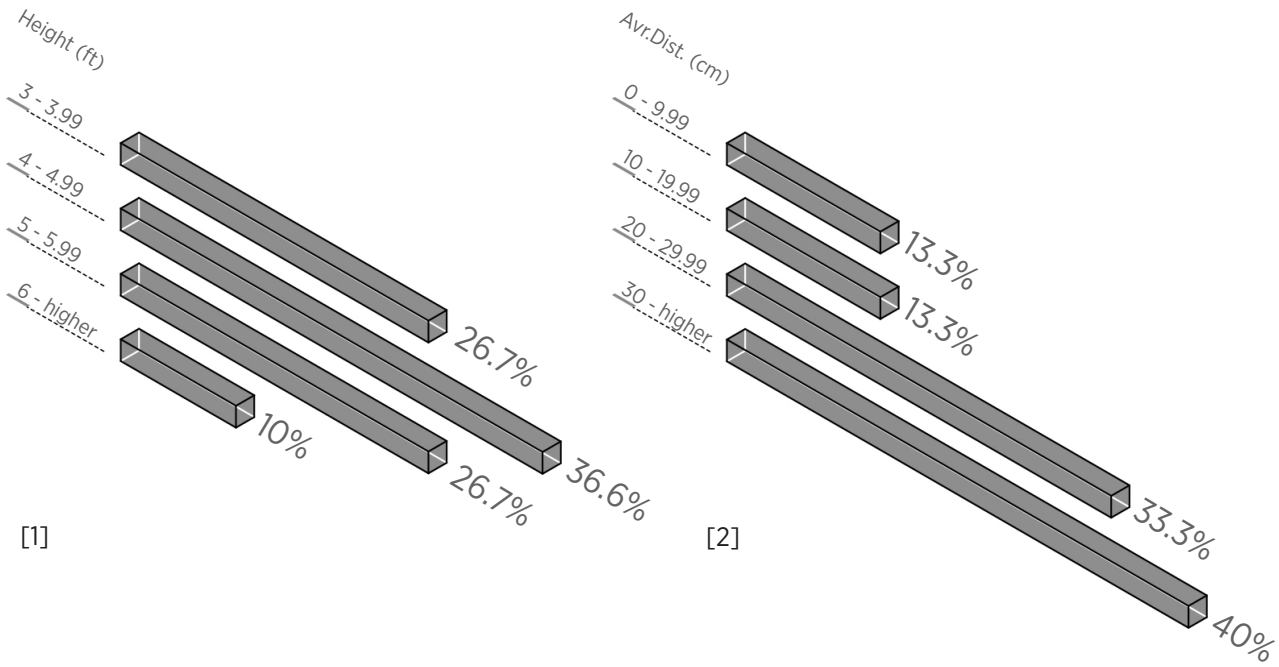
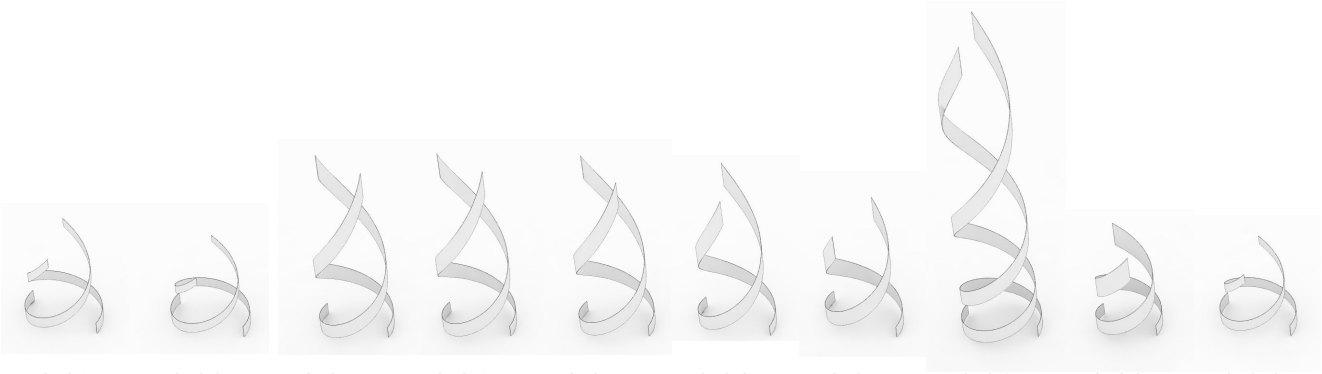



Fig.4.5.4.1 1.The height (ft) percentages of the individuals in generation 50. 2.Average distance percentages from points ‘a’ and ‘b’ to point ‘c’.



| G50.1 | G50.2 | G50.3 | G50.4 | G50.5 | G50.6 | G50.7 | G50.8 | G50.9 | G50.10 |
|---|---|---|---|---|---|---|---|---|---|
| 8.99 | 7.29 | 35.49 | 35.49 | 29.54 | 28.20 | 22.7 | 72.61 | 19.61 | 6.88 |
| 9.98 | 8.47 | 36.70 | 36.70 | 30.56 | 29.24 | 20.7 | 73.44 | 20.65 | 7.86 |
| 3.25 | 3.10 | 5.71 | 5.71 | 5.12 | 4.94 | 4.12 | 7.75 | 4.23 | 3.00 |

| G50.11 | G50.12 | G50.13 | G50.14 | G50.15 | G50.16 | G50.17 | G50.18 | G50.19 | G50.20 |
|---|---|---|---|---|---|---|---|---|---|
| 22.38 | 38.03 | 23.28 | 10.49 | 13.10 | 20.89 | 25.49 | 33.45 | 19.71 | 30.63 |
| 30.00 | 39.08 | 31.22 | 11.55 | 14.14 | 22.05 | 46.49 | 34.48 | 20.76 | 31.68 |
| 4.25 | 5.79 | 4.68 | 3.37 | 3.63 | 4.04 | 4.68 | 5.32 | 4.2 | 5.26 |

| G50.21 | G50.22 | G50.23 | G50.24 | G50.25 | G50.26 | G50.27 | G50.28 | G50.29 | G50.30 |
|---|---|---|---|---|---|---|---|---|---|
| 20.37 | 54.70 | 22.38 | 7.97 | 19.71 | 6.66 | 29.54 | 16.97 | 32.06 | 59.08 |
| 21.41 | 55.83 | 30.00 | 12.02 | 20.76 | 14.07 | 30.56 | 18.01 | 33.22 | 60.36 |
| 4.25 | 7.19 | 4.25 | 3.89 | 4.01 | 3.00 | 5.02 | 3.99 | 5.19 | 7.69 |

## Objectives

- Distance from [a] to [c] (cm)
- Distance from [b] to [c] (cm)
- Helix hieght

Fig.4.5.4.2 Generation 50 illustrates the multi-criteria objectives for a population of 30 individuals generated by Octopus

## 4.6 Fabrication

Prior to 3D printing on the carbon fiber sheet, a script was developed to enable the generation of desired patterns in any irregular shape defined by four sides. The script controlled the offset distance between the patterns' lines and their orientation angle.
The first option, a suspended helix, requires a structure for hanging the piece. The team proposed printing active material in a pattern parallel to the grain orientation of the carbon fiber sheet at the wider segment of the unrolled surface, which would enable the carbon fiber to fold. This folding allows the attachment of a ring frame at the active material side, where it would not be visible. The frame acts as an anchor point to stabilize the helix structure (Fig. 4.6.1). Nevertheless, the team eventually decided to pursue another option, in which the structure was laid onto a 42" tall table, and magnets were used strategically to stabilize the helix. Furthermore, the lights were suspended from the unistrut on the ceiling, and the wires were concealed by a 1/8" diameter steel rod.

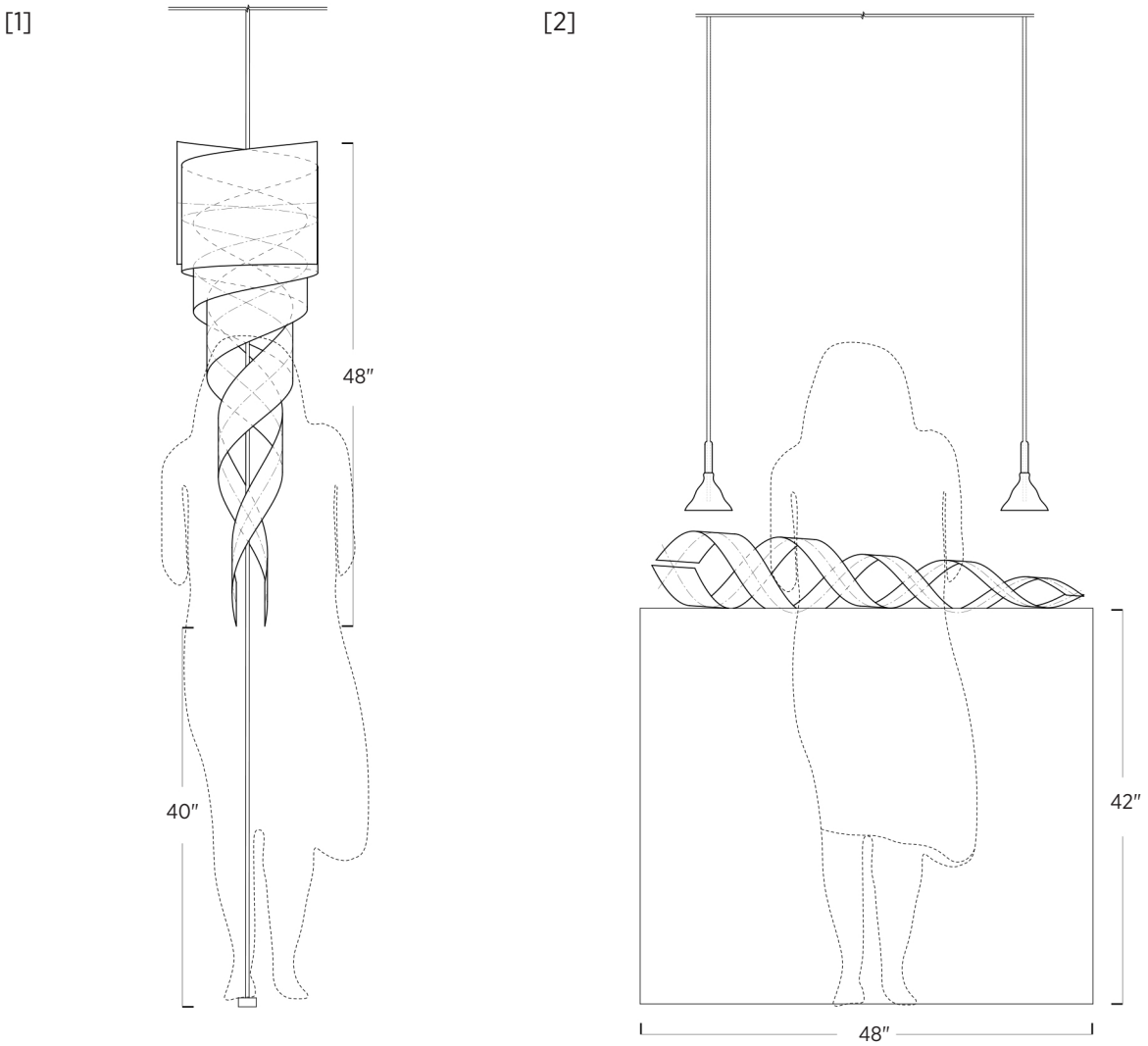



Fig.4.6.1 Option [1] suggests suspending the double helix structure from the ceiling. Option [2] proposes the double helix to be laid on a 42" height table.

## 4.7 Conclusion

This research project was developed under an experimental context, in which FDM technologies were merged with material properties to render passive forms and promote new functions. The experimental results informed the team about necessary decisions during the design process, with outcomes that vary in range.

The project's aim was to design a large-scale carbon fiber structure that, when activated by light, would transform its shape into a helix form. The team's ambition was to suspend the helix from the ceiling and electrically heat the structure for self-transformation. During the design process, and due to the complexity of this option and the safety measures regarding heat generation, the team decided to pursue a different option of laying the helix structure on a table, with two lights suspended from the ceiling triggering the transformation phase. Nevertheless, the initial goal for the installation deals with potential design aspects that will be further developed and modified for future projects and research.

One of the most important goals of this project was to realize a large carbon fiber structure from a 4' x 2' sheet exceeding 4' in length and 1' in width. This target was coupled with the introduction of different parameters that control the morphology of the helix form, involving its width, radius, and turn frequencies. A parametric modeling approach was utilized to define such parameters and achieve variations in scale, in order to satisfy certain functions and behavior. Parametric techniques were combined with genetic algorithm tools to optimize the helix form, yet these tools are considered suggestions to promote the design process, rather than being ultimate design solutions.

Furthermore, the results from the genetic algorithm test were not entirely satisfying, although they provided solutions with sufficient overall height for the helix. Notably, 90% of the resulting unrolled structures from the last generation were off by more than 10 cm in reference to the border of the 4' x 2' carbon fiber sheet. This can be resolved in later iterations if an additional Boolean operation is introduced to the algorithm that eliminates or "kills" any unrolled solution that exceeds the 10-cm margin. Since the amount of material left after cutting the sheet were more than 50%, another fitness criterion can be proposed for the algorithm, in order to maximize the ratio of the printed unrolled surface area to the total sheet area, which will result in wider strips being generated.

Regarding the performance of the final helix structure, the magnets installed on site to stabilize the structure on the table enervated the helix's global transformation, allowing only local activation on each of its ends, which could be resolved by promoting the suspended structure option (Fig. 4.7.1). The lights alternated between switching on and off, for which the timing was controlled by an Arduino device to provide an interval of 20 s on, 50 s off.

In conclusion, the installation aims to integrate multi-material FDM 4D printing techniques in order to transform a flat carbon fiber sheet into a light-responsive helix structure. Depending on the grain orientation in which the active material is printed, the anisotropic properties of the carbon fiber composite will decide the transformation action. This is coupled with parametric modeling and genetic algorithm tools to attempt to form an integrated design solution. The design process did not entirely fulfill the team's ambition to design a suspended, electrical, heat-activated double helix, yet it adequately accomplished the main goal to achieve a large-scale, light-activated carbon fiber structure.

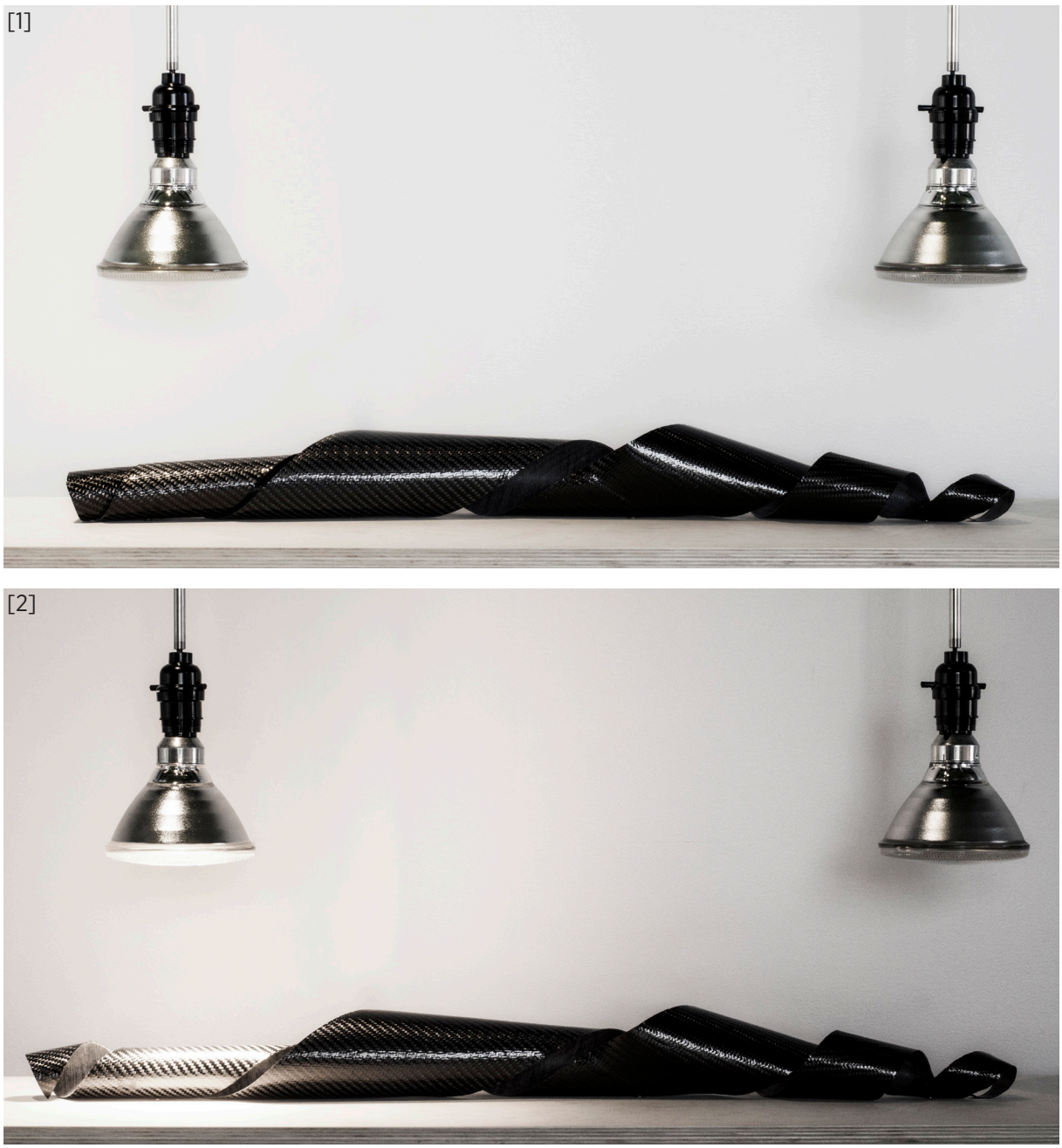



Fig.4.7.1 1. Inactivated state of the carbon fiber helix. 2. Activated state of the helix structure suggesting a local transformation on the left end.

## 5.Appendix

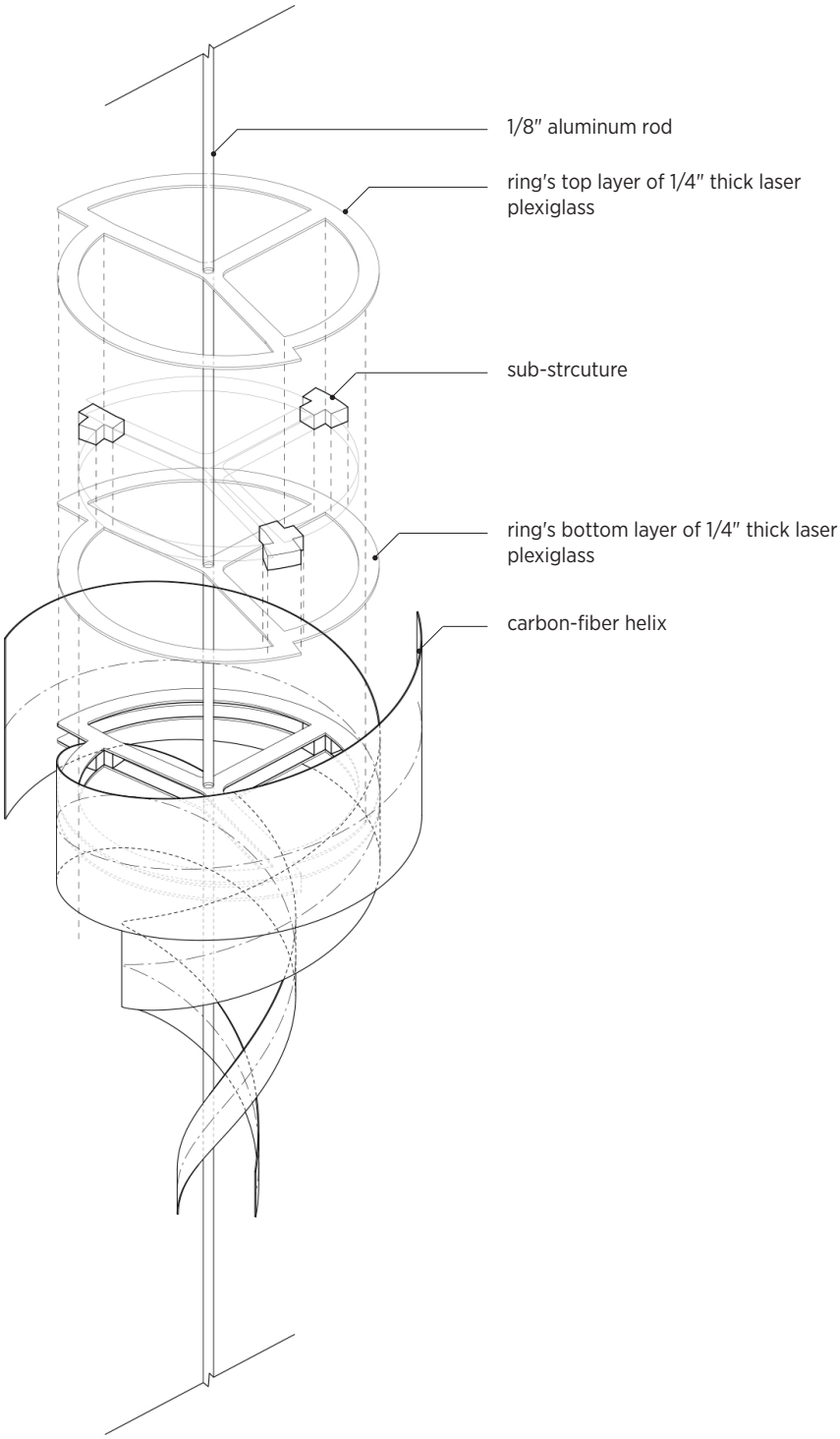



Fig.7.1 Option [1] for the double carbon fiber helix suggests a suspended structure from the ceiling. The ring component is hidden by the end that has a largest width, and by the double helix geometry. The ring is held by a 1/8" aluminum rod that extends from the ceiling to the ground.

## 6.References

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## 7.Acknowledgement

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