Heat Chair

Distribution of material stiffness through thermal bonding and density differentiation

Design Report

SCI 6359: Interface Design:
Integrating Material Perceptions

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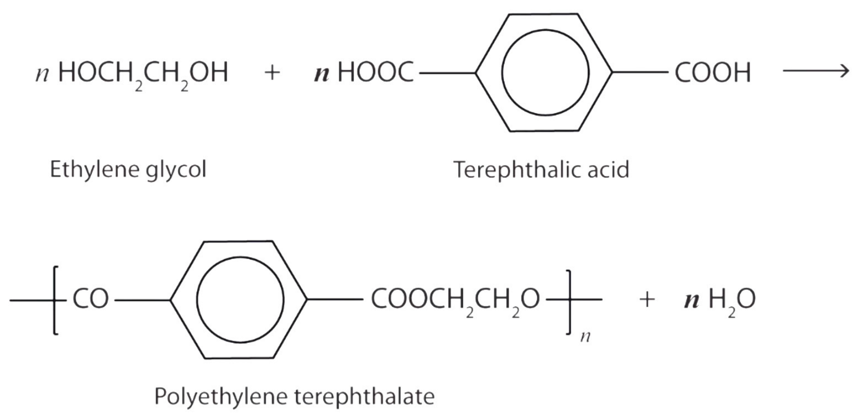
Contents

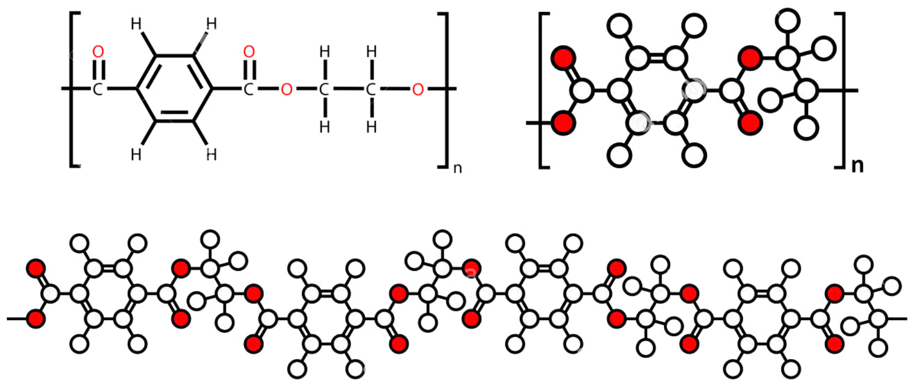
Introduction

This report presents a research that aims to develop an integrated fabrication strategy and material process in the context of polyester fiber material while taking into account its behaviour under certain controlled material treatments (such as density and heat) for the fabrication of small scale furniture, in particular a chair application.

The first component deals with identifying the physical properties of polyester fiber and quantifying its mechanical properties in respect to certain parameters, including temperature, heat intensity and material density under the glass transition phase of the material. The experiment is conducted using a Design of Experiment (DOE) approach where the importance of the aforementioned parameters in terms to their effect on the stiffness of polyesters fiber will be identified. The second component aims to utilize topology optimisation techniques on a simple cylindrical form to identify which areas will be stiffer than others. This will result in a heterogeneous distribution of stiffness along the chair's form, which is controlled by varying the distance between the heat source and material's surface under a constant temperature. The third component will integrate both the result of the optimization exercise and the DOE results to establish a fabrication strategy within a robotic environment, where rolling of a polyester fiber sheet will be adapted as the technique to distribute the stiffness along the material by varying the distance between a heat gun attached to a robotic arm and the material surface. The experiment will result in two chair prototypes, the first one deals with the distance parameter(distance between the heat source and the material surface) and the second combines the previous parameter with material density that is achieved through folding.

Polyester Fiber



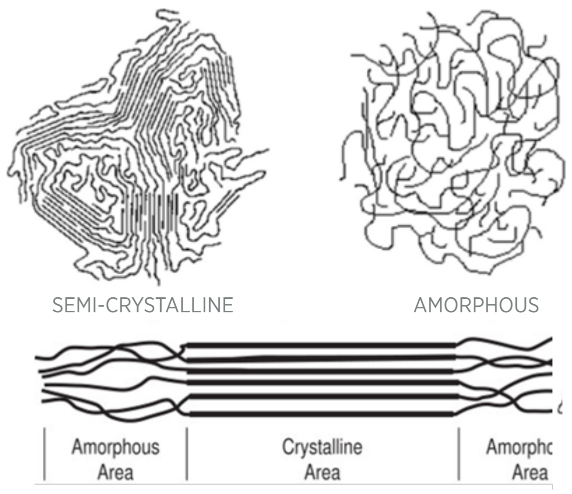


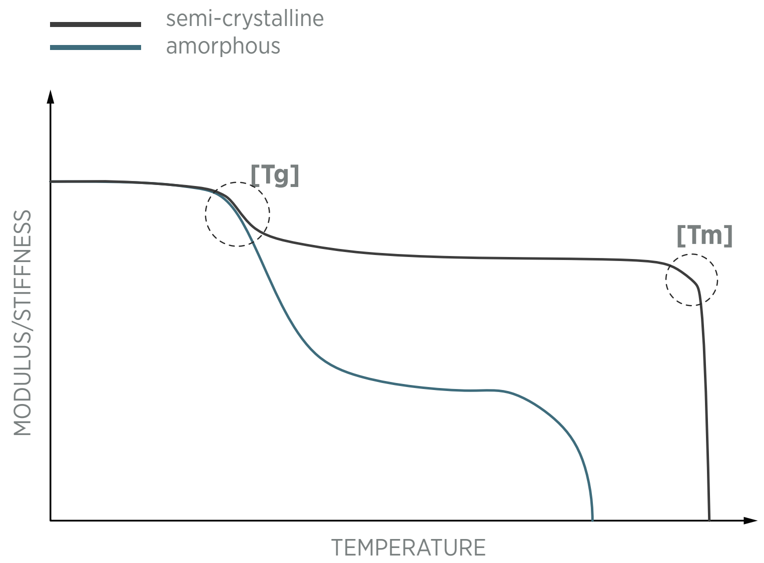
Top
Polymerization formula of polyester

Below
Chemical composition of polyester fiber

1.1 Polyester Fiber Synthesis

Polyester is a synthetic fiber developed in the years 1939-1941. It is used in the manufacture of many products, including clothing, home furnishings, industrial fabrics, computer and recording tapes, and electrical insulation. The most commonly used type of polyester is called polyethylene terephthalate (PET).
It comes from a polymerization reaction between a petroleum by-product, an acid and alcohol under high temperature in vacuum. In this reaction, two or more molecules combine to make a large molecule whose structure repeats throughout its length. Hence, polyester fibers can form very long molecules that are very stable and strong. Chemical groups present in the polyester polymer are the methylene groups: -CH2, the carbonyl groups, -CO-, and the ester groups, -OCO-.





Above
Polyester fiber structure; amorphous and semi-crystalline zones

Below
Melting temprature

1.2 Polyester Fiber Melting

Polyester consists of about 35-15 percent amorphous regions (amorphous meaning the polymer chains does not form repeating arrays), and nearly 65-85 percent semi-crystalline regions. The two regions react to heat differently. To clarify, they go through two distinct thermal transitions, i.e. glass transition and melting, the respective temperatures of which being denoted by Tg and Tm. PET has a Tg between 340 to 353 K (67 to 80 °C) and a Tm of 540 K (267 °C). In other words, when the temperature reaches Tg, the amorphous zone of PET will start to soften while the semi-crystalline zone will not be affected. As the heat level increases, the amorphous part keeps softening till it becomes completely fluid. At that moment, the semi-crystalline part will still be intact. Only when the temperature finally exceeds Tm will the semi-crystalline part suddenly melts. In our case, for the purpose of thermo-bonding different layers of PET sheets, we have to apply a reasonable amount of heat so that it is able to melt the amorphous zone, but leave the semi-crystalline zone affected for structural integrity.

Above
Pane chair, from a single polyester fiber block

Below
Pane chair: the making process

2.1 Pane Chair

Material repurposing usually involves chemical or mechanical manipulations to change the material properties for novel functions beyond its conventional uses. For instance, Japanese designer, Tokujin Yoshioka exploited polyester fiber, a soft and malleable material, and mimicked the process of baking(applying heat) to imbue it with rigidity and strength. This process can be seen in his Pane Chair (pan means bread in Italian). First, a single round block of polyester elastomer was folded into the desired chair form and covered with a sheet, then it was inserted in a protective cylindrical casing and cooked at 104 C. This enabled the material to memorize the initial form of the chair and become rigid enough to support a person's weight (Brownell, 2014).

Left
Homogeneous local structure

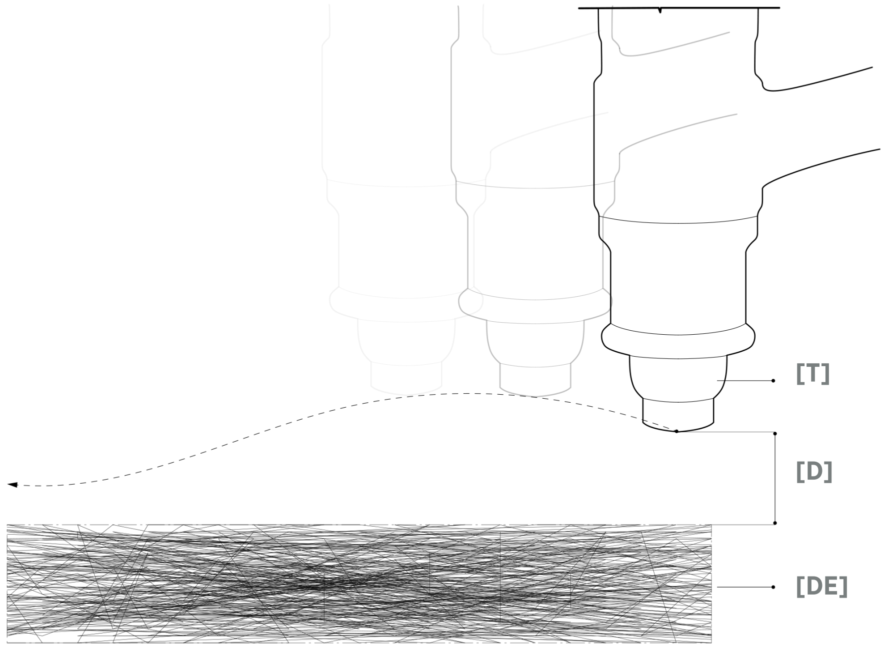
Limitation

In this project, the stiffness of the material is introduced by changing the density through twisting and folding of the polyester fiber block prior to heating. This limited the distribution of stiffness on a local scale due to the constant heat by the oven.

Hypothesis

The stiffness of PET can be controlled by varying the distance between the heat source and the PET surface while maintaining a constant temperature; this can also be tuned by varying the material density.

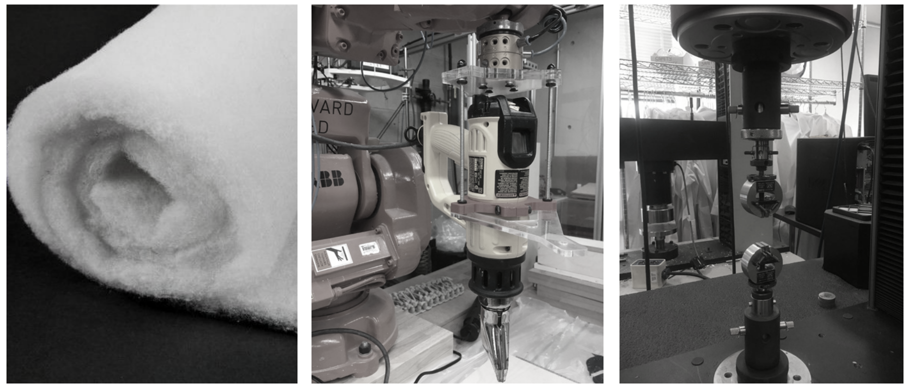
The hypothesis will aim to answer questions related to material and fabrication as follows:
Material Question : can we vary the material properties of polyester fiber, particularly its stiffness through heat and density for efficient load distribution.
Fabrication Question : Can we design a manufacturing process that turns a soft continuous polyester fiber sheet into a furniture piece



Right
Diagram illustrating the independent and dependent variables for the experiment

4.1 Independent and Dependent Variables

The independent variables include, heating temperature, the distance between the heat source and the material surface, and the material density which will be achieved by bonding two layers of material. These are the key parameters that will inform the controllability of material stiffness. Thus, the dependent variable (yield) is the young's modulus, a measure of material stiffness.



Above
Experiment components: polyester fiber sheet, robotic arm with heat gun and Instron testing

Below
The prepared samples for Instron testing

4.2 Design of Experiment (DOE) Set-up

The aim of this experiment is to understand the defined independent variables on the material stiffness after it is post-processed under the glass-temperature phase. We hypothesize that the independent variables are strongly contributing to the material stiffness. The results of the experiment would inform a process of locally controlling the stiffness of polyester fiber material. The experiment followed a Design of Experiment (DOE) method, in which Full Factorial Design (FFD) with two-level factors technique was selected to evaluate the dependency of each factor or independent variable on other factors in the design experiment, as well as their combined effects on the stiffness (young's modulus). In the context of (FFD) where three factors are set with both low and high values, eight experiments—treatments— were required. Each experiment is evaluated with three samples. Each sample of each experiment was made by applying heat with the aid of robotic arm to ensure constant heat, and the samples were 30x160x30mm.

Right
Experiment data

Independent Variables	Level [-]	Level [+]
A (Density [kg/m3])	15kg/m3	30kg/m3
B (Temperature [F])	600F	800F
C (Distance [mm])	10mm	30mm

Treatment	A	B	C	AB	AC	BC	ABC	y1	y2	y3	Mean	Standard Dev.	CV
1	–	–	–	+	+	+	–	0.3549	0.3410	0.3512	0.3490	0.0072	0.0206
2	+	–	–	–	–	+	+	0.4602	0.4515	0.4477	0.4531	0.0064	0.0141
3	–	+	–	–	+	–	+	0.4373	0.4312	0.4254	0.4313	0.0060	0.0138
4	+	+	–	+	–	–	–	0.6028	0.5936	0.5910	0.5958	0.0062	0.0104
5	–	–	+	+	–	–	+	0.2210	0.2033	0.2164	0.2136	0.0092	0.0430
6	+	–	+	–	+	–	–	0.3204	0.3416	0.3370	0.3330	0.0112	0.0335
7	–	+	+	–	–	+	–	0.2776	0.2739	0.2806	0.2774	0.0034	0.0121
8	+	+	+	+	+	+	+	0.4163	0.4006	0.4085	0.4085	0.0079	0.0192

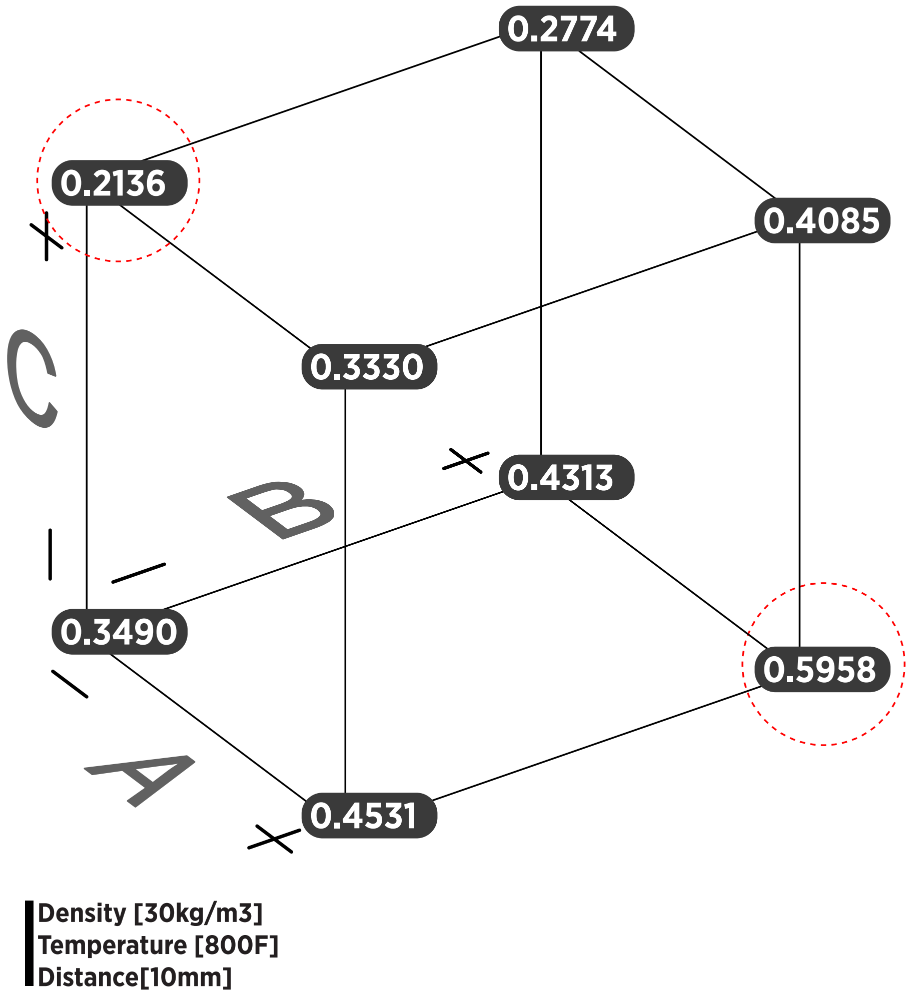
Young's Modulus = 0.3827+0.065A+0.046B-0.075C+0.009AB-0.001AC-0.011BC-0.006ABC

Young's Modulus = 0.3827+0.065A-0.075C

	Factor	P-value
[Density]	A	0.060
	B	0.085
[Distance]	C	0.052
	AB	0.379
	AC	0.775
	BC	0.330
	ABC	0.501

4.3 Analysis

In order to understand the impact of different independent variables (density of polyester material, temperature of the heat source, distance between the heat source and the heated polyester surface) on the stiffness of thermo-bonded polyester material, a design of experiment was set up. For each independent variable, its maximum and minimum values were adopted. To specify, we prepared identical polyester specimens of 15kg/ m³ and 30 kg/ m³ density, treated them with a heat gun at 600F and 800 F from 10mm and 30mm away according to the same pass. In total, we produced 8 different groups of samples, with 3 specimens in each sample group.

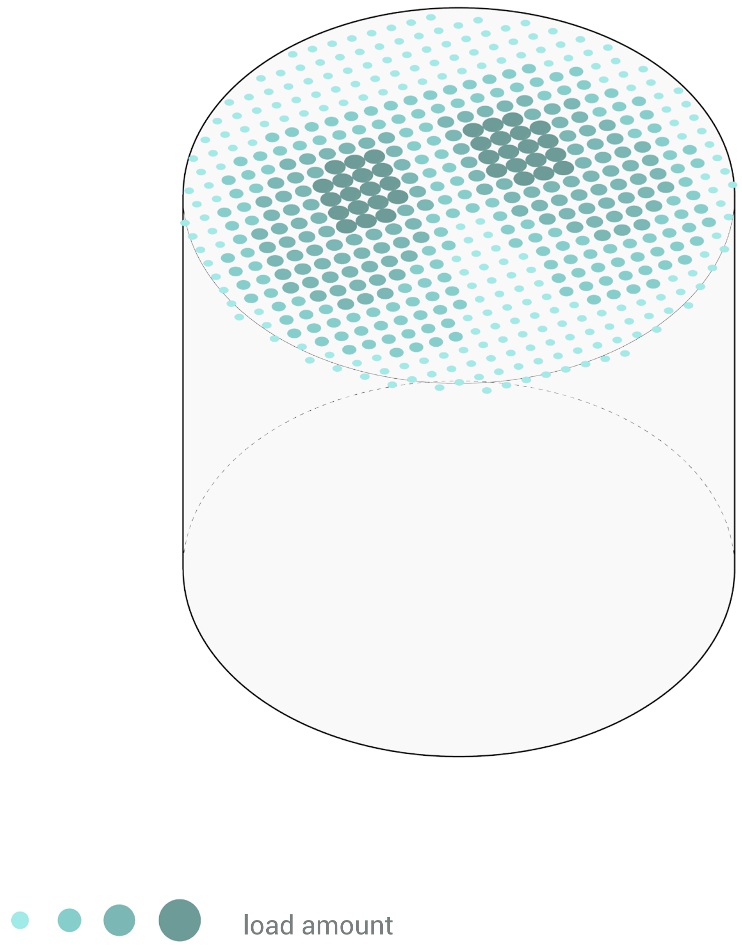


Left
'cube plot' showing the effect of the paramters

4.4 Results and Evaluation

After data collection and analysis of 24 specimens, it was found that density (of material), as well as distance (between the heat source and the polyester) play a bigger role in determining the stiffness (of the thermo-bonded polyester). That was why we chose to vary these two parameters in our following fabrication process.

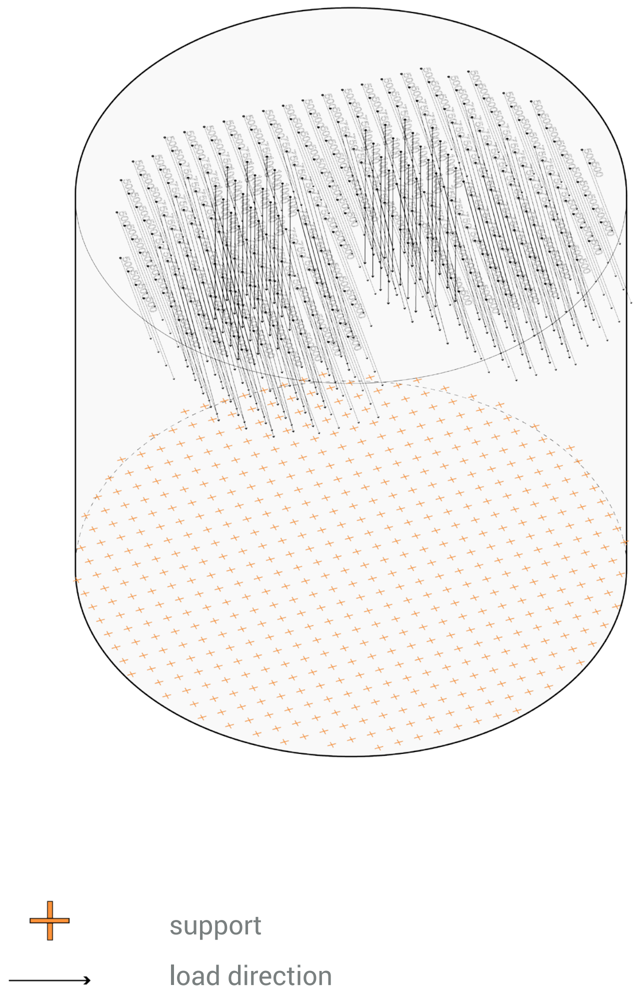
Right
Load distribution



5.1 Structural Analysis Set-up

Load Distribution Logic

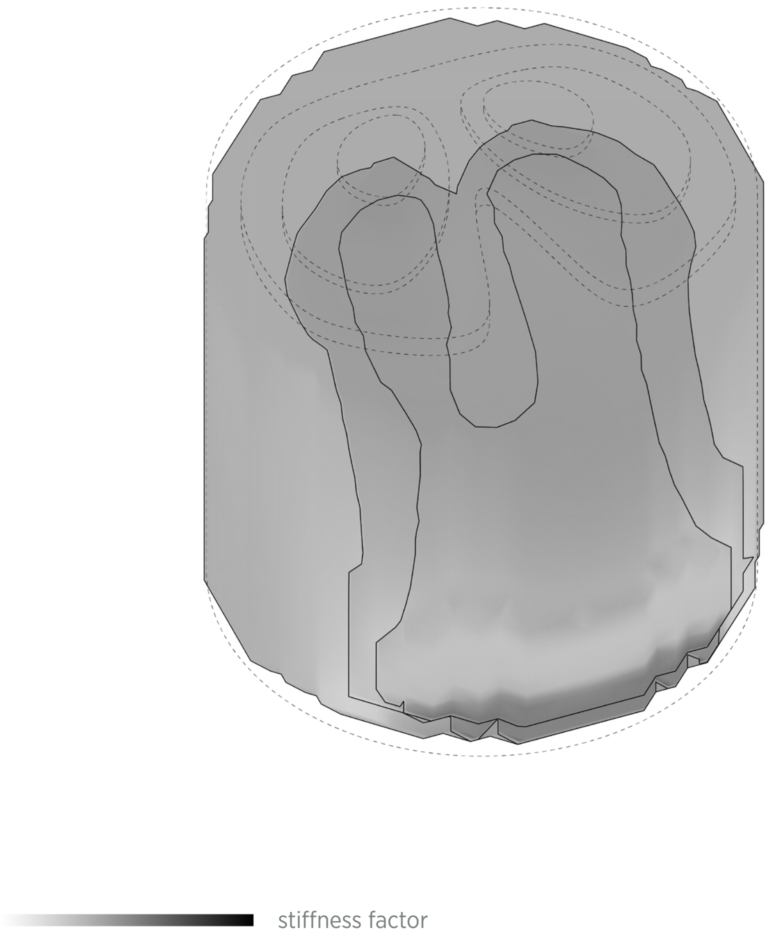
The aim of the topology optimization exercise is to inform the most efficient distribution of stiffness (thickness distribution) in the geometry. This optimization was carried out through the Millipede plug-in for Grasshopper3D, where a simple cylinder representing the geometry of the chair was modeled, and a loading amount was distributed and applied in specific direction, and finally a support condition was defined. Regarding the load distribution, the applied load was set to reflect double the weight of a standard human weight at 1400 N. In reference to a research done by Herman Millar on chair ergonomics, the applied load was hierarchically distributed so that the center zone (dark blue) [fig] corresponded to the highest amount of pressure or load, and consequently less pressure around the periphery. The form of the distribution reflects the pressure maps obtained from Herman Millar document.



Left
Load direction and support conditions

Load Direction and Support Conditions

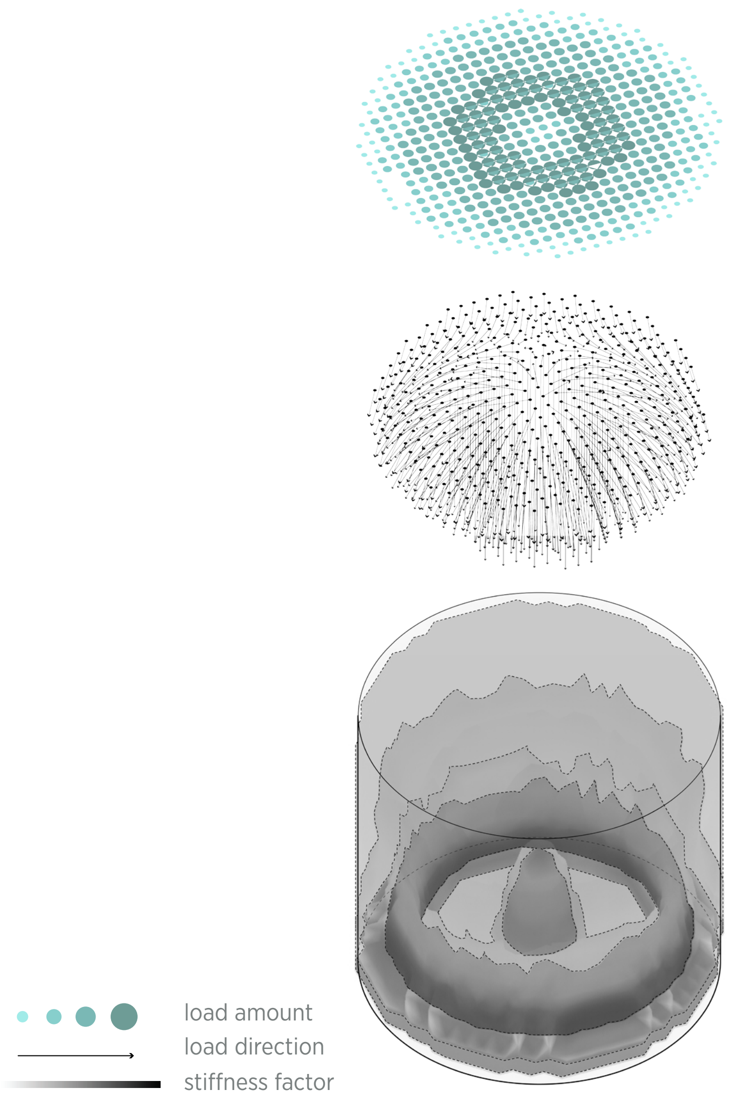
After assigning the appropriate load capacity for each division point on the surface, they were assigned a direction based on their intensity. For instance, the direction of the load in the center zone where the load capacity was the highest, the load direction is perpendicular to the load area. On the other hand, vectors of 60 and 45 degrees were assigned to the other load zones, respectively.
The support conditions at the bottom were defined so that only translation around the X,Y and Z axes were restricted.



Above
Topology optimization visualization

Material Density - Stiffness Factor

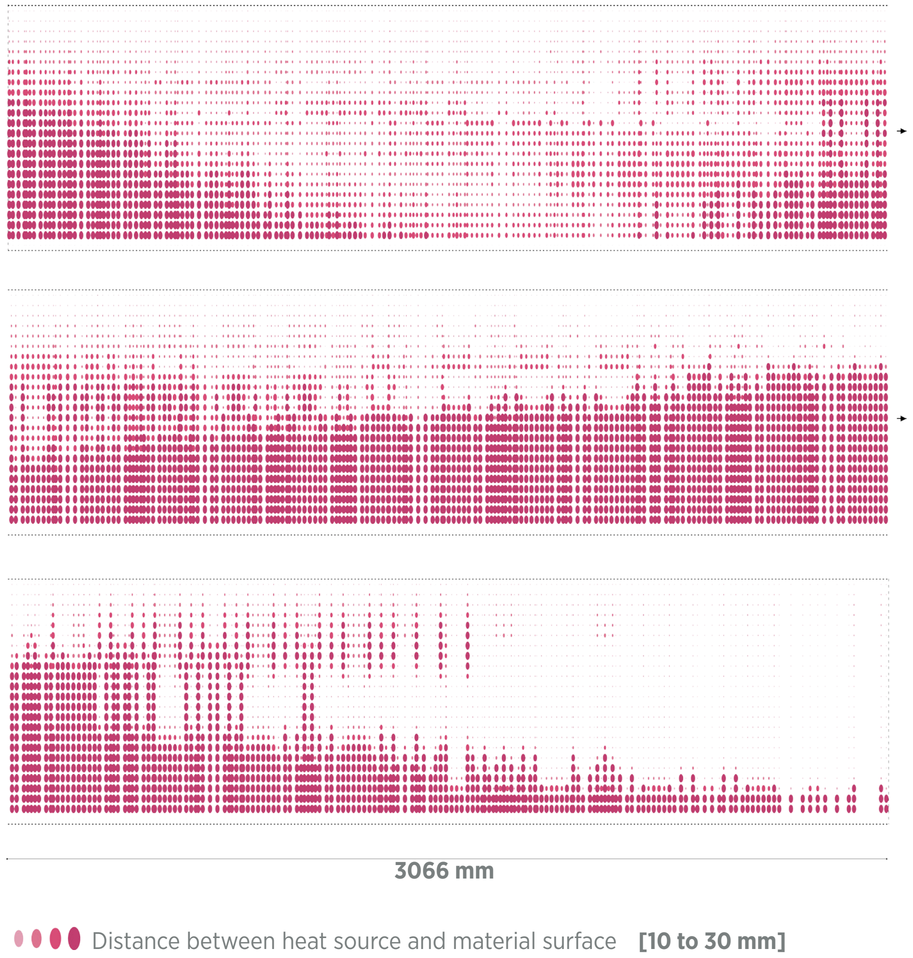
After setting the load and support conditions, the optimization analysis was run through an iterative process using the Millipede structural optimization component. This component aims to maximize the overall stiffness while minimizing the weight, providing a visualization and information about thickness distribution. [Fig] shows that the analyzed geometry is required to have more material around the base in the location of the loads' direction, and at the center as well. A gradient distribution of stiffness is also observed between the bottom and the center zones of the analyzed geometry where the stiffness is required the most.



Left
Combined loading condition for the final chair prototype

5.2 Analysis and Results

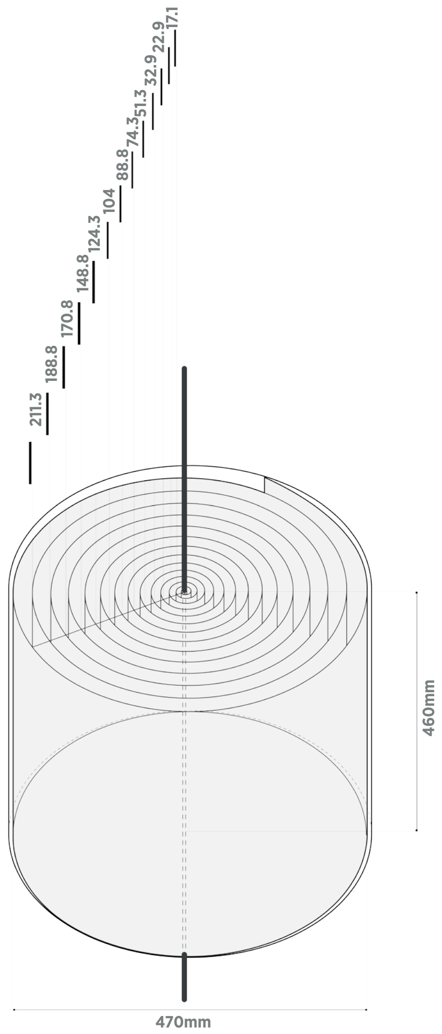
For the purpose of this furniture application, the goal is to fabricate the chair from one continuous sheet of polyester fiber, and also to have the seating zone confront to all sides of the cylindrical geometry. Thus, a loading condition with similar amount of force distribution and direction was introduced six times around the center of the geometry with uniform rotation. This would ensure that the chair's form is optimized for all seating positions.
The chair will be created from the a continuous sheet of polyester fiber by rolling it on itself as many times as required. It is found that a number of thirteen rolls would yield a chair with a width of 460mm. Hence, for the analysis, it was required to set the resolution to 26 divisions in order to distribute the information on each roll, and thus minimizing the case where one nodes would appear on more than one roll.
The result of the optimization showed that the maximum material thickness was required at the peripheral bottom boundary and at the center.



Right
Mapped stiffness values on the unrolled chair surface

6.1 Fabrication Logic

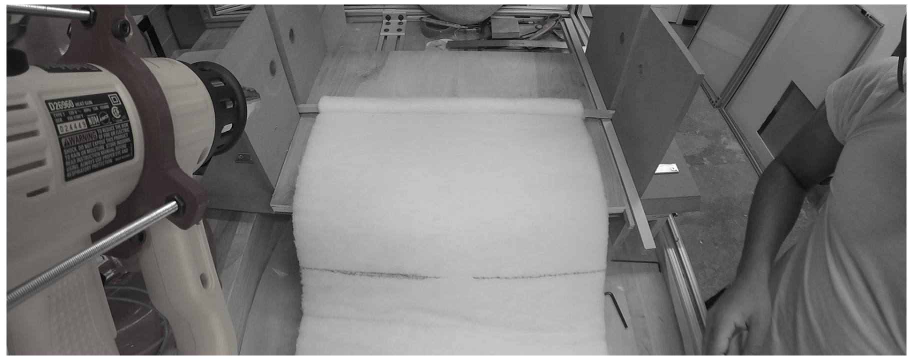
From the previous optimization exercise, a value for each node within the geometry was obtained to reflect the material thickness at that location, which fell between 0 (minimum thickness) and 1(maximum thickness). To map these values to their corresponding location on the actual rolled geometry, they were projected to their closest perpendicular projection path to the rolled surface (the chair geometry). Afterward, the surface was unrolled along with the projected points, and these points were translated along the Z axis by their thickness value (stiffness factor). A domain was defined for the translation distance based on the material knowledge gained from the physical experiment, and set to be between 10 and 30 mm—this corresponds to the distance parameter, which is the distance between the heat source and the material surface—. [Fig] showed the unrolled chair with the corresponding mapped points, in which the dark red represents a close distance between the heat source and the material surface, hence, increased stiffness, and on the contrary,

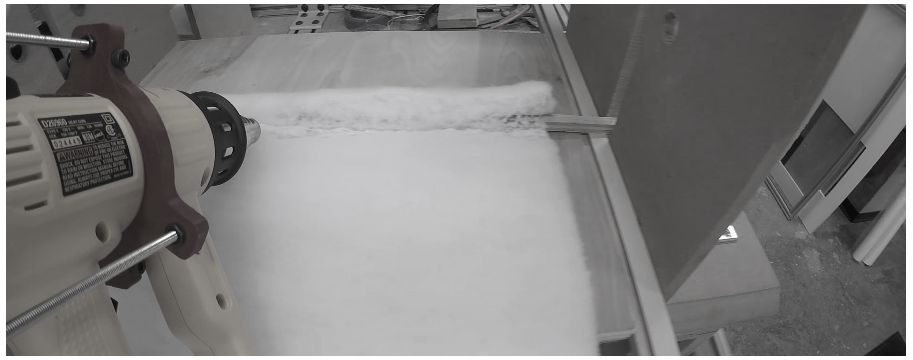


Left
Rolling strategy and radius growth

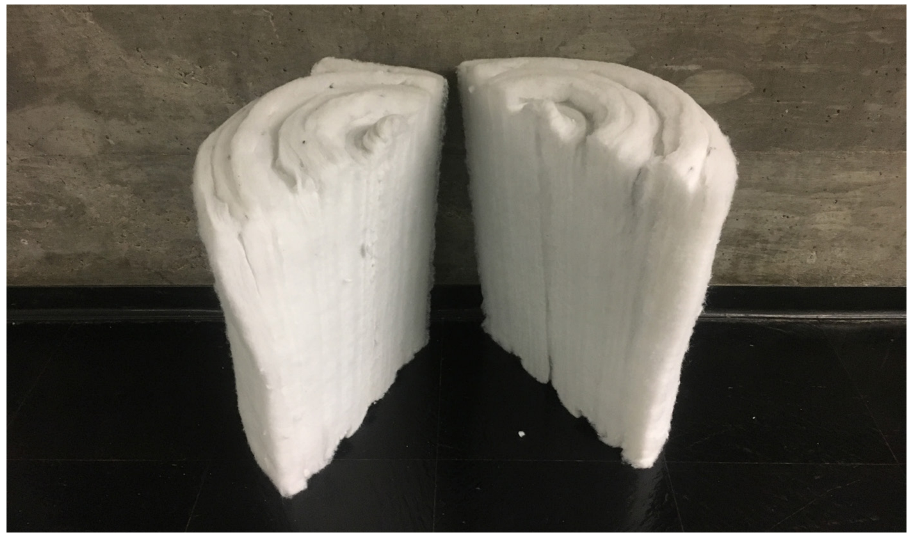
a decrease in stiffness at the light-red areas.
This process was followed by dividing the unrolled surface into regions that corresponded in dimension to the diameter of each roll. This was important to compensate for the radii growth after each roll, and to determine the incremental change in which the robotic arm had to adjust to cover the correct area. The dimension of each radius for each roll was determined by rolling the actual polyester fiber sheet and recording the radius using a ruler. The reason for this is because the rolling required a continuous pressure, and with this applied, it was difficult to precisely model digitally.

Fabrication Process





Right
Fabrication process



Above
Chair prototype implementing the distance parameter

Below
Prototype section

6.2 Robotic Fabrication Set-up

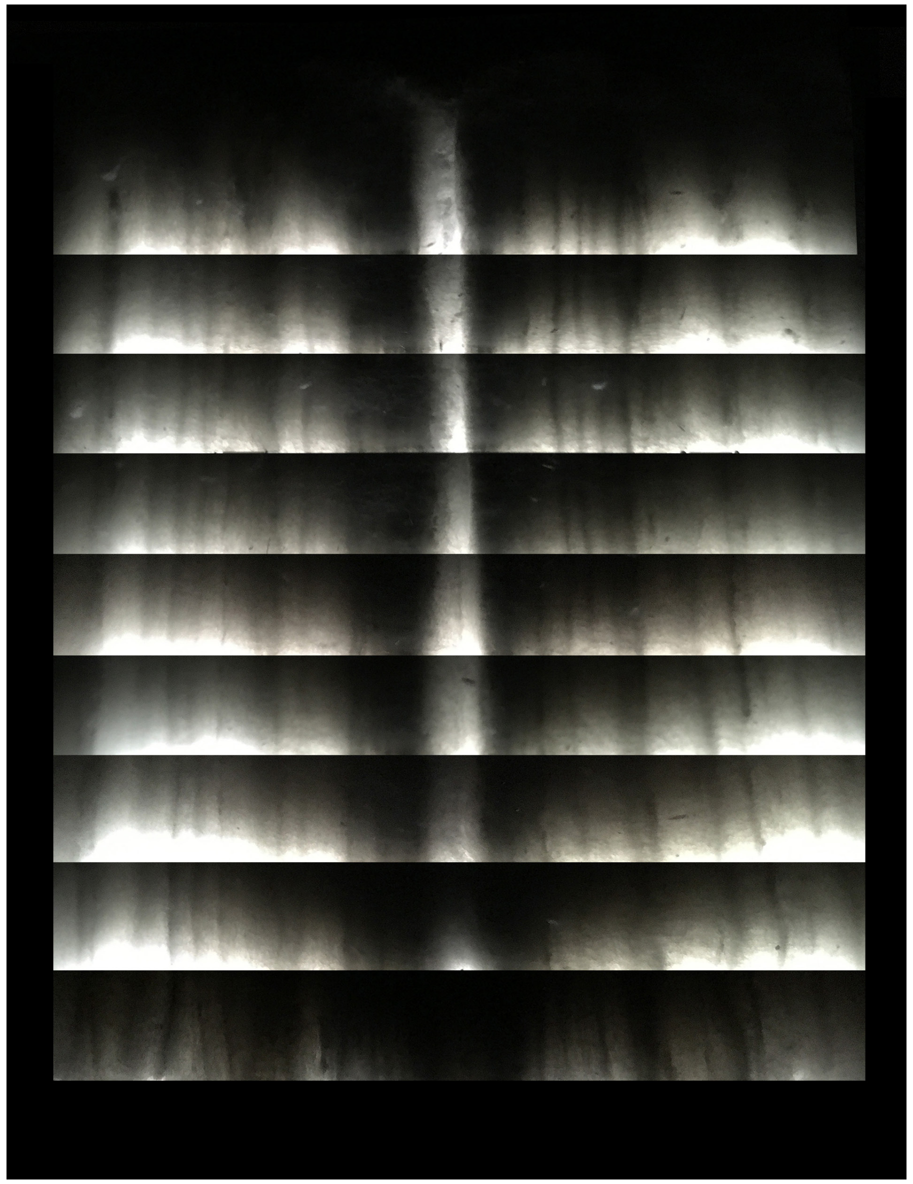
The robotic fabrication involved constructing a tool path that was perpendicular to the longer side of the polyester fiber sheet. To generate the tool path, it was important to consider the coverage area of the heat source, in which a head with diameter of 40mm was utilized for the heating process. This required the unrolled surface to be divided into 40cm width regions. Thus, each region would have a tool path composed of points with different height (the height corresponds to the amount of stiffness required). In addition, the incremental change of the radii growth was considered in the tool path to ensure heating at the correct position. The fabrication process began by rolling the polyester fiber sheet with a squared section stick (0.5" x 0.5"). This was done manually in a pre-fabricated base with slits on both side for the stick to slide in. The slits were designed to accommodate for the radii growth, and to prevent shifting the original coordinate of the rolled geometry, hence the robot movement would properly heat each designated region without overlapping with the already heated regions.
The robotic tool path was generated with Machina plug-in for Grasshopper3D, and a 6-axis ABB robot with a customized end effector to hold the heat gun, was utilized for the heating process. The fabrication process started with manually rolling a small portion of the first end of the polyester fiber sheet with constant pressure to ensure proper bonding upon heating and uniform rolling across the heating process. The robotic arm was run continuously in the following manner: first it heated the first region starting from the positive X to negative X directions. Once the heating was done, the robotic arm retracted away to allow for an appropriate time to manually roll the polyester sheet for the next region to be heated. The robotic arm then moved towards the new region starting from its current position to begin heating the new region in the opposite direction. This process continued for the heating of the remaining regions.

6.3 Chair V1 | Results

The resulted prototype was tested by sitting on it, and it was able to withstand a person's weight without exhibiting any failure. The prototype was cut from the middle into two halves in order to validate the stiffness information from the topology optimization result.

Fabrication Process

Right
Tomography process



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Tomography result

6.4 Validation Technique

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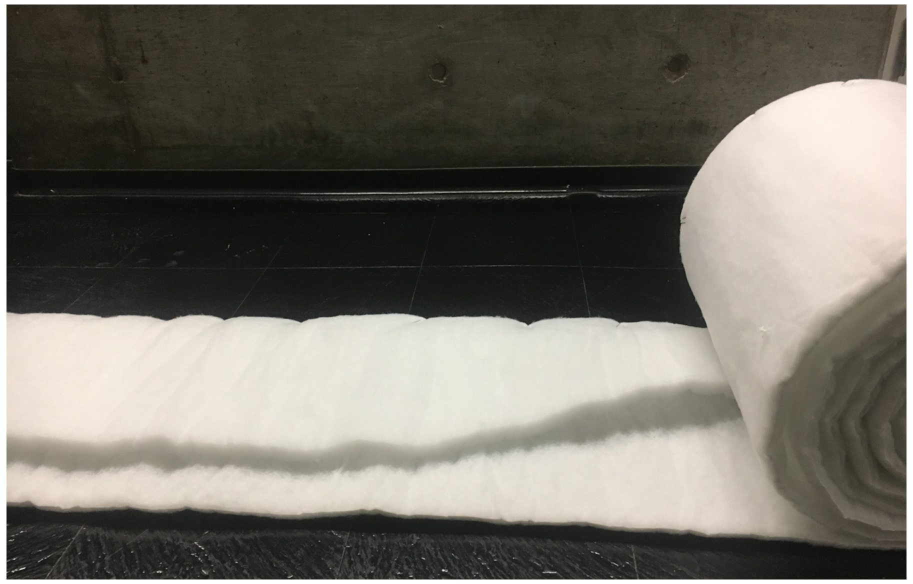
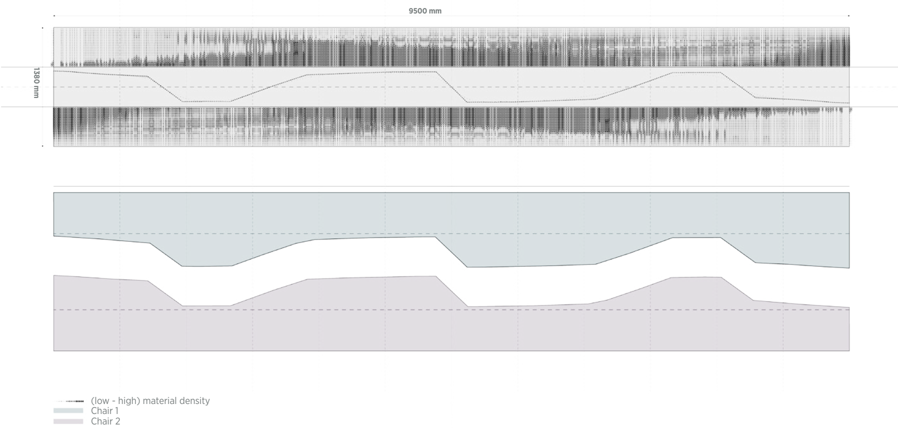
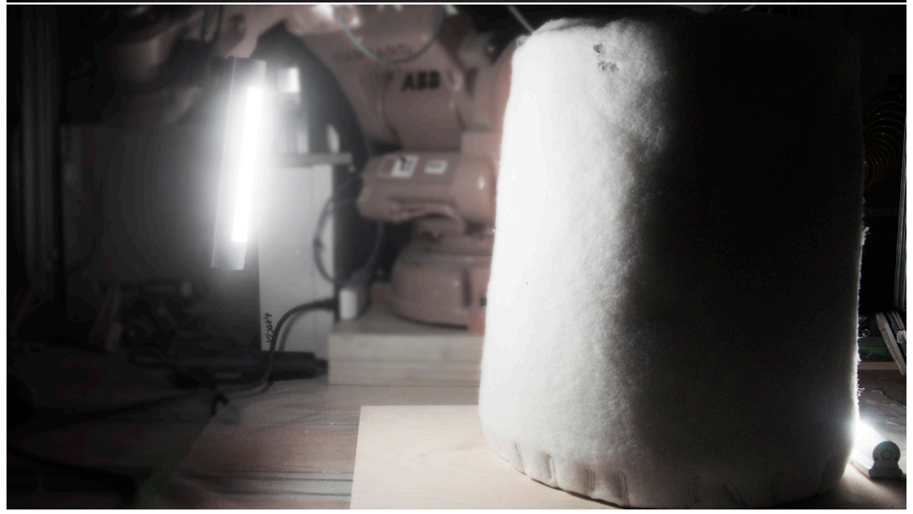


Right
Folding process



6.5 Material Density through Folding

The second chair prototype involved combining both the distance and material density parameters. Folding technique was used as a method for increasing the material density. The raw material as it is being delivered from the manufacturer came with a dimension of 1.38m in width and almost 18.5m in length. The first chair prototype had a dimension of 0.46m and 9.25m in length. That means six chair prototypes can be produced from the single sheet obtained by the manufacturer. The sheet was equally divided into six regions. However, the aim for this prototype was to increase the material thickness, and as a result, a decision was made to use the middle portion of the divided sheet in order to construct the folding outline. This outline was optimized so that it could produce identical chairs while covering the areas that required high material thickness based on the topology optimization results



Above
Final prototype

Below
Final prototype

6.6 Chair V2 | Results

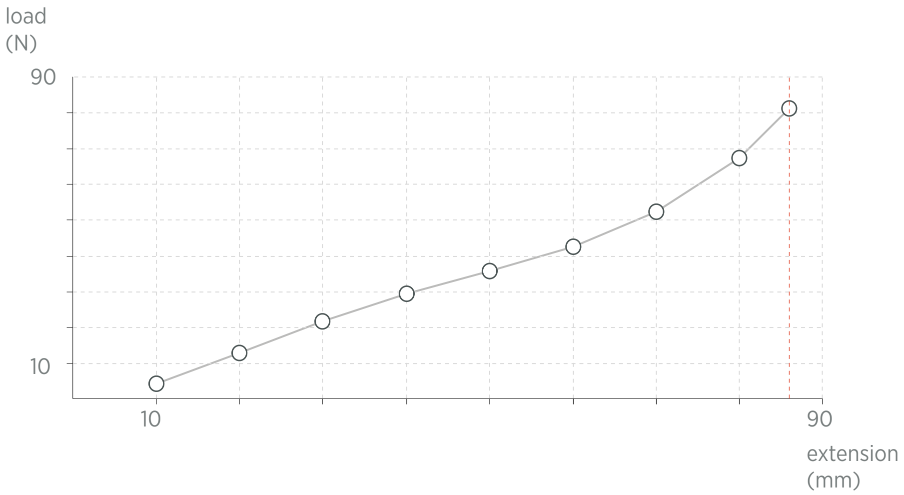
The resulted prototype was tested by sitting on it, and it was able to withstand a person's weight without exhibiting any failure. The combination of the two parameters: distance and material density proved their effectiveness for better structural performance.

Conclusion and Further Development

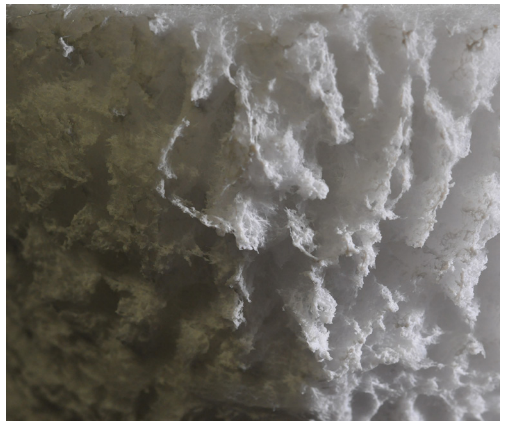
This research proposed a material process for controlling the stiffness of polyester fiber through thermal bonding and material density for the fabrication of a furniture application, particularly a chair. The design of experiment approach evaluated the effect of a set of defined parameters, including, heat temperature, distance between the heat source and the material surface and the material density. It was concluded that the distance and material density parameters and their combined effect yielded a higher young's modulus among others, hence, they were adapted for the chair fabrication. This was possible by using topology optimizing techniques for efficient material distribution, and through the aid of robotic fabrication. The earlier was utilized to inform the material thickness distribution in the chair form, in which the thickness values were translated into distances. These distances generated the robotic tool path for heating the polyester fiber sheet while it was being rolled. The final chair prototype combined the effect of the two parameters, in which increasing the density was achieved with folding the material onto itself. Not only did it show an increase structural performance, but also an increase efficiency of material use, creating a zero waster fabrication process. For future work, the research will aim to explore the opportunities for personalizing the chair application to address specific weight, seating geometry or location, texture, and others. In addition, other technique to increase the material density will be investigated. Finally, automating the rolling process and calibrating it with the robotic tool path will be implemented.

Appendix

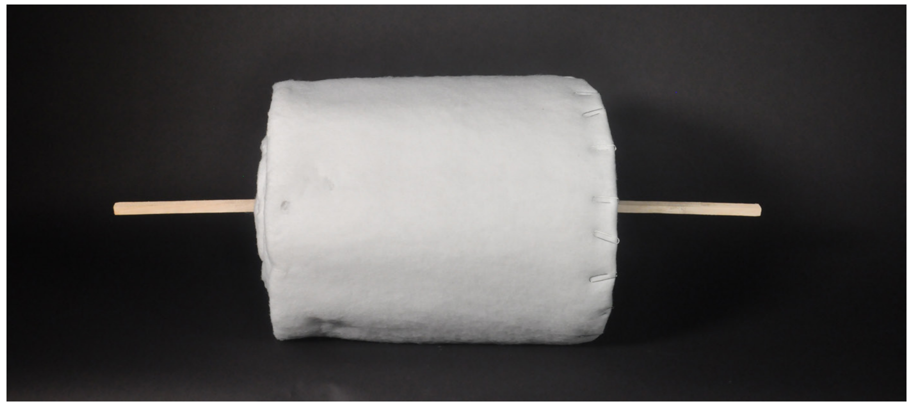
Compressive Analysis - Instron Testing



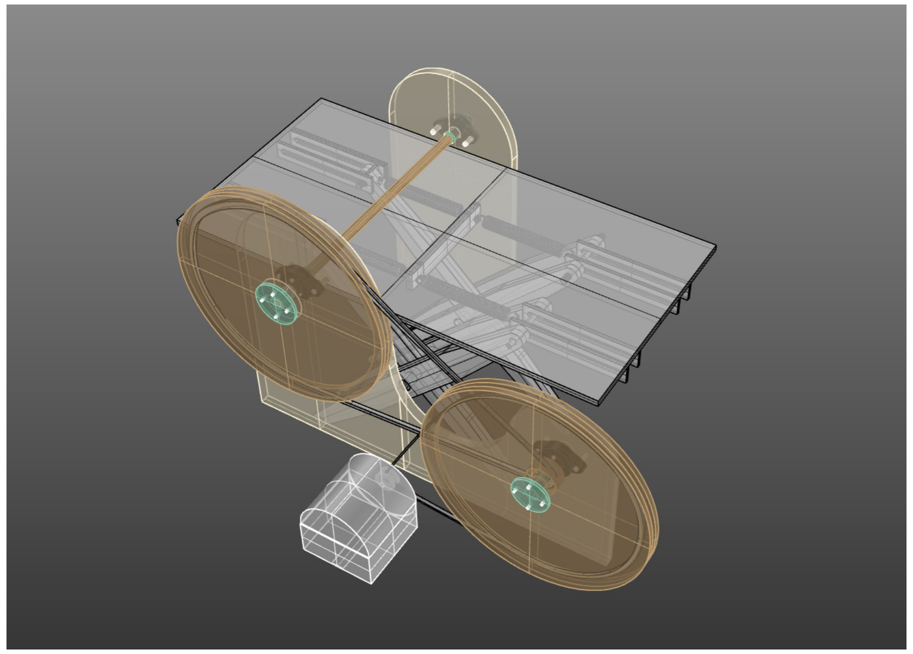
Earlier Prototypes



Final Prototypes



Proposed automated rolling device



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