Heat Chair: Controlled Stiffness Gradients through Thermal Bonding and Density Differentiation

Abstract

This research aims to develop an integrated design and fabrication strategy in the context of polyester fiber material utilizing its phase-change behaviour under certain treatments (e.g. density and heat) to achieve controlled local stiffness variation for specific design and structural purposes. This research will be contextualized within a design proposal for the fabrication of small scale furniture, in particular a chair application.

1 Introduction

Functionally graded materials (FGM), often originating from spatial variations of chemical composition, microstructure and geometry of the material ingredients, are omnipresent in nature. The gradients bring myriad mechanical as well as functional advantages to organisms. For example, in the stem of a palm tree, the density increases from center to periphery, introducing non-uniform distributions of both local mechanical strength and stress which leads to more efficient load-bearing and support of the stem [1]. In a design and fabrication context, 3D printing techniques have been extensively utilized to innovate FGM products. However, the computation process involved is generally over-complex and indifferent to materials. In some cases, the inherent problems of 3D printing including, extended printing time, poor dimensional accuracy and onerous post-production render it less practical for mass production. Alternatively, a material-based approach generates design and fabrication methods from the material opportunities. With a material-based approach, there is a wider design interface to capitalize on the specific material behaviors which can form gradations in an efficient, continuous and controllable manner. In this paper, the author reports on a series of experimental studies that test a computational design and robotic fabrication workflow which exploits the material behavior of polyester fiber during a vitrification state. This process culminates in the ability to control the stiffness gradients of polyester fiber for efficient structural and functional systems, promising the mass production of FGM products for industrial application at larger scales. In addition, aspects of the research can be utilized to address the increasing need for a more personalized and energy-efficient production in the emerging future.

2 Background

The use of novel fabrication approaches such as 3D printing has demonstrated the potential of personalizing intricate FGM products. Precedents were examined here to illustrate the significance of synchronizing design with fabrication and material knowledge for more productive FGM applications.

Dutch designer Lilian van Daal 3D prints the Biomimicry Chair with nylon to imitate the plant cell structure in nature. Varying zones of stiffness within one chair is gained by orienting the structure horizontally or vertically in the design. Manuel Jiménez García and Gilles Retsin at The Bartlett School of Architecture UCL also 3D print a single-material chair with heterogeneous structural properties. But it is realized through distributing voxels of multiple hierarchies of scale and density according to the stress levels. The voxels are subsequently connected to form a continuous tool path for printing. The design and fabrication processes are well-integrated in this case, however, material knowledge needs to be further involved for better control of the printing process.

On the other hand, multi-material 3D printing has empowered designers to materialize gradient materiality in a more direct way. The Durotaxis Chair [4] by Alvin Huang is as such a 3D printed dual-position rocking chair using both the harder cyan material and softer white material, characterized by a densely packed wire mesh that gradates in size, scale, density, color, and rigidity in relation to the structural and functional applications. Due to the limit of the printer, in actual fabrication, the mesh was divided into a series of stepped gradients, each assigned with a certain proportional mix of the two materials for printing. Thus, although the digital workflow from design to fabrication allows an automated translation from the designer's mental gradient to the materialized gradient, the result is less than continuous and the process is still labor-intensive.

While these precedents successfully leverage advanced fabrication techniques such as 3D printing for FGM product innovation, the computation process is often expensive and inattentive to materials. In many cases, the cost to performance ratio of 3D printing renders it less practical for mass production. Alternatively, a material-based approach seeks design and fabrication opportunities from a material perspective, taking advantage of appropriate material phenomena that can form gradations in an efficient, continuous and controllable way. It has the potential of enabling the mass production of FGM products for industrial application and at larger scales.

Some institutions and designers have been exploring various material combinations for rapid gradient generation. Institute for Advanced Architecture of Catalonia experiments with mixing different percentage of resin, sawdust and beezwax to achieve gradient translucency in a casted piece. The Mediated Matters group at MIT Media Lab has worked on controlling the density in concrete by varying the ratio of aluminum foaming agent through an automated mixing chamber for continuous gradients. [5]

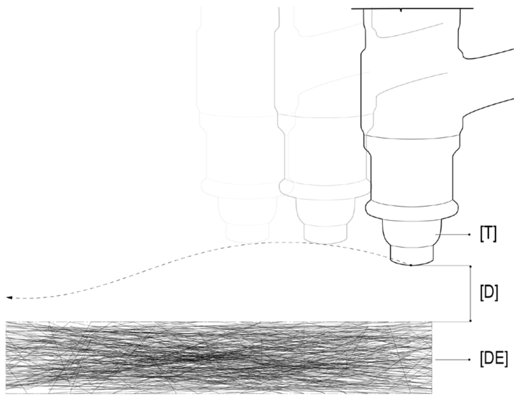
Apart from directly manipulating the chemical composition in a multi-material blend, the Pane Chair by Japanese designer Tokujin Yoshioka exploits the phase change phenomenon of polyester fiber to change its stiffness. [6] To specify, the soft and malleable polyester bulk is folded into the designed chair form and covered with a sheet, then inserted into a protective cylindrical casing and baked at 104 C in an auto-clave. The folding as well as heating treatment imbues the soft material with rigidity and stiffness, although the stiffness in the baked chair is still relatively homogeneous because of the uniform heat condition in the auto-clave. Inspired by the Pane Chair, this research will focus on further exploiting the heat-induced glass transition behavior of polyester to attain varied stiffness. The authors aim to combine the material knowledge with computational design and robotic fabrication methods for achieving locally tunable material gradiences adapted to various applications. Moreover, developing a zero-waste and cost-effective way of FGM production for mass manufacturing will be investigated.

Method

In order to control the stiffness of polyester fiber during the vitrification state, three processes were designed which together enables the making of the chair prototype. The first is related to stiffness manipulation through an external heat source, which is the primary factor to induce a phase change material effect; this is quantified and informed through a Design of Experiment (DOE) approach where the effect of factors such as heat temperature, material density and heating distance were carefully examined. Second, to utilize the results from the physical experiment to build a varied-stiffness prototype, a computational strategy of a topology optimization technique was developed to inform an efficient distribution of material stiffness under certain loading conditions. Third, a fabrication process was developed where rolling of a complete polyester fiber sheet is calibrated with a 6-axis robotic arm that allows the control of heating distance to the material, a very time-efficient process for continuously varying the stiffness of polyester fiber material.

2.1 Design of Experiment

The aim of this experiment is to understand the effect of the independent variables on the material stiffness after it is post-processed, particularly during its glass-temperature phase. The independent variables include, heating temperature, the distance between the heat source and the material surface, and the material density which is achieved by pressing two layers of material and heat bonded them together (Figure 3). These are the key parameters that will inform the controllability of material stiffness. The dependent variable (yield) is the young's modulus, a measure of material stiffness. We hypothesize that the independent variables are strongly contributing to the material stiffness, and 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 conducted and evaluated with three samples. Each sample of each experiment was made by applying heat with the aid of robotic arm to ensure a constant heat, and the samples were treated with low values of 600 F, 15kg/m^3 density, 10mm distance from heat source to the surface of the material, and on the high levels: 800F, 30kg/m^3 , and 30mm respectively.



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

Fig. 3. Right: Independent variables including, heat temperature [T], distance between heat source and material surface [D] and material density [DE], Left: Minimum and maximum values of independent variables in the experiments

In order to calculate the stiffness of the samples, an Instron device was used to measure the Modulus of Elasticity (young's modulus) of each sample. This was set up under a tensile method with constant rate of extension where the strength of the sample is inferred by a stress-strain curve. The curve depicts the relationship between the applied force (N) and the elongation of the sample, which was almost linear in the initial portion of the test before experiencing a material failure. It was observed from the curve that there were moments of local material failure depicted by a slight-sudden drop, that were immediately followed by a linear relationship. These failures occurred at the weak regions of the sample where large pores are located. The young's modulus was calculated by finding the slop of the curve before experiencing local failure or between two local failures where the curve is linear, using the following equation:

$$E = \delta \text{ (Applied Force or load) } / \varepsilon \text{ (Elongation or Displacement)}$$

Results and Analysis

The experiment showed that the maximum stiffness was achieved with 30kg/m^3 density, 800 F temperature and 10mm distance (figure 4). In addition, the probability values were calculated for each factor and its interaction with other factors, which informed that the material density and the distance from the heat source to the material surface were the most significant to the young's modulus or material stiffness. Hence, the two aforementioned factors were selected as parameters to control the stiffness of polyester fiber. In addition, a linear regression model was generated in which the stiffness could be estimated through the following equation:

Young's Modulus = 0.3827+0.065(Density)-0.075*(Distance)*

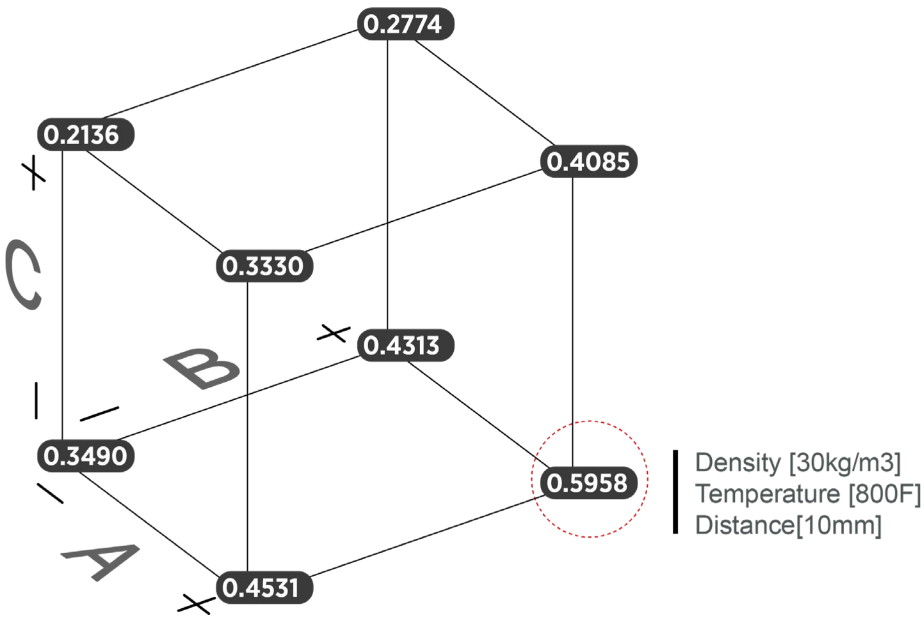


Fig. 4. 'Cube plot' showing the significance of parameters' effect on the material stiffness

Might need more explanation for data analysis

2.2 Distributing material density through topology optimization

In order to inform the most efficient distribution of stiffness (thickness distribution) in the intended prototype, a topology optimization was carried out through Millipede plug-in for Grasshopper3D, where a simple solid cylinder representing the geometry of the chair was modeled. As mentioned previously, 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 geometry, and thus, a loading condition with similar amount of force distribution and direction was introduced six times around the center of the geometry in a uniform manner. The applied load was set to reflect double the weight of a standard human, at 1400 N. The load was distributed with gradation amount and direction, in which the highest amount of force was applied perpendicularly in the center and the lowest around the periphery with an angular direction; this was based on studies done by researchers using pressure sensitive mats to identify the distribution of load in a form of pressure maps (Herman Millar). The support conditions at the bottom where defined so that only translation around the X,Y and

Z axes were restricted. The optimization analysis was run through an iterative process using the Millipede structural optimization component, which maximizes the overall stiffness while minimizing the overall weight, providing information about thickness distribution through the ‘stiffness factor’ option. The result of the optimization showed that the maximum material thickness was required at the peripheral bottom boundary and at the center (figure 5).

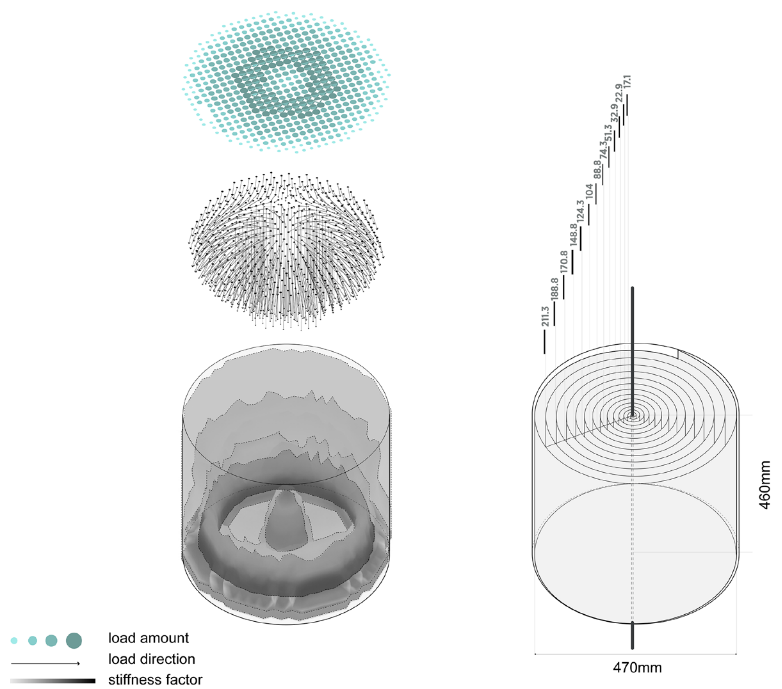


Fig. 5. Left: Topology Optimization of material distribution based on stiffness factor; Right: Rolling strategy and radius growth

The resolution of the analyzed 3D model was set to 26 divisions , corresponding to rolling the polyester fiber sheet in thirteen circles to create a chair of size 470x470x460mm. The rolling was exploited to generate the chair form a continuous sheet of polyester fiber, a design intent. Each analysis node has a float value between 0 and 1, reflecting minimum and maximum material amount respectively. The nodes with their values were mapped on another modeled rolled surface of thirteen circles by projecting them to their closest perpendicular projection path to a closest circle. Followed by this, the surface was unrolled with its projected nodes. The nodes were translated along the Z axis by their stiffness value which in turn was remapped to a domain between 10 and 30 mm to reflect the distance parameter— the distance between the heat source and the material surface— suggested in the previous physical experiments. The unrolled surface was divided into regions that corresponded in dimension to the diameter of each circle. This was important to compensate for the radii growth when rolling to determine the incremental change in which the robotic arm needed to adjust to, in order to cover the correct area for heating. The diameter for each circle was measured by rolling the polyester fiber sheet with applying pressure to ensure proper heat-bonding, which was non-trivial to precisely model digitally.

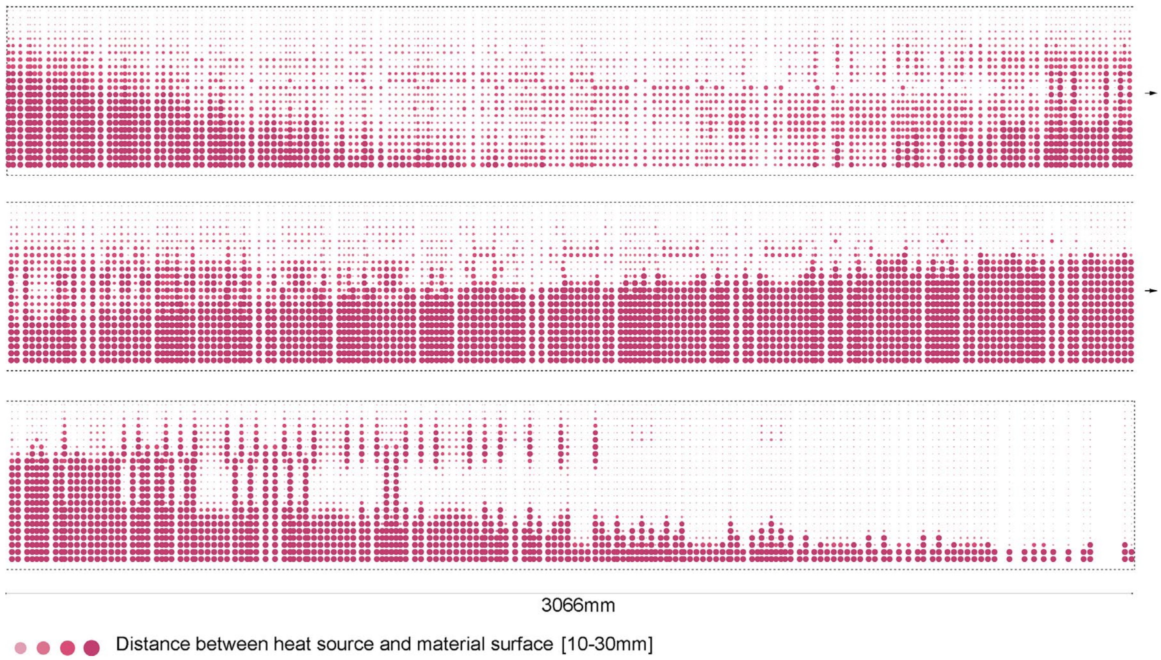


Fig. 6. Mapping the stiffness values from the topology optimization result on the unrolled surface to determine the distance between the heat gun and the material surface

2.3 Robotic Fabrication Setup

The robotic fabrication involved generating a tool path that was perpendicular to the longer side of the polyester fiber sheet. In this process, 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 further into 40mm width regions. Each region had a distinct tool path constructed from points with different height—correpsonding to the distance parameter. 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 comprised of rolling a 10 meter polyester fiber sheet by using a squared-section wooden stick (0.5” x 0.5”). This was done manually in a pre-fabricated wooden apparatus 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 ones (figure 7).

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 one end of the polyester fiber sheet with constant pressure to ensure proper bonding upon heating, and uniform rolling across the heating process with 40mm increment. The robotic arm was run continuously while rolling the polyester fiber sheet until it reaches its other end. First, based on the toolpath, the robotic arm hovers over the initial region of the rolled polyester sheet with a heat gun and heats from one side to the other. Once heating is performed, the robotic arm moves away from the sheet to allow for an appropriate time to manually roll and prepare to heat the next region. This process was performed to heat the entire divided 40mm regions.

Fig. 7. Fabrication setup and the calibration between the rolling and heating processes

3 Results and Evaluation

The first physical product was a result of incorporating the distance parameter alone, which proved its ability to withstand a person's weight without exhibiting any failure. This parameter was responsible of locally controlling the stiffness of polyester fiber. Thus, in order to validate and compare the stiffness of the treated polyester fiber with the topology optimisation results, the produce was cut from the center into two halves, and one of them was examined through a simple imaging technique. A high lumen LED light was closely directed to the section-cut region, in which it revealed the dense areas—more stiff—as dark regions, and less dense ones—less stiffness—as bright regions. A series of images were taken from top to bottom and were digitally stitched together. It was observed that the centre and bottom-peripheral parts of the chair were the darkest—stiffest—, and comparing this outcome to the topology analysis result, it was concluded that the robotic and computational workflow was indeed an efficient process towards mass customisation with feature of functionally graded materials.

A second physical product combined both the distance and material density parameters. Folding was used to increase the material density. The raw material is delivered from the manufacturer as one continuous sheet with a dimension of 1.38m in width and almost 18.5m in length. The first fabricated product had a dimension of 0.46m and 9.25m in length, which means six chairs can be produced from one single sheet, and thus the sheet was equally divided into six regions. However, the middle two regions were utilized for folding to increase the material thickness, which meant achieving four chairs in total. The outline for the folding was optimized so that it could produce identical chairs while covering the areas that required high material thickness based on the topology optimization results. The second product proved high structural performance, handling the weight of two persons.

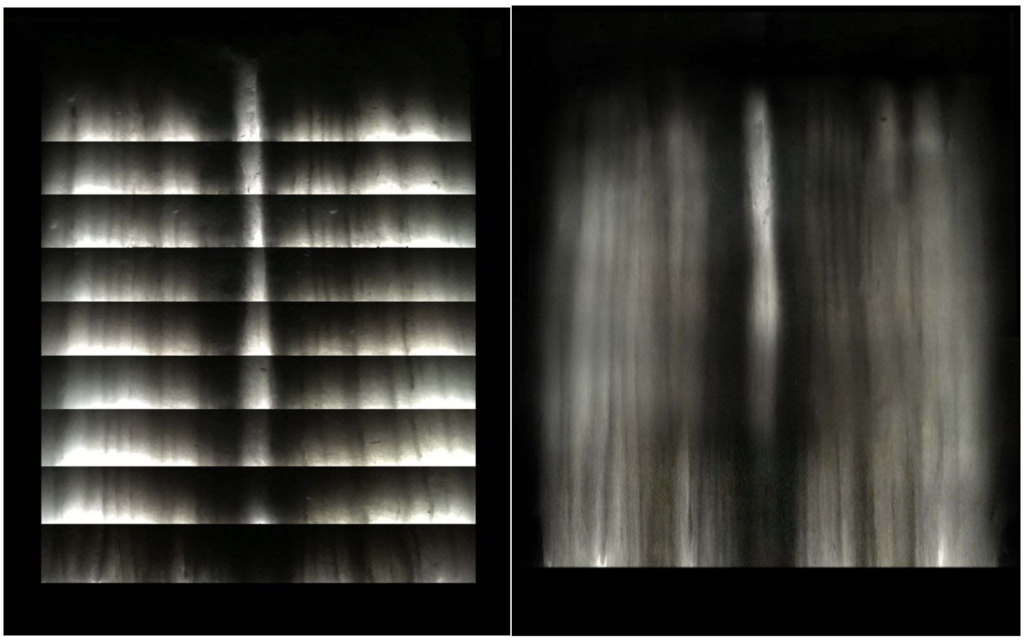


Fig. 7. Imaging technique to inform the material density distribution as dark areas resemble high amount of material and bright areas reflect less amount of material

4 Conclusion

This research proposed a material process for controlling the stiffness of polyester fiber through thermal bonding and material density for the fabrication of furniture product. 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 product 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 a cylendrical 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. The process Not only did it show an increase in 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.

Fig. 7. Final product

5 References

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