Title
Bending-active Structures A Case study for an Office Chaise Lounge

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Bending - active Structures

A Case study for an Office Chaise Lounge

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This paper seeks to explore the process of elastic bending in furniture design and presents a case study that demonstrates the creative and structural potential of bending-active structures as possible improvement to the current state of the art. This case study brings together design procedures, borrowed from declarative design in software engineering, architectural design, and material science in order to envision new applications for bending-active structures. It investigates how bending can be used strategically for the design of furniture scale objects and, particularly, an office chaise lounge for one person. Active-bending implementation is the key for creating structures that achieve new milestones beyond the perceived limits of material and process. Moreover, the project stands as a great opportunity for the development of a pipeline for fabrication that automates the translation of a given high-level description of a design, to the production of the data required for fabrication via a particular material system.

Keywords: *Bending-active structures, Matter compiler, Optimization*

INTRODUCTION

Architectural practice has been significantly influenced by the development of cutting-edge design tools that have set the scene for new ways of understanding complex forms, analyzing their constraints, and optimizing their performance accordingly. Latest improvements in software and the increasing accessibility of design tools have allowed designers to shift from a purely experimental state of extensive trial and error, towards a more scientific integration of design constraints to enrich the design process. Current design tools allow for additional parameter integration beyond formal description, such as physics, material properties, or environmental constraints. Designers are able to integrate those factors already in the early stages of the design process by simulating forces, structural performance, and material behavior accurately. This paper will focus on active, elastic bending in plate structures and will explore the formal and structural possibilities that are available through bending, both as a form-finding method, as well as a strategy for achieving challenging structural performance. Elastic bending in plate structures has already been implemented at various scales. In this paper we will examine the principles of elastic bending and its benefits at furniture scale design, by analyzing a case study for an office chaise lounge. In order to provide an informative frame-work for our research on elastic bending in furniture design, we will analyze the groundwork of bending in furniture design through a series of examples that operate as precedent studies on the field.

BENDING IN FURNITURE DESIGN

Figure 1
Left: Matthias Pliessnig, Amada bench [4], Right: CODA office, Graz chair [8]

A major innovation that designated substantially the design of mid 20th century and beyond, was the introduction of bending in furniture design. The first method that was implemented in furniture and particularly chair design, was bending by means of heat-forming. Heat-forming enabled the creation of natural and organic shapes that were refreshingly different in their aesthetic to the previously used modernistic standardized forms. The strategic use of bending made it possible to fabricate furniture with less pieces, which had great impact in preserving the continuity and fluidity of the overall form. However, bending was not only implemented to increase the aesthetic value of the design. Moreover, many designers recognized that bending as a novel fabrication technique was a real paradigm shift that had the power to revolutionize furniture industry by significantly reducing production costs.

Heat - Forming Bending Plywood

One of the most suitable materials for heat bending applications was plywood. Plywood veneer offered designers the flexibility not only to explore more complex forms but also allowed for manual post-processing and premium quality finish. Another advantage of using plywood bending was the possibility to accommodate the comfort factor, as these shapes were friendlier to the human body geometry and usually had nice tactile qualities. The most common heat-forming process was steam bending of a dried piece of lumber or a multilayer arrangement of plywood veneers that are bound together with glue with their grains perpendicular to each other. The shape is given when the structure is bent under pressure with heat. Here, hot steam was a particularly suitable medium since it was able to penetrate deep into the plywood to momentarily soften its fibers and enabling it to be bent in multiple directions. Then, the plywood is let to cool down in order for the deformation to become permanent. Unlike natural wood, the resulting material does not have the same material properties at the final state, as it is less likely to split when exposed to moisture. The shipbuilding industry was an early adopter of this technique for forming the curved members used to build ship's hulls. This paper will portray three examples of heat-formed furniture design, two of which are considered to be primary pioneers in the mid 19th and 20th century and a third example that represents its contemporary evolution nowadays.

Examples of heat-formed furniture

Michael Thonet, Chair No 14. The first example is Michael Thonet's Chair No 14. Thonet made significant advancements in steam bending techniques for chair design and he patented the process of multiple plywood veneer lamination. He also managed to standardize and refine the existing techniques that were based in empirical know-how solely by specialized craftsmen and incorporate it in the industrial process. Hence, Thonet engendered an assembly line of bent furniture that could be flat packed ergonomically and easily assembled, an idea that is the progenitor of the IKEA assembly line. Thonet's Chair No 14 expresses and elegant and ergonomic design that involved 6 pieces of steam-bent wood rods that were easily disassembled and flat packed for transportation. Thonet minimized not only the number of pieces, but also the number of joints and connections. Thonet was competing on the sector of cafe chairs and he outperformed the cast-iron competitors with a much cheaper and lighter alternative (based on bent plywood). The Chair No 14 was very easy and cheap to produce by unskilled workers. It became vastly popular across the U.S. and Europe and sold millions of units.

Charles and Ray Eames, Lounge Molded Chair (LCW). The second example is the Chaise Lounge and the Molded Plywood Chair by Charles and Ray Eames. The Eames have pioneered in inventing strategies to craft complex forms. They experimented with wood molding techniques and developed strategies to achieve curved complex forms out of planar, thin sheets of plywood. One of their main design drivers was to develop a compound-curved chair that either consisted out of very few or even a single shell single-shell. To accomplish this goal, the Eames invented their own machine to press large-scale plywood sheets, which enabled for example the molding of unprecedented large aircraft parts (Eames 2012). Prior to furniture, the Eames took advantage of bending characteristics (elasticity, resilience), to manufacture stretchers and crutches for the World War II. Later on, they implemented a similar strategy in furniture design and their pioneer methods had a profound effect in the way future designers perceived form and matter. However, due to the limits of the plywood itself, they were unable to make a single-piece shell out of molded plywood as originally intended. Only years later they found a way to produce the single-shell chair they were striving for, by using a new material that has never been used in furniture before: plastic.

Matthias Pliessnig, Amada Bench. The third example is the steam bent benches of Matthias Pliessnig (Figure 1). Pliessnig reframes heat bending through the lens of contemporary digital craft and he is interested mainly in human proportion integration. His design is characterized by minimal shapes inspired by wave flow and fluid dynamics in general. Pliessnig's design combines craftsmanship and comfort, structural stability and strength with sculptural finesse (Pliessnig 2010). As Pliessnig became familiar with surface modeling tools, such as Rhinoceros, he discovered similarities in the way the geometry is described within the digital environment and the way a boat scaffold is constructed. Same as is in boat shell constructions, there are leading ribs that designate the shape as cross section elements and secondary curves that bend along the ribs, forming a curved grid. Pliessnig implemented the exact same logic in his bench design. The workflow that he developed starts from a digital model and then continues with constant refinement of the heat bent pieces until a perfectly smooth surface is achieved. He starts by drawing a free-form shape and then contouring it in temporary wooden ribs that are CNC cut and put along the target outline curve. Then he bends temporary wooden slats, which he calls "Sketching Stringers" (Pliessnig 2010), because they operate as guides to visualize the overall shape. After replacement of all temporary pieces, he steam bents final slats until they form a continuous surface. Lastly, he strengthens the structure with epoxy and pins at the intersections and sands the surface in order to become as smooth as possible. Pliessnig's benches clearly address the notions of variability and fluidity combined with ergonomics to suit the human body, as well as evident beauty and elegance.

ELASTIC BENDING AND BENDING-ACTIVE STRUCTURES

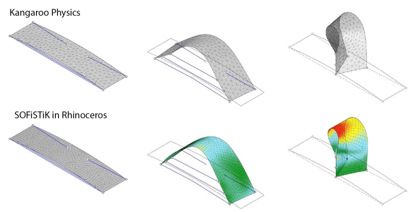

Figure 2
Digital simulation of bending process in Kangaroo Physics and SOFiSTiK (Schleicher et al. 2015)

While the key concept behind the previous examples is based on bending as means of plastically deforming a structure, the following case study will introduce and investigate the alternative of elastic bending as active and holistic forming process for shape exploration. Moving away from steam bending applications, we will now investigate elastic active bending as a holistic process that addresses form exploration, as well as structural performance integration. The term "bending-active" is introduced by Knippers et al. to describe curved beam and surface structures that base their geometry on elastic deformation of initially straight or planar elements (Knippers et al. 2011). Active bending can be defined as a form-finding process that derives from the elastic deformation of a rod or plate structure. It is a process that creates curved geometry out of planar, straight members or surfaces (Figure 2). One of the key aspects of bending-active structures is that they deviate from the existing structural typologies, such as space frame structures, planar or curved trusses etc. As Lienhard et al. explains, bending-active structures are distinguished as an approach rather than a distinct structural typology (Lienhard et al. 2014). This is because they allow for heterogeneous configurations and nonlinearities in their load bearing behavior. The latest advancements in Finite Element Analysis software (FEA) (Piker 2013, Lienhard et al. 2011) allow engineers to analyze and simulate structures beyond the existing typologies with a high level of accuracy in the load calculation. Bending-active structures offer a wide field of experimentation on non-standard load configurations, as they derive their complex geometry from elastic deformation processes. Finally, in comparison to the previous existing structural typologies, in the resulting lightweight structures, bending is not avoided but instrumentalized to create complex curved geometries on the basis of standard, semi-finished building products. A particular advantage of this approach to construction (design approach to bending-active structures based on elastically deformed members) is the opportunity to continue using conventional flat-based manufacturing processes but in an unconventional way. As usual, parts can be produced on CNC routers, laser cutters, and waterjets in a cheap, quick, and reliant manner. As is newly introduced with my research, the materials then get bent and coupled together to form highly complex origami-like structures. This fabrication method provides a very time and material efficient alternative to traditional construction processes since it is neither depended on the fabrication of expensive molds nor on the auxiliary support of complicated formwork. Before moving on to the case study that this paper mainly focuses on, we will examine an example of elastic bending plywood in chair design.

Elastic bending of plywwod, CODA Graz Chair

The Graz chair by CODA office (Figure 1) is an outstanding example of elastic bending plywood and has operated as a precedent for our case study. The original design is a revision of the Medea chair by Vittorio Nobili that suggests improvements in the fabrication methodology and the quality of the plywood layers. The design suggests a flat, rectangular piece of plywood that carries some CNC smart slits. When the naked edges of the slits are overlapped and connected, the shape of the chair is formed. The groundbreaking idea of this design is that it achieves double curvature without requiring expensive, specialized equipment or craftmanship as the previous examples. It also allows for customization and adaptability in a wide range of target shapes. These principals influenced our design and motivated us to push the boundaries further, explore more complicated shapes and achieve stability by a single operation method (in our case, elastic bending of flat surfaces).

Bending-active as a form finding process

Form-finding is generally understood as the process of developing the geometric form of a structure based on mechanical behavior (Lienhard et al. 2014). This means that the resulting form is designated by a particular set of loads that operate on it within a constrained set of parameters (material, scale). In bending-active structures, since the form derives from an elastic deformation of a planar shape, the resulting geometry is hard to predict with high accuracy without a real time bending simulation. Computational tools such Kangaroo Physics, or FEA software allow the user to apply loads on a structure and simulate the deformation in real time and therefore; observe the result as well as the intermediate steps of the simulation. Having real time feedback from the process, the user is able to better understand the relationships between the variables of the system and adjust them until the desired result is achieved. Although this process offers the user freedom to explore new forms, it is worth mentioning that form-finding result does not necessarily correspond with the most efficient load-bearing solution. Hence, the main challenge is to optimize the set of variables to a functioning relation that addresses both aesthetic qualities, as well as sufficient load-bearing capacity and stability. Furthermore, to successfully create a bending-active system it is important to incorporate material properties, as well as to experiment with physical modeling. We will examine the contribution of physical scaled models in the following sections of the paper.

HOLISTIC DESIGN PROCESS

Based on what was mentioned above, this section will describe the design process that was implemented in the chaise lounge case study. The goal of this case study is to achieve an optimum balance between comfort, stability, easier material handling, weight and cost. To achieve that we will start from identifying two strategies, in which the design process was based on.

Matter Compiler

The first strategy of the design process suggests the construction of a continuous workflow that is called "Matter Compiler". This approach borrows some of the principals of declarative design (Bachrach 2012) in software engineering. It promotes a pipeline of linked processes that are automated in order to reduce large manual effort and enhance the search for better and more efficient designs. The matter compiler suggests the building of a system with contributing variables, such as forces, material properties, human proportions etc. where all the processes are part of a single workflow that transfers data from one phase to the subsequent. The benefits of a continuous workflow lie on the fact that the designer operates at a high level set of intentions for the design, such as overall size, number of users, seating posture etc. and the system translates them in a set of instructions for fabrication.

Accommodating comfort

The second strategy that defined the design process was that of body conscious design (Cranz 2000). One of the objectives of this case study was to improve the basic configuration of the conventional seating posture. To achieve that, we analyzed seating postures of existing furniture and ended up in choosing the chaise lounge posture as one of the most comfortable and with the best stress and load distribution for the body (Figure 3). Lounging, which can be defined as halfway sitting and lying down, takes load off the spine neck and head. After analyzing in detail designers' chaise lounges as precedent models and as role models for the correct angles that fit the human body, we ended up isolating the main variables that are associated with the comfort factor. These variables are, the points of contact with the human body (arms, hands and legs), the alignment and support requirements of those points and the angles that are formed between the points of contact.

CASE STUDY: BENDING CHAISE LOUNGE

This section will delve into a more detailed analysis of the processes that are engaged in the case study, from form-finding methodologies to fabrication and assembly.

Form-Finding method: Pinching

This case study approaches bending-active structures topic under the lens of minimal material employment, in order to prototype a chaise lounge out of the minimum amount of bended surfaces with the highest structural performance. A geometrical inspiration that gave direction to the form-finding process was the exploration of conical bending. Inspired by Plücker's conoid as reference geometry enabled

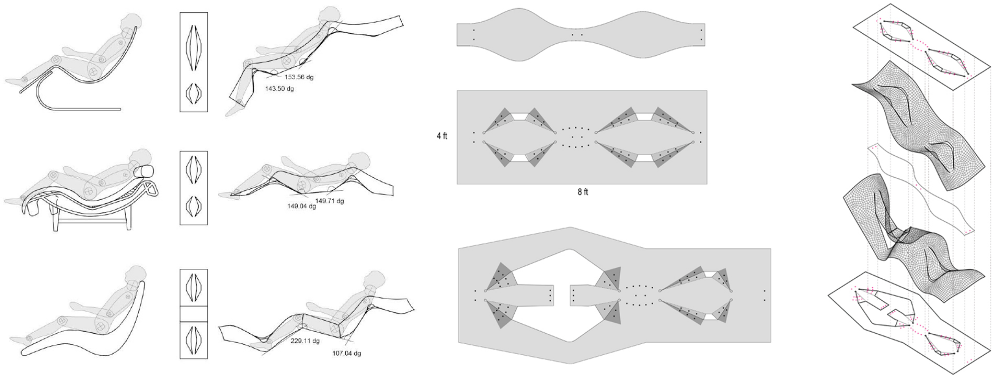

Figure 3
Angle study of precedent designs, Final pieces of the prototype

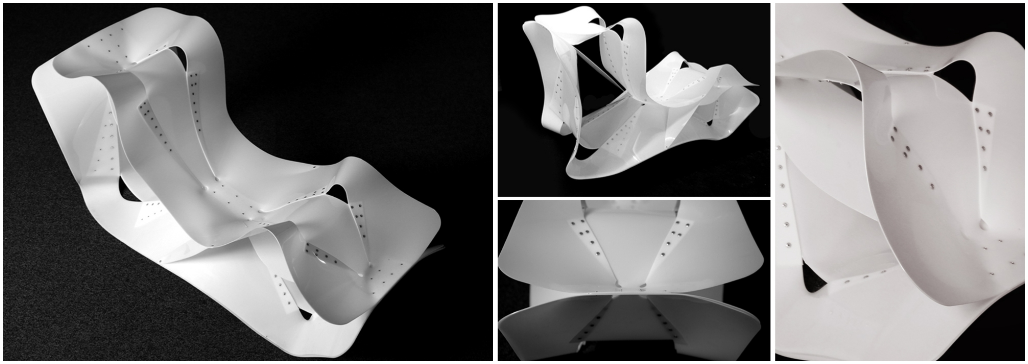

Figure 4
Prototype chaise lounge built out of 1:16" thickness HDPE sheets

us to formulate a methodology for achieving similar shapes out of planar surfaces and examine their structural performance. The method we resulted in is called pinching and it is described as the process of strategically removing an internal part of a planar surface and connecting the naked edges of the cut out shape, allowing the surface to bend accordingly in three dimensions (Figure 5). The main motivation for the pinching method lies in the simplicity of producing complexly curved elements. This process appears to have two benefits: first, it produces intricate shapes out of a single planar surface; second, it creates three-dimensional shapes that perform structurally in the bended state.

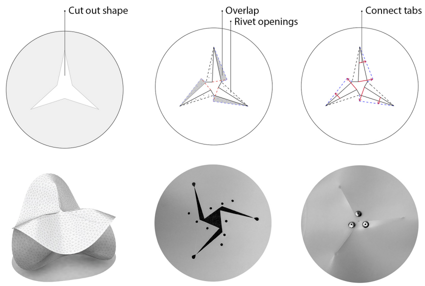

Figure 5
Pinching as a form-finding technique

Matter Compiler: Steps and Processes

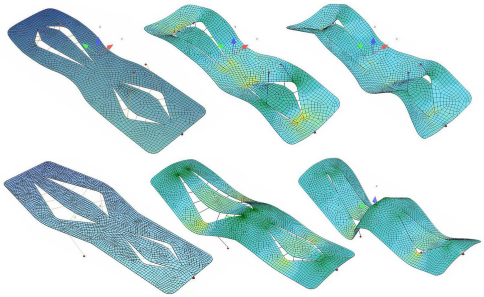

Figure 6
Digital simulation in FEA software SOFiSTiK

As stated above, the pipeline used for this project suggests the use of a "Matter Compiler" that translates high-level descriptions of a set of intentions or the design to low-level instructions for digital fabrication and construction documentation. This method is constrained by a particular material system, a specific method of joining/assembly and a specific process of fabrication. Our compiler suggests the following main steps:

- Form-finding
- Geometric rationalization
- Joints and seams handing
- Layout automation - Fabrication

The following paragraph describes the workflow in terms of types of processes, relationships and included variables. The first step involves the Form Finding process that was rendered through the pinching methodology that was described above. This involves a parametric model of the planar surface with the cut out shapes. The first simulations were done in the Grasshopper plug-in Kangaroo Physics and later in the Finite Element Analysis software SOFiSTiK (Figure 6). The Finite Element Analysis produced more accurate results, as we were able to calculate the stress and loads along the surface and observe the stress distribution. Along with the digital simulations, a large part of the form exploration was carried out with physical models. The physical experiments were scaled models of either paper or the actual material in smaller thicknesses that were created for actual material testing and for cross-referencing the results of the digital simulation. The second step involves geometric rationalization of the outcome shape, in order for it to adapt to the human body proportions and ergonomics. We created different families of cut out shapes along the planar surface that correspond to different angles when the surface bents in three dimensions, hence this leads in achieving postural variation. Based on the analysis that was carried through in precedent chaise lounges, we depict target angles and proportions that lead to a comfortable seating posture. The third step consists of the handling of joints and seams. In our case, the joining of the naked edges is by the technique of riveting and particularly, blind riveting. The same method is used to join multiple surfaces together. Rivets were preferred because they can support tension loads, as well as shear loads. Riveting is achieved by the creation of parametric tabs along the given edge with a number of holes at a certain distance from each other that overlap completely and are connected with blind rivets. Having said that, it is apparent that given a modification in the length of the edge, due to form adjustment, the tabs and the hole pattern adjust accordingly. For the riveting process we used steel rivets and washers, as well as a rivet gun. The fourth and final step of our compiler is the layout automation that provides the data for fabrication. Since the main goal of this project was to achieve best structural performance, while using the minimum amount of joints and pieces, the layout automation process is a straightforward 2D nesting process of few planar outlined shapes in 4ft. by 8ft. planar sheets.

Materialization

In this section we will analyze all the contributing processes from design to construction of the chaise lounge. We will divide the processes in two categories, high-level and low-level intentions. High-level intention processes are those, which affect primary properties of the design, such as comfort, aesthetic, size, proportions, stiffness, stability etc. Low-level intention processes are those, which are responsible for the production of the prototype, such as, detailed shape refinement, tab creation for assembly, hole pattern for the rivet joints and data for fabrication. Low-level intention processes translate the digital, optimized model into a set of components that are constructible by the chosen fabrication equipment within a set of feasibility constraints.

Form development and Optimization. Investigating further the technique of pinching, which was described above as a form-finding strategy, the further development of the design was to define the correlation between angle of cut out shape and angle of bended shape. In that way we would be able to test the ergonomics, angles, lengths and proportions and make the necessary adjustments. The initial test models included symmetrical shapes (circle, ellipsoids), in order to assess the relationship of the 2D shapes with the 3 dimensional bent forms (Figure 5). The relationship between the elements was linear for most cases, meaning the wider the angle of the cutout, the smaller the bending radius was, causing higher deformation to the surface. Once a principal model was developed, the variation of angles and proportions allowed for fine calibration of the geometry. The modifications concentrated on adjusting the angles of the cut out shapes, so that the bended outcome shape is comfortable and adapted to the human body. Hence, the outlines (exterior, interior) of the planar surfaces were optimized to respond both in terms of functionality; the object has to perform as a chaise lounge, as well as in terms of structural stability; the object has to support the weight of a person without material breach. The final shape of the chaise lounge was determined by simulating the planar surface with cutout shapes in the right locations and sizes, with a given load set. The bending simulation was processed in the Finite Element Analysis software, SOFiSTiK, following the elastic cable approach. This approach involves defining the fixed and sliding points of the geometry, as well as contraction cables that join the naked edges of the planar surface causing elastic deformation. The simulation terminates, when the cables' length reaches the value of zero.

Material depended geometry. Along with the form development strategy to address comfort, the process of high-level description of the design involves material property integration, such as the minimum bending radii and the Young's Modulus of the material, in order to predict and exclude in advance certain dimension ranges that would cause material failure. The material system chosen in this project is 4ft. by 8ft. high-density polyethylene (HDPE) sheets of 1/16" thickness with a Young's Modulus of 1200N $/ mm^2$. The material itself, when in the flat state, did not demonstrate characteristics of stiffness, however when bent, it provided enough stability to hold the weight of one person. The simulation aided us to best utilize material resilience and strength when bent, by providing numerical feedback regarding the loads and stresses along the bent shape. As mentioned before, along with the digital simulation, we carried out multiple physical experiments. Experimenting with physical models speeded up the optimization process, because it allowed an instant understanding of the load and stress distribution, as well as the association of the variables with resulting geometry. However, scaled models tended to appear stiffer than they actually operated in 1:1 scale and the same type of material demonstrated different properties in different scales. This condition had to be studied carefully in the digital simulation in order to make sure that the material used in the prototype demonstrates the desired properties.

Low-Level processes. The Low-level process includes four processes. The first process includes the refinement of the bended shape by trimming and adjusting the outline of the bended shape in order for it to meet the desired shape expectations, such as filleting sharp corners and removing unwanted material from areas that do not affect the structural stability of the chaise. Since shape refinement can only happen when the surface is bent and the chosen method of fabrication operates in 2-dimensional shapes only, an additional process is required. This process involves the re-flattening of the bended surface, in order to get the exact outline of a planar surface for fabrication. This process is necessary because the bended shape cannot be predicted before simulation; therefore the refinement takes place after the bending process. However, since our fabrication method applies only to flat surfaces, re-flattening the bended surface after bending is required. The second process suggests the creation of tabs along the edges of the interior cutout shape that are important for connecting the edges together. In this project we explore the limitations of this technique in terms of dimension constraints, as well as the maximum material thickness where rivet joining is still effective. The tabs had to provide sufficient surface area for the rivets to be placed in a way allows equal stress distribution along the tab surface to avoid tearing. Also, i is important to mention that the calculation has to be as exact as possible so that when all the tabs of the structure, the hole pattern will much so that the rivets can pass through the holes. Any discrepancy in the simulation or the generation of the tabs would cause difficulties in the assembly process. The third process involves removal of material in areas of high stress concentration. Based on the minimum-bending radius of the material and the stress information from the simulation we were able to allocate areas of high stress distribution that would cause the material to tear. To avoid that, we strategically removed those areas before the bending so that they are within the range of the bending radius of the HDPE polymer sheet. The fourth and last process is nesting the pieces in 4ft. by 8ft. HDPE sheets for fabrication. The overall shape of the chaise lounge is composed by 2 bended surfaces connected in 3 critical areas, in order to provide strength to the structure, as well as a third smaller surface that creates tension in the whole structure, preventing it from self-load deformation. The fabrication method that is most suitable for this material, in terms of cost, speed (1 hour setting up and cut time) and accuracy is cutting in the "Zund" blade cutter (tool: blade Z10, setting: multi-pass, 3 passes). (Figure 4, Figure 7)

CONCLUSION

The objective of this paper was to provide general insight into form-finding and structural analysis of bending-active structures. The work aimed to explore the potentials of bending-active structures in furniture design as an approach in generating new forms and structural strategies. Briefly, the parts of the case study that were considered successful were the accurate translation of software results into fabrication, as well as the accurate simulation of angles, forces and material property integration that resulted in a comfortable chaise lounge that can bear the load of one person. It is worth mentioning that the overall cost of the chaise was low (around 100 USD) and it was ight weight in relation to its size and load bearing capacity (around 20 kg). A future development of the project would be a larger design space exploration that would respond to a wider range of demands, in terms of functionality and use, such as fit multiple people, accommodate extreme load cases with local material reinforcement. Also, in terms of joinery and assembly, the possibility of disassembling and re-assembling the chaise lounge, by introducing temporary, yet strong connections would be desirable. Another aspect that is definitely worth looking into would be the use of a more sustainable material. However the challenge would be to allocate a material with similar structural properties. The potential of plywood as we saw in the Graz chair example was considered, but was excluded eventually due to the large bending radii that it requires. Moreover, we were aiming for an easier handling in terms of weight and fabrication speed. Before ending up choosing high-density polyethylene (HDPE), we ran some tests with polystyrene as well as with low density polyethylene. The results were disappointing in terms of structural stability and stiffness, as Polystyrene was too brittle and low density polyethylene (LDPE) was not stiff enough. A potential answer might be lying in recycled High-density polyethylene, in case it maintains its original properties after the recycling pro-

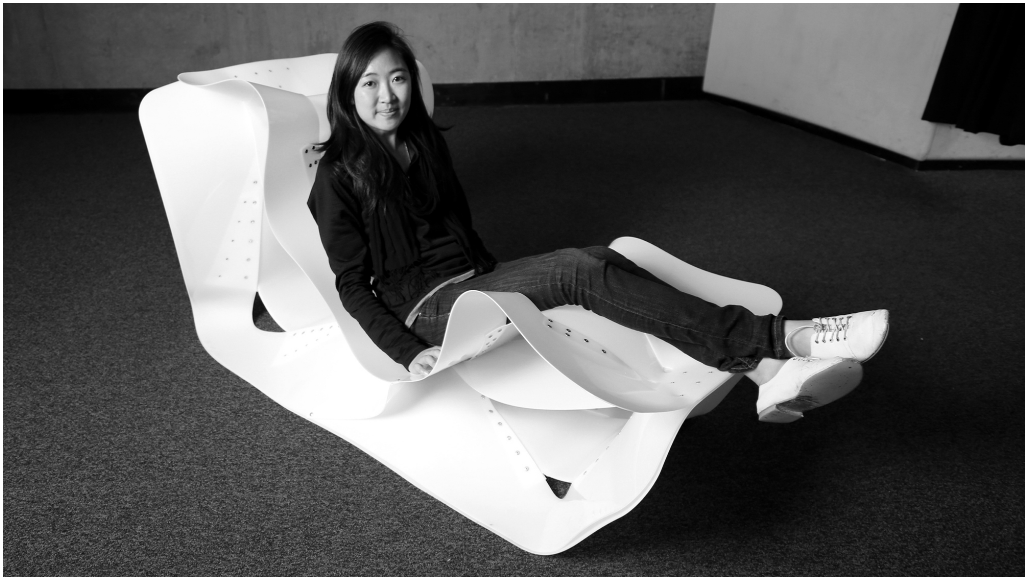

Figure 7
Prototype chaise lounge built to of 1:16" thickness HDPE sheets, proof of concept

cess, however this is a topic that needs to be looked into and experimented upon.

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