Architecture Challenge 16 - Robotic Contouring

Researching Robotic Bending of Straight Profile Plastic Beams for Full Scale Production

Andrei Gheorghe[1], Philipp Hornung[2], Sigurd Reiss[3], Robert Vierlinger[4]
[1]University of Applied Arts Vienna / Institute of Architecture [2]University of Applied Arts Vienna / RWC Lab [3]Clever Contour GmbH [4]Bollinger + Grohmann Ingenieure
[1]a.gheorghe@uni-ak.ac.at [2]hornung.philipp@googlemail.com [3]reiss@clevercontour.com [4]robert.vierlinger@gmail.com

This paper provides insight into a new robotic plastic forming process through the prototypical construction of a full scale structure. The process explored the potential development of an automated setup, which utilizes robotic movement to create three-dimensional components from straight profile plastic beams. Polyethylene beams with a rectangular profile were bent with the help of an infrared heating ring and a 6 axis robotic arm. The digital process with custom-created Rhino/Grasshopper components allows the creation of forms with a high degree of customization in relation to the needed construction time, therefore providing for a highly flexible and quickly developable structural formwork without the need of a mold.

Keywords: *plastic beams forming, 6 axis robotic fabrication, profile contouring, computational optimization, structural formwork, light weight structures*

INTRODUCTION:

The research project was a collaboration of the University of Applied Arts Vienna (UAA) with Clever Contour GMBH, Vienna, where the plastic bending process was developed and patented (PCT/AT2015/050307, Patentnumber 516371). The aim was to test and explore the capabilities of the robotic plastic forming technique which CC develops as an industrial-scale fabrication process for design and architecture, and also holds a patent of. Hereby the UAA is developing software tools for the design with CC bending technology to complement the machinery offered by CC. The research is co-funded by the FFG Austria.

The used construction for the project uses an industrial solution from the Clever Contour GMBH. This is an automated production line (milling, heating, bending, cooling) to produce structures consisting of 3D bent plastic profiles. Previous projects and the actual prototype of the production line are presented on the homepage www.clevercontour.com. The forming process has been already tested in combination with sound absorption applications and as a replacement for framework for various freeform structures.

This paper describes the testing of this new technique through the construction of an approx. 5m high, robotically contoured plastic beam structure during the Angewandte Architecture Challenge 2016 workshop (www.architecturechallenge.org). In order to test the possibilities and limits of the fabrication process, a design of a skeletal framework structure with a directive to achieve a maximal height while retaining structural stability was outlined at the outset with the consideration of a limited number of beams. These guidelines provided the grounds for the design of the structure to develop in a manner where the structural rigidity of the material could be tested, while also giving insight into the potential applications created through the material and fabrication process. The main target was the design and construction at a scale where humans come into direct contact with surfaces i.e. mainly interiors and furnishings. The paper will first introduce the details of the material and technique used during the fabrication process and further-on address its application in the structure, whereas the boundaries of the fabrication process along with the design criteria are considered.

FORMING TECHNIQUE:

Required Components: The fabrication process, aided by digital design methods is constructed of three main components, which are: (1) Material, (2) Heating Element, and (3) Robotic Arm. Polyethylene beams are manually placed into a guide after which a robotic arm maneuvers it through a focused infrared heating element and finally angles / twists, or applies both forces to the material, in order to create a single three dimensional component.

Material Characteristics: The material was chosen due to its material properties as a thermoplastic. It can be easily heated up, formed and cooled, within in a low temperature range. The material used in the present case was a 2000mm long Polyethylene (PAS-PE5) beam produced by Faigle Plastics (Product name PAS-PE5), with a 30x30mm square profile. Data on the material properties (Fig. 1) was used to simulate the structural capabilities during the design process.

Density	**Usage Temp. [°C]**			**Thermal Expansion**	**Volume Price**
[g/cm3]	Min. duration	Max. duration	Max. short	Lengthways / across 10-6 x K-1	1 = low 20 = high
0.95	-100	80	100	150-200	1

Yield / Breakage stress	**Yield / Breakage stress**	**Elastic Modulus**	**Creep Tendency**	**Max. perm. Compressive stress**
[N/mm2]	[%]	[N/mm2]		[N/mm2]
28/36	10/>400	1000	0.37	6

Figure 1
Physical properties of Polyethylene beam PAS-PE5

Customized Setup: In order to adapt the process to the available Robotic Setup at the Robotic Woodcraft Lab, University of Applied Arts in Vienna, where the project took place, a customized setup was created (Fig. 2). The setup used a (KUKA Quantec KR120 R2500 PRO) robotic arm with a customized pneumatic gripping End-Effector. At the base of the robotic arm, a channel was used as a material feeding guide which led to a Infrared Emmiter ring with gold reflector which was protected on either side with insulation and two pneumatic parallel grippers on the entry (Ground-Gripper 1) and exit (Ground-Gripper 2) side of the heating device. The grippers are required to hold the material in place during heating, as well as when the robotic arm applies the bending force to the beam. A pair of pneumatic cooling nozzles below the bending area were used to cool down and solidify the softened portion of the material after the bend was successfully executed. The Infrared Emitter ring is an important part of the setup as the material is most delicate at the time of heating, and the heating temperature and time need to be balanced in order to soften the material consistently without causing damage. Using an Infrared Reflective Emitter provides for a focused beam of energy to be directed at the material allowing for flexibility and precision during the bending process. If the material is heated consistently, the robotic arm needs less power to bend the material and the bended / twisted area is more accurate.

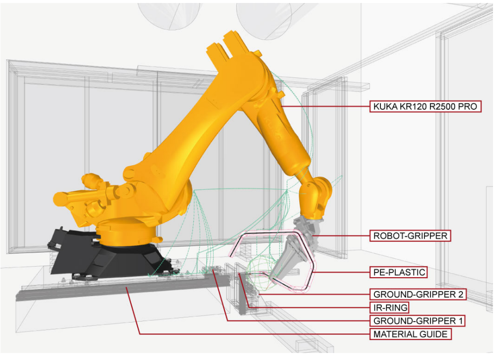


Figure 2
Robotic Setup

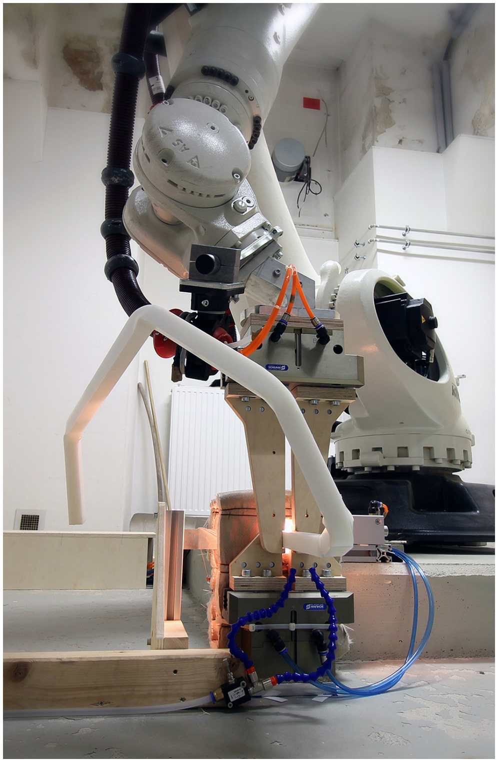


Figure 3
KUKA robot in wait while IR ring is heating

Automation Process: The beam is placed into the guiding channel and aligned to a starting point, the robotic arm then feeds the assigned length of the first bend of the beam through the Infrared heating ring after which the Ground-Grippers 1 and 2 hold the material in place while the heating ring activates. (Fig. 3). Multiple tests were performed on the beam in order to determine the optimal heating time required to soften up the material and therefore make it malleable, which permitted the beam to be bent without causing damage to the material. The tests therefore concluded a three minute heating duration for a beam with a 30x30mm cross section. After the heating time is complete, the grippers are released and the robotic arm pulls out the beam from heating to bending position. The grippers once again close and the arm applies the prescribed bend (pitch, yaw and roll) at the heated portion on the beam, after which cool air is blasted at the node in order to solidify the softened portion of the material. The process is then repeated incrementally along the length of the beam in order to create a three dimensionally curving plastic spline that can be used as a component in a larger free form structural framework.

METHOD:

Design Process: Formally, the project introduces the idea of spatial frames with a high degree of freedom, bending and twisting in space. The design process began primarily with the consideration of the bending angles (Fig. 4), structural rigidity, and joining technique with the aim of maximizing the height as well as the ability to incorporate fabric textile as an aesthetic and surface detail. Fabric surfaces are produced from linear elements with textiles, creating different spatial and surface depth effects. The entire process was guided by a computational workflow relying heavily on the Grasshopper environment for Rhinoceros 3D where the structural analysis, contouring data, as well as the robotic simulation and code were produced. The initial design was developed and tested with the Finite Element Analysis tool Karamba and later examined with Clever Contour's custom components - which were developed specifically for the plastic bending process - the information was then used to produce commands to be input into the KUKA|prc (parametric robot control), in order to prepare instructions for the robotic arm. Using Karamba, Clever Contour's components and KUKA|prc which work within Grasshopper, provided the ability to work within a single software environment allowing for a seamless workflow from concept to fabrication, as well as provided for the initial design to be easily altered while receiving active feedback. The interconnection of the workflow therefore allowed for flexibility during the design process making it possible to investigate the structural limits of the material within the fabrication constraints.

Figure 4
Possibilities of bending angles through Clever Contour's Grasshopper components.

CC Design Tool: Incremental 3d bending with torsion is a distinct fabrication process which opens up many possibilities in freeform design, but poses challenges in the transformation of shape to data. For example, simply drawing a 3d polyline does not provide any information on the torsional orientation of its segments. To subdivide a smooth 3d grid shell into produce able polyline curves can be tedious and complex depending on the desired qualities and conditions. A plug-in for the parametric modeling environment Grasshopper serves as the link between designer and fabricator, following three main goals: produce buildable designs, ease of use, and possible detailed control. A prototype of this tool was developed at the UAA for CC, and was put to test in the project: To check build ability and get bending curves and volumes, polylines and helper geometry were provided. The application in the project used the tools' basic functions for torsion solving, error checking, visualization and output of a machine-readable file. A built-in subdivision algorithm and particle-based constraint solver were not used for the chosen design. The information provided was then used to create commands for the robotic arm with the help of KUKA|prc.

Structural Analysis: Provision of Finite Element Analysis within Rhinoceros proves to be a great advantage to the design process as it allows for design iterations to be quickly checked without restarting the workflow. To build a parametric structural model, the input design geometry is processed through a set of geometric operations: the lines have to be fully connected and grouped after different material thickness due to bundling of multiple rods. Properties of Polyethylene were provided and physically calibrated on small bending samples, where the low stiffness (elastic modulus) of just about 1/100th of steel required the final design to be adjusted many times to achieve reasonable stability in the digital simulation. As the bolted details were stronger than the rods, no joint-element had to be introduced to the model to simulate a reduced stiffness of the connections. Vertical and horizontal line- and punctual loads were applied in four directions, giving a basic quantitative feedback on the deformation. However, the conception and application of realistic load cases can be challenging for delicate indoor structures. As an alternative, the calculation of natural vibration shapes and their according frequencies can be performed on the same structural model and does not necessarily need the specification of loads. The lowest frequency and its deformation shape typically represent the weakest part, or the weakest mechanism in the structure. The higher the lowest frequency, the stiffer is the entire structure. This principle served as a helpful aid in fixing weak mechanisms one by one, which with traditional load application were not clearly visible for the designers. Displacement (Fig. 5) and Material Utilization (Fig. 6) of the design were tested through the software in order to provide a successful construction.

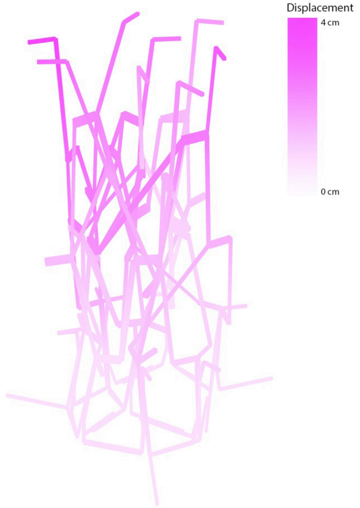


Figure 5
Maximum displacement of 4cm recorded under gravity load

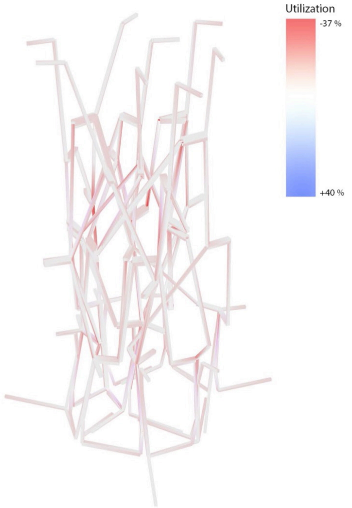


Figure 6
Material Utilization under gravity load

Fabrication Data: In order to provide a direct translation of the design to an array of data for robot programming, Clever Contour's Grasshopper components were used. The components provided a set of tools where polylines defining the design along with information of segment lengths and maximum bending angles could be loaded which automatically provided optimized bending positions, z Angles, y Angles, Torsion Angles, and Bending Lengths. The information provided by the Clever Contour's Grasshopper components were then translated with the help of KUKA|prc into a fully automated sequence (Fig. 7) of robot commands including gripping, feeding, heating, bending as well as cooling. The robotic fabrication process was digitally pre-analysed for qualitative and quantitative optimization (reachability, collision, part re-orientation and re-gripping) and then compiled to the KUKA robotic language (KRL) and sent to the machine.

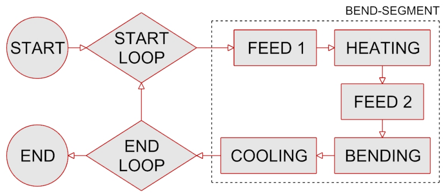


Figure 7
The fully automated sequence of the custom robotic fabrication process

FABRICATION AND ASSEMBLY

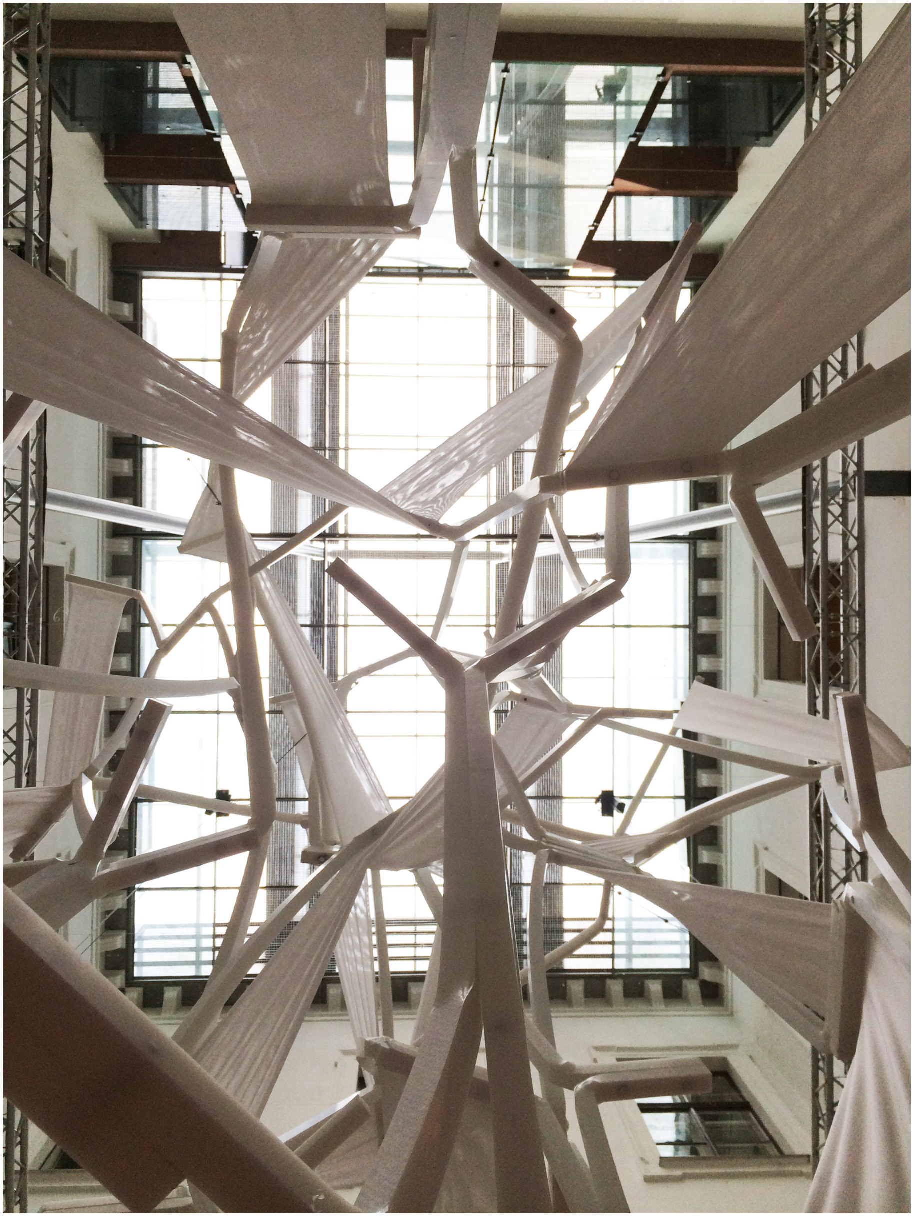
Fabrication Components and Time: Once fabrication data for the individual beams via KUKA|prc is produced, it is fed to the robotic arm while the material is loaded into the guide. As production time was limited, the number of bends per beam were kept to a minimum. The majority of the fabrication time is taken up by the heating and cooling of the material. During the process the material must be cooled rapidly in order to be brought back to solid state, as the angled position of the beam must be maintained during the cooling process so that post angling deformation due to the materials weight can be kept to a minimum. Over the course of multiple tests, an op-

Figure 8
Structure suspended with four 4mm diameter steel wires.

timal heating and cooling time of three minutes per action was determined and used for the production. Therefore beams with three bends had an approximate time of between 20 to 30 minutes after consideration of the time for the robotic movements.

Assembly and Aesthetics: While the contoured components were fabricated they were labeled during the process to know their individual placements. The components were assembled using screws of different lengths depending of the number of overlapping beams and attachment of a fabric surface, which was used as an aesthetic detail had to be considered. The fabric was wrapped around the horizontal sections of the beams which was also used as connection points for other beams and continued along the height of the structure as horizontal streams. The fabric was used to give the structure a more volumetric depth and to portray an example of how a structural framework using plastic contouring could implement and influence surface characteristics. While attaching the individual components clams were also used to hold the components

Figure 9
View upwards through the beam structure with textile elements



in place while the screws were added. The structure was designed so as to be divided into four separate horizontal levels making the assembly process simpler as sections could be fabricated simultaneously and worked on a flat plane. The sections were assembled in pairs with the lower two and upper two being assembled together. The upper portion of the structure was then lifted and secured over the lower level.

CONCLUSION:

The research process also provided insight on how the method could use improvement. One of the areas of improvement is the moment after the material is softened up and the robotic arm must pull the material out from the heating element in order to be bent, at the time the material is soft and therefore the pulling of the material causes a certain level of elongation along with a slight amount of spring-back that is usually experienced while working with polymers.

These events therefore end up increasing imprecision in assembly tolerances. Another area is the moment where the beam has a final bend towards the end of the beam and must therefore cantilever from the grippers. This causes the position of the beam to be changed physically from where the robot believes the beam to be according to its simulation, and therefore is unable to grip the material properly. This had to be adjusted manually during the fabrication process.

Finally, the position of the heating and gripping component could be revised as the position that was used was extremely close to the ground and therefore limited the bending angles. As the bending geometry used in the present design was not extremely complicated, the issue was easily compensated, but may prove to be a larger problem in fabrication of more complex contoured components.

In conclusion, the prototypical structure was successful in testing the structural and design capabilities of the robotic plastic bending technique and proved the advantages of using such a fabrication method as it allowed to quickly develop a three dimensional structural framework without the use of a mold. The structure also proved to be extremely lightweight and as it was at a site with a high ceiling it was lifted easily where it was suspended at times in order for the space below to be utilized for certain events (Fig. 8). This fabrication technique and the qualities of the material (Fig. 9) therefore provide for extremely flexible applications although more research needs to be conducted on the large scale application of the method.

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