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Form to Fabrication

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Abstract: A creative idea is always constrained with lot of factors such as aesthetics, material, fabrication, tools etc. With the introduction of the digital and robotic fabrication, some constrains can be denied and at the same time some new constrains are added. In this study, we discuss how to prototype a creative idea with different fabrication approaches in the framework of student studio course. The student groups compare two different digital fabrication technics using robots. The task of the students is to design and fabricate a full-scale textile concrete furniture. In order to cast respectively laminate the concrete, students need to build a formwork. Free form designs are complex and strenuous work. For this reason, an industrial robot is used for the fabrication of these molds. Due to the limitations of the robot hardware and processes, not all the forms are feasible for fabrication. In this study the workflow, fabrication methods along with its limitations and the result of a full-scale textile reinforced concrete furniture are discussed.

Keywords: Freeform Design, Curved Surfaces, Mold, Concrete Lamination, Robotic Fabrication

Introduction

In addition to the use of the robot for classic production work for prototyping and model making (milling/drilling, etc.) the question of the necessity of a robot in the field of architecture education arises repeatedly. In our view, expanding digital literacy and deepening the understanding of technological dependencies and ways of working today is essential for architects and all designing professions. Our world, which is characterized by comprehensive networking and digitization and ever faster, technical dynamics, must also be taken into account in the education of the future generation of architects by promoting problem-solving skills in the technical field.

The digital linking and linking of the trades, sub-areas and working methods, which are also described in the concept *Industry 4.0*, can be made directly tangible on a small scale and in certain technological areas involving the robot.

In addition, the approach of so-called parametric design (also computational design, algorithmic modeling) is becoming increasingly widespread among creative students. Computer-aided software applications are used to develop shapes and objects that deviate from conventional architectural solutions. Biomorphic geometries and free-form surfaces can be found but also implemented. In order to be able to offer a consistent digital chain from design through 3d modelling software to robotic production, the use of the industrial robot and the training of architecture students in this field of technology is certainly desirable and useful.

This paper presents the students' project called "praxis-project". This project is an initiation with a motive to focus and deepen the understanding of building technics and materials both in theoretical and practical way. Each semester a building material and building technic is defined as project task. This year the task is to design and fabricate 3D-textile reinforced concrete furniture. This requires the fabrication of a mold either using the conventional or digital fabrication technic. Four groups with four students in each have worked together. The project has four phases for the semester: Material handling and testing, design, fabrication of mold and laminating or casting. The workflow, drawbacks, limitations of the fabrication and the results of the groups are compared and presented.

Introduction to Fiber Reinforced Concrete

The first production methods of glass fiber reinforced concrete are developed in 1970's. These methods are developed to produced flat panels are limited when dealing with complex shapes. Currently two alternative

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production methods exist for production of FRC, sprayed methods and the premixed method.

For the sprayed method, fibers are mixed with cement slurry, which is sprayed on mold in layers using air pressure gun. Each layer is sprayed perpendicular to another and periodically compressed with small rollers to minimize the porosity and enhance the density. This method produces high fiber content, good surface quality, no visual fibers and good fiber distribution. However, this method has low tensile capacity of concrete and labor intense.

On the other hand, for premixed methods the fibers are mixed in the cement slurry. The fiber content is calculated based on the intended use, which cannot be higher than 2%. The fibers need to be uniformly distributed while mixing the cast while making sure the fibers do not break during the mix. For this method advantages such as ultra-high performance concrete, self-compacting concrete can be used, the mold can be vibrated and the process is less labor intense. However, this method produces the low fiber ratio, no uniform distribution of fiber and consistent surface quality is not achieved. (Henriksen, 2017).

Contrary to fiber reinforcements of concrete where the reinforcement is meant to reduce after break crack propagation Textile Reinforcement of Concrete (TRC) performs similar to steel reinforcement and increases structural performance for areas with high tensile stresses. The fabric mesh material consist of fiber rovings in one or two directions. Rovings are made from textile fibers that are aligned and glued by a matrix (Koutas *et al*., 2019).

Mold/Formwork

In general wooden, steel, rubber and polystyrene foam molds are used for single curved and flat surfaces. For complex geometries such as double curved or freeform surfaces, 3D Computer Numerical Controlled (CNC) milled molds, flexible tables with pistons or actuators and membranes are used. Each method has its limitation based on the size, labor costs, production time, labor intensity and reusability (Henriksen, 2017) (Table 1).

Material Testing and Handling Concrete

In first part of the Material testing phase, students evaluate the mechanical properties of concrete. As an exercise, concrete blocks are casted and tested for 7, 14 and 28 days for compressive strength to obtain the efficiency of curing. The mortar used consists of a fine aggregate (0-2 mm), a cement of the strength class 42.5 N/mm² was used as a binder.

In order to achieve suitable material properties and an improvement in workability, the mixing ratio of limestone powder was added. To determine the material properties, mortar prisms were produced and subjected to a bending tensile and compressive test.

Flexural Strength

The flexural tensile strength on mortar prisms was determined in accordance with DIN EN 12390-5. The prism samples with the dimensions 40×40×160 mm were placed on two rolls as shown in Fig. 1. The prism is loaded at the center of the sample until it fails.

The maximum failure load determined is converted to the flexure tensile strength f_{ct} using the following formula:

$$f_{ct} = \frac{F \cdot l}{d_1 \cdot d_2^2} 1.5$$

Where:
F_{-max} = Breaking load [kN]
l = Distance between the supports [m]
d_1 = Breadth of the cross section [m]
d_2 = Width of the cross section [m]
1.5 = Factor for central load

The tests show a flexural tensile strength of 5.22 N/mm² after 28 days with a standard deviation of 0.72 N/mm² (Table 2).

Compressive Strength

The compressive strength of the mortar samples was determined based on DIN EN 12390-3. The fracture halves of the flexural tensile test are used here as test specimens. This turns 3 prisms into 6 compressive test specimens (Fig. 2).

The compressive strength f_c is determined from the maximum compressive force as follows:

$$f_c = \frac{F}{A}$$

Where:
F_{-max} = Breaking load [N]
A = Area [mm^2]

The results from the compressive test series are shown in Table 3. The compressive resistance of sample 1.7.2 differs significantly from the other values; the reason for this is an error in the test. The named value hence rated as an outlier and is no longer taken into account.

From the Fig. 3 the compressive strength tests result in a 28-day compressive strength of 53.32 N/mm² with a standard deviation of 1.73 N/mm².

Reinforcing Textiles

Textile reinforcement for concrete structures is state-of-the-art and widely used for the main reasons that it is very light, needs less concrete cover and do not corrode.

The concrete textile composite has a much higher structural performance than a (polymer) fiber reinforced concrete. The fabric reinforcements have comparable tensile strength as steel. The woven fabric reinforcement is placed and aligned in our case in the mold according the relevant maximum stresses (Rempel, 2013).

Table 1: Comparison of different mold types (+ good, o neutral, - negative). (Henriksen, 2017)

Mold type	Labor intensity	Cost (Material and labor)	Mould Production time	Reusability of the mold
Wooden molds	0	Material 25€/m²; Labour 40€/h MaterialApprox.50€/m²	2-4 h/m²	1-20 times
Steel molds	+	Material approx. 50€/m²	5-8 h/m²	20-500 times
Rubber mold	+	Material 80-200€/m²	3-5 h	10-50 times
Polystyrene form molds (wire cut)	-	Material € 30/m³	1 h	5-30 times
CNC milled molds (Foam, plastic)	-	300-400/m²	5-10 h	5-10 times
Flexible tables with pistons	-	High machine cost	20 min	Motors 10,000 times Surface 100-500 times
Flexible tables with actuators and membranes	-	High machine cost	5 min	Motors 10,000 times Surface 500 times

Table 2: Results of the flexural strength over 28 days

	Sample age [days]	F_{max} [kN]	f_{ct} [N/mm²]	Average f_{ct} [N/mm²]	Standard deviation
Prism 1.7	7	1,98	4,64	4,47	0,15
Prism 2.7		1,92	4,50		
Prism 3.7		1,82	4,27		
Prism 1.11	11	1,99	4,66	4,93	0,43
Prism 2.11		1,96	4,59		
Prism 3.11		2,36	5,53		
Prism 1.14	14	1,93	4,52	4,97	0,40
Prism 2.14		2,09	4,90		
Prism 3.14		2,34	5,48		
Prism 1.28	28	1,80	4,22	5,22	0,72
Prism 2.28		2,38	5,58		
Prism 3.28		2,50	5,86		

Table 3: Results of the compressive test the first over 28 days

	Sample age [days]	F_{max} [kN]	f_{ct} [N/mm²]	Average f_{ct} [N/mm²]	Standard deviation
Prism 1.7.1	7	64,40	40,25	39,19	1,15
Prism 1.7.2		33,36	20,85		
Prism 2.7.1		59,37	37,11		
Prism 2.7.2		63,43	39,64		
Prism 3.7.1		62,11	38,82		
Prism 3.7.2		64,17	40,11		
Prism 1.11.1	11	64,40	40,25	43,57	1,03
Prism 1.11.2		33,36	20,85		
Prism 2.11.1		59,37	37,11		
Prism 2.11.2		63,43	39,64		
Prism 3.11.1		62,11	38,82		
Prism 3.11.2		64,17	40,11		
Prism 1.14.1	14	64,40	40,25	44,86	1,29
Prism 1.14.2		33,36	20,85		
Prism 2.14.1		59,37	37,11		
Prism 2.14.2		63,43	39,64		
Prism 3.14.1		62,11	38,82		
Prism 3.14.2		64,17	40,11		
Prism 1.28.1	28	64,40	40,25	53,32	1,73
Prism 1.28.2		33,36	20,85		
Prism 2.28.1		59,37	37,11		
Prism 2.28.2		63,43	39,64		
Prism 3.28.1		62,11	38,82		
Prism 3.28.2		64,17	40,11		

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Table 4: Material properties of carbon fabric

Roving	a [mm]	b [mm]	A [mm²]	Fmax [N/roving]
Weft	4,5	1,2	5,4	-
Warp	2,8	1,5	4,2	2032,1
Fabric	Cross section single roving [mm²]	Roving count [pcs/m]	A total [mm²/m]	Weight [gr/m²]
Weft	5,4	31	167,4	269
Warp	4,2	40	168	

Table 5: Material properties of glass open mesh fabric

Roving	a [mm]	b [mm]	A [mm²]	Fmax [N/roving]
Weft	0,54	2,25	1,215	3233,6
Warp	0,6	0,6	0,36	3038,6
Fabric	Cross section single roving [mm²]	Roving count [pcs/m]	A total [mm²/m]	Weight [gr/m²]
Weft	1,215	120	145,8	218
Warp	0,36	160	57,6	

Two different textile materials (regarding base material and fabric construction) are used for the fabrication of the furniture (Fig. 4). On the one hand a non-crimp mesh fabric from carbon rovings (according the properties in Table 4) is used. The mesh openings are approx. 30×30 mm. It is used in the field of refurbishment of concrete structures (e.g., bridges, shells) (Seidel *et al*., 2013).

Due to the fact that the fabric is comparatively stiff and hard to use for small radii an alternative material is offered. It is a common open mesh leno-fabric from glass fiber filaments for reinforcement of thermal insulation composite systems and plaster systems (StarTex Grob, Baumit) (Table 5).

For both materials, the base properties (weight, yarn count and cross section) are evaluated. The mechanical properties are determined in tensile tests.

Following the material behavior/rigidity the students used the carbon fabric for the reinforcement of more flat and laminar areas of the furniture. For the curved parts with small radii the more flexible glass fabric was used.

In the second part of the training, students are introduced to textile reinforced concrete. Fine aggregates, concrete admixtures such as superplasticizers are introduced. Students evaluate the bending strength from thin textile reinforced beams as shown in the Fig. 5.

Apart from the evaluation of mechanical properties, students also evaluate the surface quality of the concrete for their project. Two important factors that influence the surface quality are the separation agent and surface lamination of the mold.

To obtain a good surface quality of the concrete, various lamination materials such as bee wax, epoxy, putty (plaster and dispersion adhesive) and solvent free paint are tested on the mold surface and are compared in Table 6. The results of the tests are shown in the Fig. 6 and 7. Epoxy among all the lamination agents resulted in very fine surface quality and the mold was sustainable for the second lamination without any further releasing agent shown in Fig. 6. Furthermore, pigments for coloring are tested Fig. 8 and lamination technics with textiles are exercised as shown in Fig. 9.

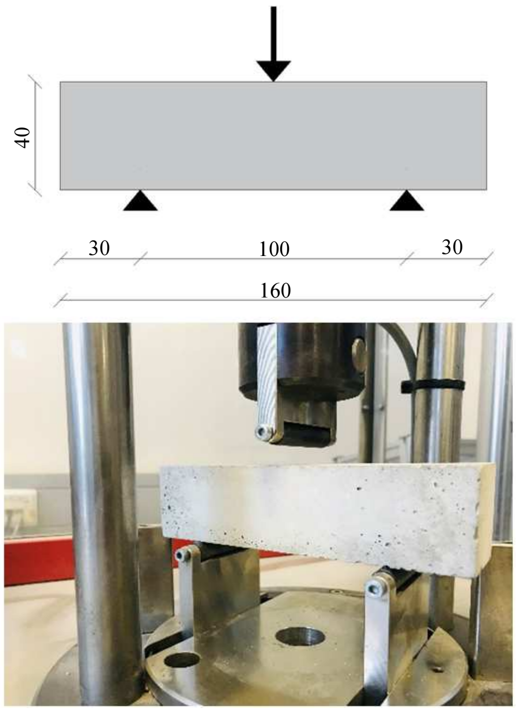

Fig. 1: Dimensions of the sample and support system for Flexural strength

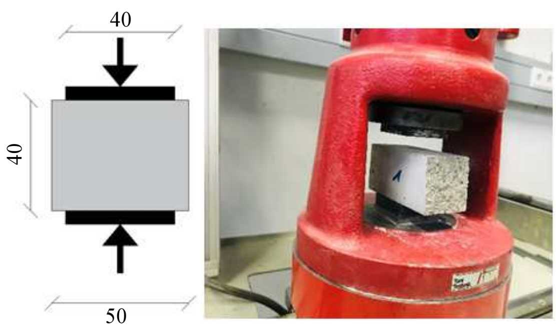

Fig. 2: Dimensions of the sample and support system for Compressive strength

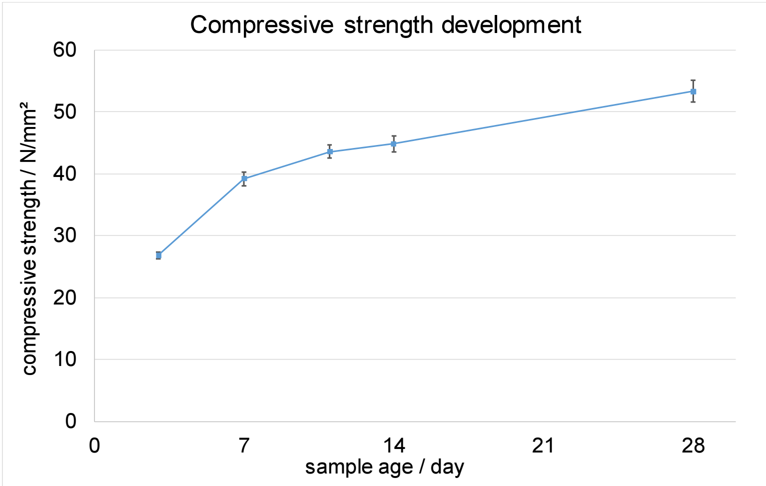

Fig. 3: Compressive strength developed over 28 days

Fig. 4: Base carbon fabric (left top), base glass fabric (right top), tested and failed carbon roving (left bottom), failed fabric strip mounted for tensile test (right bottom)

Fig. 5: Four point bending test for textile reinforced concrete

Fig. 6: Molds tested with epoxy resin as surface finish

Fig. 7: Surface quality tests with releasing agents

Fig. 8: Concrete blocks with different pigments

Fig. 9: Hand lamination specimen with different concrete mix ratios

Table 6: Comparison of surface finishing materials (+ good, o neutral, - negative)

Lamination Material	Surface quality	Reuse of the mold	Need of Releasing agent	Material cost
Bee wax	o	-	✗	+
Epoxy	++	++	✓	- -
Putty (plaster)	-	-	✓	++
Putty (dispersion adhesive)	+	o	✓	+
Solvent free paint	o	+	✓	+

Adapting the Design Concept/Idea

After the training process, students develop and present ideas in the form of hand sketches and models with either paper or clay. The designs are evaluated and refitted based on aesthetics, structural and functional aspects. The production difficulties, which play an important role when working with the robot and special tools, are discussed in detail. The available machine processes are milling and hotwire cutting.

Geometry of Surfaces

The question which fabrication process and material suits best the surface design (with the main goal to achieve a reduction of fabrication complexity) can be answered after dealing with the following considerations on surface curvature. For instance, one can fabricate at ease all flat, conical and cylindrical shapes (Gauss curvature = 0) with a hot wire cutting device from a Styrofoam block. Furthermore, ruled surfaces can be produced using the hot wire tool as the straight profile line (Henriksen *et al*., 2016).

Only limited by the reachability and the dimension of the cutting tool (length and depth) the fabrication strategy and the programming of the tool movement can be a big challenge nevertheless.

All the surfaces that are more complex like synclastic and freeform shapes need a 2,5 to 6 axis milling procedure. The freedom of form and detailing is much more elaborate with this process than with the later. For the multiple material options for mold making different parameters need to be specified and the machine setup have to be figured out. All the common fabrication technological aspects like feeds and speeds as well as the overall milling strategies need extensive programming.

Fig. 10: Surface qualities as a result of different milling strategies

Surface Quality

The question of the final surface quality is crucial for the product impression. The traces left by milling need to be optimized either by using appropriate milling tools or by adjusting the toolpaths (roughing and smoothing) as shown in the Fig. 10. For an optimal result with the hot wire cutter, the speed of the tool is adjusted to the width of the cut as shown in Fig. 11.

Fabrication Time

In current scenario with high economical priority all fabrication processes follow time optimization and

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reduction of complexity. Various strategies to simplify surfaces are common. For surfaces that are originally developable, not much effort is needed. However, for surfaces that are more complex one can either approach simplification by discretization or remodeling the geometry into developable surface patches.

Milling is a process with a tedious effort to cut by stock removal. Whereas with hot wire larger blocks of material is cut away in shorter time span.

Workspace and Dimensions

With Kuka KR 16-2 the maximum reachability from the robot center point is 1800 mm in radius. To maintain accuracy of the processes only 1000 mm radius range is free for fabrication. For this reason, the fabrication is planned in segments of working piece. The principal reachability of the tool of every production step should be ensured. This is checked with offline robotic simulation.

The width of the hot wire tool is 750 mm but the cutting width is between 500 to 600 mm depending on the type of material.

The accuracy of both of the processes depend on the position of the tool. The more away from the center of the robot the lesser accuracy can be achieved.

Structural Performance

Beside the digital modelling of the model and the robotic programming for fabrication, Grasshopper is used for the structural analysis of the projects. With the use of the plugin for Grasshopper Karamaba3D (Fig. 12) students were able analysis It provides various analysis tools e.g., the shell line analysis for force flow, principal stresses, deformation and stress ISO-lines. From the nurbs-surface model (generated in Rhino) a consistent and sophisticated meshing procedure (with different Grasshopper mesh tools) transfers the model into an adequate mesh object for FEA analysis. The supports, the load cases as well as the material properties and shell thickness must be defined, the model must then be assembled and the deflections are calculated with the Karamba3D solver. This plugin helped the students to orient their design not just on the ascetic values but also the structural properties of the project.

To evaluate the results obtained from Grasshopper from students, a results from professional software Ansys (structural FEM software) is used for verification (Table 7). In order to simplify the model, the concrete is modelled without reinforcement with young's modulus of 25 MPa and Poisson's ratio of 0.3. A critical load case scenario with two people (100 kg each) sitting on either side of the bench is applied as a surface load as shown in the Fig. 13 is considered for verification.

Another aspect of the structural performance is the design and orientation of the reinforcement, based on the stress trajectories as shown in the Fig. 14 for the same load case. The tensile and compression zones are calculated and the textile is oriented for maximum efficiency in tensile zone. Though the principle stresses results in Table 7 are comparable. The stress trajectories obtained from grasshopper are not comfortable with Ansys. But for a holistic approach, the results obtained from grasshopper are satisfactory.

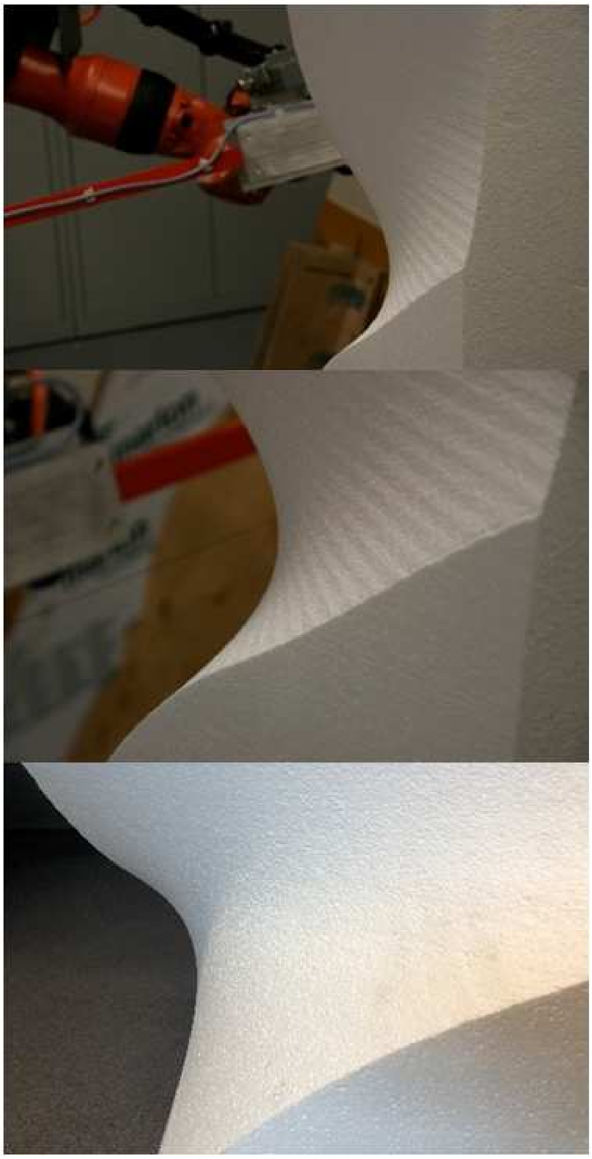

Fig. 11: Surface qualities as a result from hotwire cutting with different cutting speeds

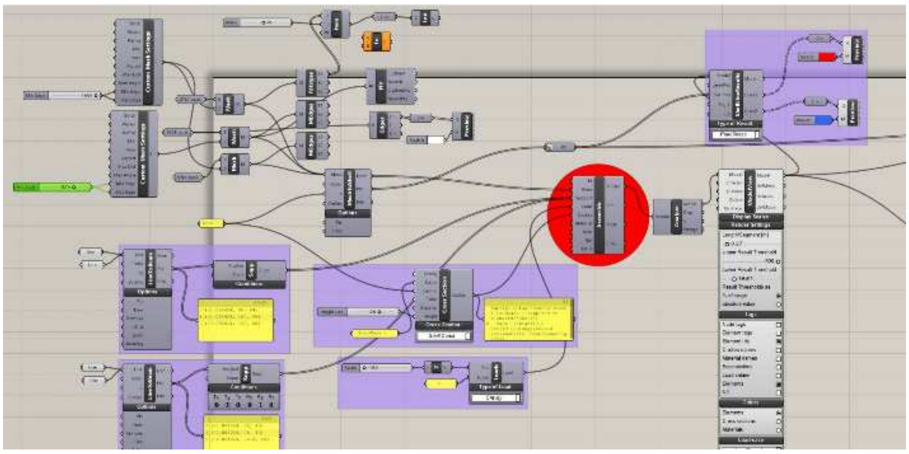

Fig. 12: Grasshopper/Karamba3D script

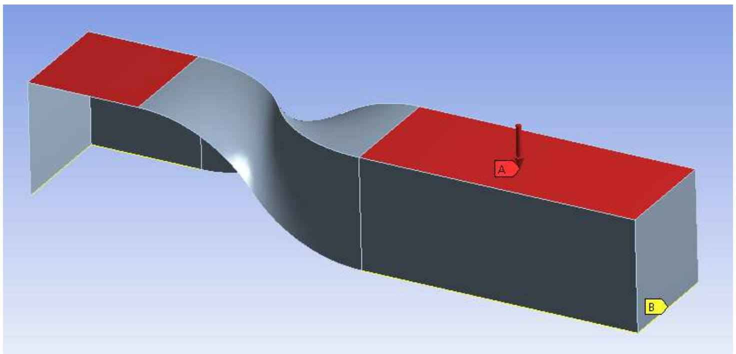

Fig. 13: Load application in Ansys model on the bench project

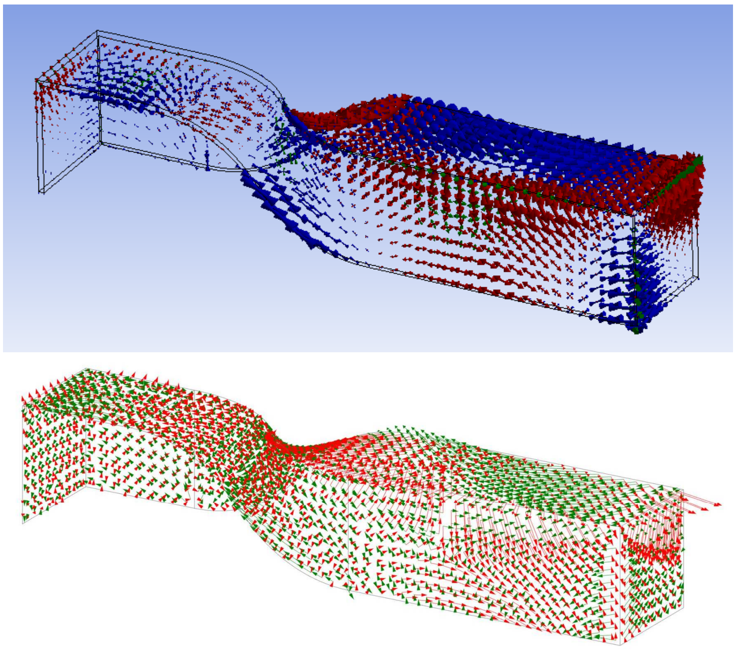

Fig. 14: Representation of principle stress trajectories; Top: Ansys (Blue-compressive stresses, Red-tensile stresses); Bottom Grasshopper (Green-compressive stresses, Red-tensile stresses)

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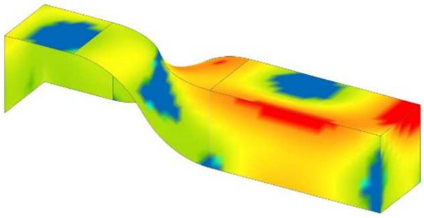
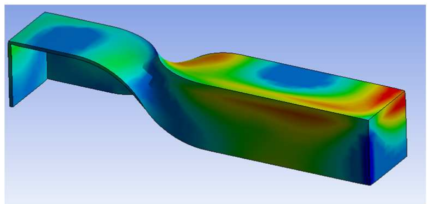
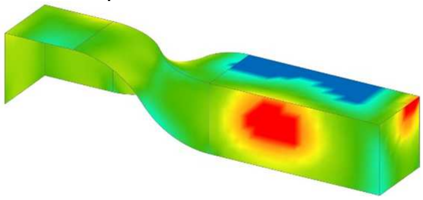
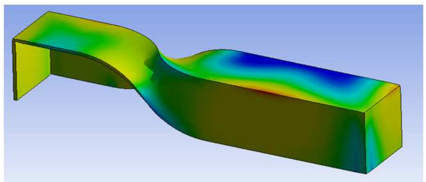
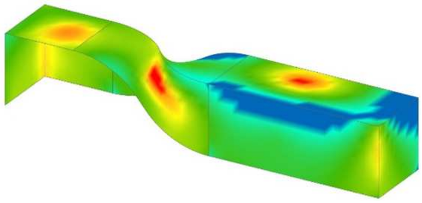
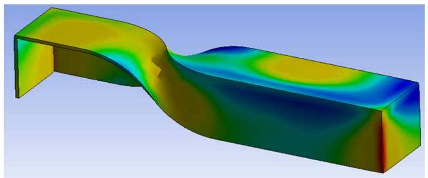
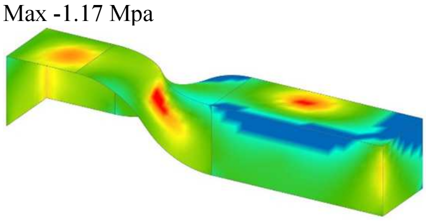
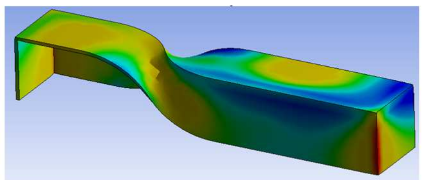
Table 7: Results from Grasshopper and Ansys (Max. Principal stresses on top of the surface and bottom of the surface)

Principal stresses	Grasshopper	Ansys
σ1 Top	 Max 2.0 Mpa	 Max 1.6 Mpa
σ1 Bottom	 Max 1.2 Mpa	 Max 1.28 Mpa
σ2 Top	 Max -1.17 Mpa	 Max -1.2 Mpa
σ2 Bottom	 Max -2.19 Mpa	 Max -1.9 Mpa

Fabrication of Mold

The last phase was the implementation of the designs as a full-scale prototype. For this, the digital fabrication groups had to convert the design from the physical model into a digital model. This either can be done by 3D scanning or by 3D modelling using computer aided design programs like Rhino. The segmenting of the object into feasible working piece blocks with a focus on seam lines and stripping of the mold adds complexity and design feature to the project.

The modelling of the design object as well as the generation of the adequate mold elements need elaborate digital modelling. Flipping the mindset from a positive object into a negative mold requires a specific 3d thinking skills.

One design is a bench with the dimension of 2200×400×550 mm. It consists of two flat segments to sit on and a twisted intermediate and connecting element (Fig. 15). The side segments are of regular dimensions and rectangular so conventional fabrication methods are used. For intermediate element which is a ruled helicoid spiral surface the formwork was fabricated with the help of the hot wire cutting tool. A perfect example of a ruled surface geometry. The formwork was modelled in Rhino and the robot was programmed with Grasshopper and KukaPRC (Fig. 16 to 18).

The second project is a lounger (Fig. 19), which is adapted to the human stature. The dimensions of the chair are 1510×700×1030 mm. There is a main part for laying down and a supporting element attached to the bottom side. The main part is divided into two pieces that fit into the Styrofoam stock size of 1000×1000×500 mm (Fig. 20). The freeform shape in the overall design and the elaborate detailing requires the use of a milling process (Fig. 22).

Autodesk Fusion 360 was used for the programming of the milling paths (Fig. 21). The complete range of machining parameters need to be set up for the programming. The students get an insight into the topics of tool selection, milling strategies, feeds and speeds.

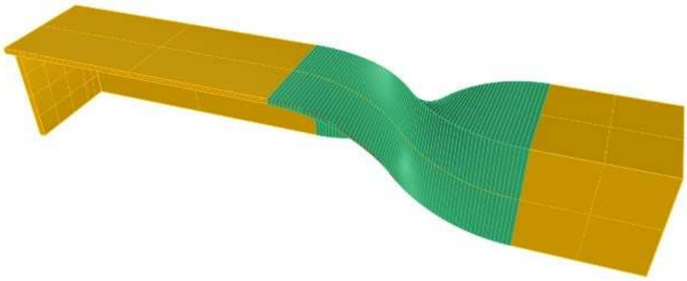


Fig. 15: 3D model of the bench project in Rhino

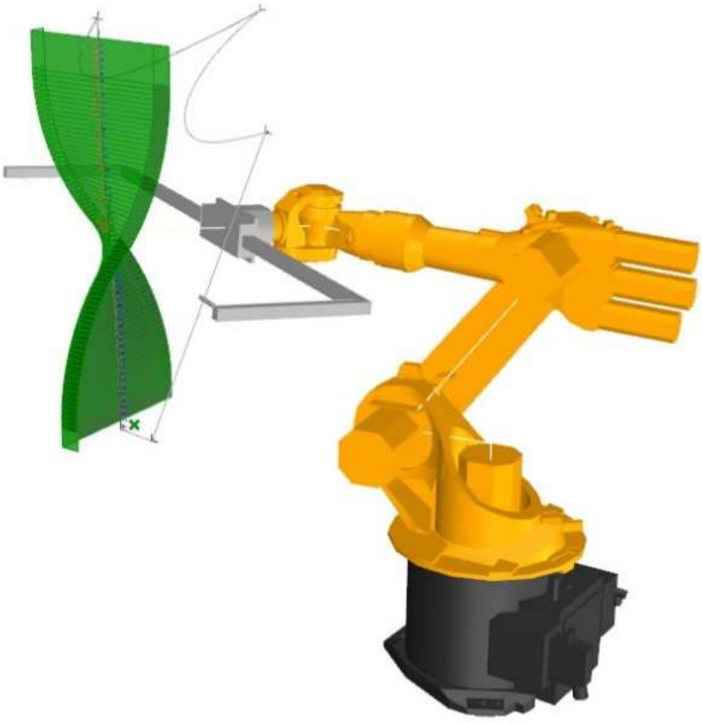


Fig. 16: Simulation of the robotic program

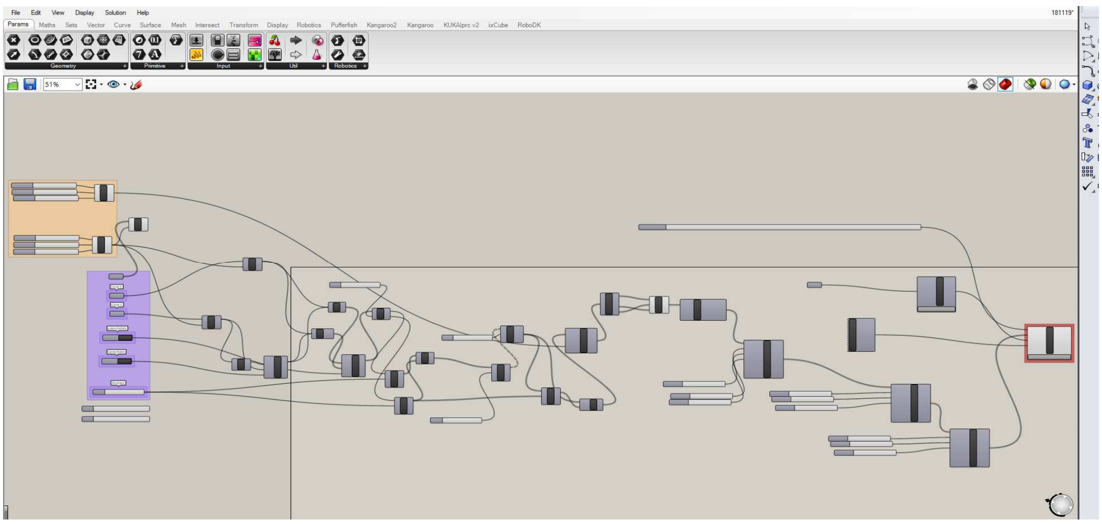


Fig. 17: Grasshopper interface for the robotic simulation

With these experiences, the students developed the following evaluation sheet (Table 8). This comparison shows that the machine- and CNC-based manufacturing methods are not always the first choice (Table 8). The statement that (almost) everything is possible with the robot should always be supplemented by fundamental questioning. Each manufacturing approach requires a careful balancing of the above parameters such as machining time, costs, accuracy, freedom of form etc. (Stavric and Kaftan, 2012).

Fig. 18: Robot cutting the prototype in full scale

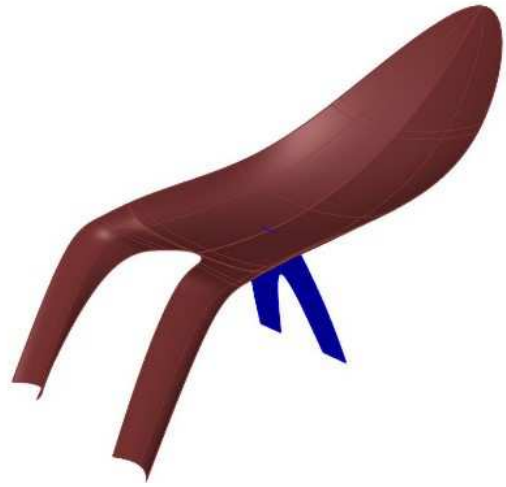


Fig. 19: 3D-model of the lounger in rhino

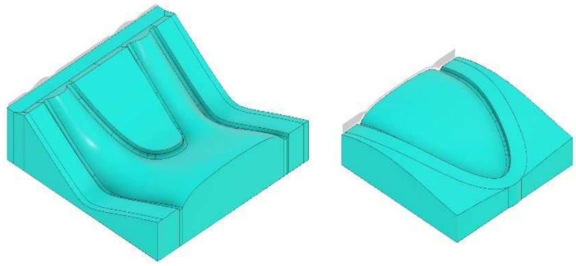


Fig. 20: Digital Mold model divided in two segments for fabrication

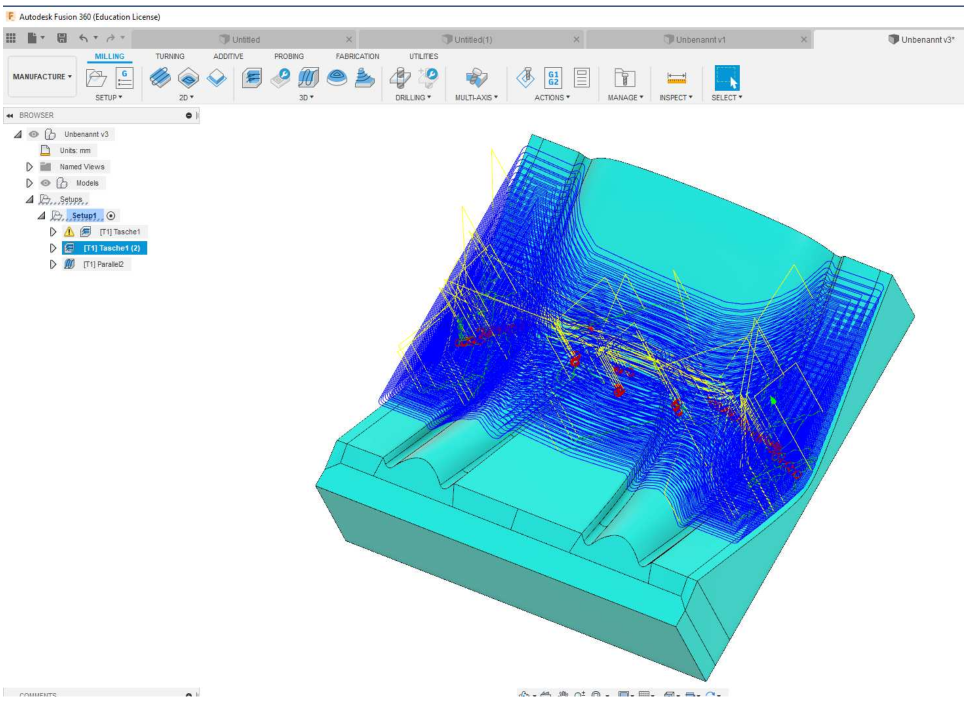


Fig. 21: Robotic programming and tool paths with Autodesk Fusion 360

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Fig. 22: Robot milling the segments in full scale

Table 8: Comparison of hand guided machines vs industrial robots (+ good, o neutral, - negative)

	Hand Guided Machines	6-axis Industrial Robots Milling	Hotwire Cutting
Versatility	+	++	+
Acquisition time, First piece	+	o	+
Production time, Second piece	+	-	o
Material efficiency	o	+	++
Dimensional consistency	+	++	+
Repeatability	o	o	o
Working space and variability	o	o	+

Laminating the Prototype

Bench

The prepared Styrofoam molds were joined together (Fig. 23) and prepared for the concreting process. Figure 24 shows how to attach the spacers to maintain the concrete layer thickness.

Because of the hotwire cutting process, the produced Styrofoam surface shows regular unevenness. However, this should not be reflected in the concrete surface, so different grinding processes and surface finishes were tested in advance (Fig. 6 and 7). Favored was a multiple application of putty (dispersion adhesive), which resulted in an even and cost efficient surface.

A conventional formwork oil from the manufacturer PCI was applied as release agent between the final surface coating and the concrete (Fig. 25). The concrete was applied layer by layer to the formwork in a time consuming lamination process. A carbon fiber mat was used to prevent cracks in the near-surface area (Fig. 26). Subsequently, additional layers of concrete were applied until the necessary material thickness of 2-3 cm was achieved (Schneider, 2013) (Fig. 27 and 28).

A special challenge was the stripping of the hardened concrete from the Styrofoam formwork. As the mold was not damaged, subsequently another work piece was produced.

Lounger

The steps for making the lounger (Fig. 29 to 34) are the same as the sequence of the bench (Fig. 23 and 29). Due to a non-effectiveness of the release agent the reuse of the Styrofoam formwork was not possible. The only way to extract the lounger from the mold was a destructive method as shown in Fig. 33.

In general, the concrete mix had to be adapted to the production process. The essential factor here was to choose the water-cement ratio and the fine fraction of the concrete so that the plasticity of the material corresponds to a leveling compound. Since partly the concrete had to be applied to vertical surfaces.

Furthermore, it was necessary to observe the heat of hydration during the hardening process. As Styrofoam is a good insulating formwork, the heat generated during hydration can be released only to one side to the uninsulated side. This can lead to temperature-induced stress cracks. Preliminary tests showed no problematic temperature gradients within the concrete cross-section during hardening, so a monitoring of the concrete temperatures was not needed.

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Fig. 23: Assembly of the Styrofoam mold parts

Fig. 24: Adding the edge detail

Fig. 25: Applying formwork oil as release agent

Fig. 26: Laying of carbon reinforcement mesh

Fig. 27: Finishing of the edges

Fig. 28: Final prototype

Fig. 29: Assembly of the milled Styrofoam mold parts

Fig. 30: Surface with Styrofoam filler and measuring of material thickness

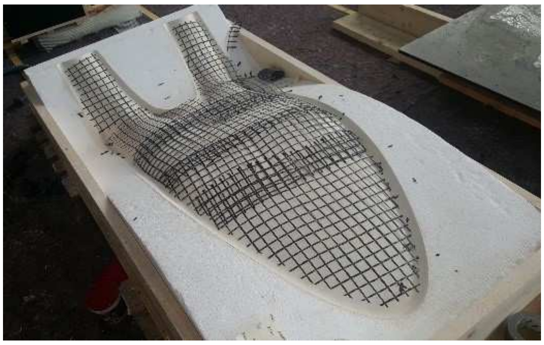

Fig. 31: Laying of carbon reinforcement mesh

Fig. 32: Laminated concrete surface

Fig. 33: Stripping procedure

Fig. 34: Final prototype

Conclusion

The project demonstrated the student's ability to design, develop and fabricate textile reinforced furniture as free-from robotic-fabricated products. The use of the furniture fulfills the design and user requirements. The concrete quality exceeds standard concrete in terms of strength and crack dimensions. The permanent use as an outdoor product has been demonstrated. Satisfying outdoor long-term experiences exist with comparative objectives at our campus built for years ago.

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Author's Contributions

All authors contributed to design the study, write and revise the manuscript.

Ethics

This article is original and contains unpublished material. Authors declare that are not ethical issues and no conflict of interest that may arise after the publication of this manuscript.

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