Robot-Aided Fabrication of Materially Efficient Complex Concrete Assemblies

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Abstract. This paper presents a novel approach for the materially efficient production of doubly-curved Expanded Polystyrene (EPS) form-work for in-situ concrete construction and a novel application of a patented Glass Reinforced Concrete (GRC) technology. Research objectives focus on the development of complex form-work generation and concrete application via advanced computational and robotic methods. While it is viable to produce form-work with complex geometries with advanced digital and robotic fabrication tools, a key consideration area is the reduction of form-work waste material. The research agenda explores methods of associating architectural, spatial, and structural criteria with a material-informed holistic approach. The digital and physical investigations are founded on Robotic Hot-Wire Cutting (RHWC). The geometrical and physical principles of RHWC are transformed into design inputs, whereby digital and physical tests inform each other simultaneously. Correlations are set between form-work waste optimization with the geometrical freedom and constraints of hot-wire cutting via computational methods.

Keywords: Robotic fabrication, Robotic hot-wire cutting (RHWC), Glass-reinforced concrete (GRC), Waste optimization, EPS form-work.

1 Introduction

The research presented in this paper aims to outline an innovative strategy for the materially efficient production of stay-in-place Expanded Polystyrene (EPS) form-work for in-situ concrete construction and a novel application of a patented Glass Reinforced Concrete (GRC) technology. Research objectives focus on the development of complex form-work generation with no material waste and concrete application via advanced computational and robotic methods.

In recent years, robotic fabrication processes implemented in architecture have begun to incorporate digital and physical paradigms in an unparalleled way due to the multi-axis freedom of an industrial robot arm, its speed, precision, and low tolerances [1]. This development, in turn, has fueled the revival of complexity found in volumetric assemblies, moving away from previously standardized component fabrication [2].

The employment of complex form-work for concrete structures has the potential to yield architecturally diverse and materially efficient assemblies. While it is viable to produce form-work with complex geometries via advanced digital and robotic fabrication tools, a key consideration area is the reduction of form-work waste material in subtractive manufacturing methods. The potential to incorporate this constraint in the preliminary design process as a design driver will pose advantages in waste optimization as well as production costs. Recent investigations on 3d-printed stay-in-place formwork demonstrate the advantages of employing this method by correlating the geometric flexibility of the formwork with the structural capacity of concrete [3].

While current research mostly facilitates form-work waste reduction by leveraging computational techniques such as geometry optimization or fabrication-based techniques such as the employment of adaptive moulds, the research described in the paper correlates waste optimization with geometrical freedom through the selected fabrication technology. Methods of associating architectural, spatial, and structural criteria are explored with a material and fabrication informed holistic approach. The digital and physical investigations are founded on Robotic Hot-Wire Cutting (RHWC) technique. The geometrical and physical principles of RHWC are transformed into design inputs, whereby digital and physical tests inform each other simultaneously. Correlations are set between form-work waste optimization with the geometrical freedom and constraints of hot-wire cutting via computational methods.

The one-to-one scale prototype presented in this paper is a case study to test the proposed methodology through the design and construction of a vault structure with the use of stay-in-place form-work and GRC. The dimensions of the structure are 1,600 mm. width, 6,900 mm. length, and 2,740 mm. height. The location of the case study is the outdoor area of Istanbul Bilgi University.

The explorations are conducted as part of an international workshop, Architectural Association (AA) Istanbul Visiting School. The workshop is structured in two stages. During the first stage, participants familiarize themselves with material processes, computational methods, and various fabrication techniques, and they are introduced with core concepts related to complexity in design practices. During this phase, basic and advanced tutorials on generative design algorithms and analysis tools are provided, and advanced fabrication techniques are introduced. Participants are asked to form themselves into teams and propose design interventions following the brief of the course. A design competition is held, whereby the most relevant concepts evaluated according to a set of predefined criteria are selected to move forward to the second phase of the programme. During the second stage, participants are formed into new teams according to the fabrication and assembly requirements, and work towards the completion of the full-scale working prototype.

Research timeline has been structured to allow sufficient timing for the researchers to conduct GRC material testing with the industry partner, Fibrobeton, prior to the commencement of the workshop. Moreover, experimentation on potential computational workflows and candidate assembly processes have been considered prior to the workshop in order to accommodate for versatility and adaptability to potential design and fabrication alternatives during the workshop.

The research agenda is tested in the following areas: Computational methodology, physical experimentation, material technology, robotic tool path development, fabrication, assembly logic and construction.

2 Computational Methodology

The generative design process has been initiated by principles driven by waste reduction, whilst bearing the capacity for generating an architectural element with a sufficient degree of formal freedom. In addition to the imposed constraints on waste production throughout the design, construction, and assembly, fabrication restrictions of robotic hot wire cutting have been taken into consideration from the early stages of schematic design. The prototype presented employs Expanded Polystyrene Foam (EPS) as the base form-work for in-situ Glass Reinforced Concrete (GRC) Shotcrete. EPS foam is used extensively in the architectural construction industry as insulation layers due to its cost and energy efficiency.

Waste optimization constraints have been predominantly applied in the application of EPS foams for the final form-work and assembly processes. Constraints such as reduction of negative parts after cutting a piece of an EPS foam and a modular approach to the global configuration of the assembly have been applied from the early stages of form-finding processes through computational methods. The modularity of the EPS blocks, with each block being 330 mm. by 330 mm. by 330 mm., has driven the design options to examine modular approaches and simultaneously explore ways of utilizing all pieces produced from every cut into the final formal configuration. This ambition necessitates the dismissal of the conventional binary approach that treats pieces of form-work as ‘positive’ and ‘negative’ products, but rather explores each fabrication step as producing ‘positive’ modules that actively contribute to the final formal configuration of the architectural assembly.

The selected manufacturing methodology, Robotic Hot Wire Cutting (RHWC), eases the fabrication process of complex geometrical forms with high precision [4]. However, in addition to the already imposed constraints driven by principles of waste reduction, the selected fabrication method also introduces an extra set of geometrical limitations by which the EPS formwork should be modelled and constructed digitally.

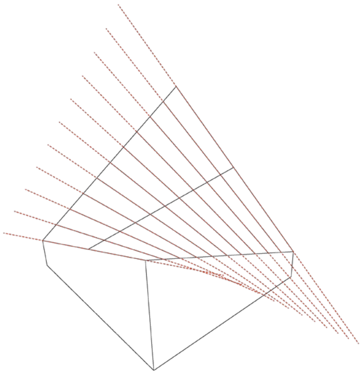


Fig. 1. Doubly-curved ruled surface generation for RHWC.

In order to take full advantage of RHWC in the fabrication process, the geometries to be cut with the robot should be modelled as ruled surfaces. As Pottmann et al stated in *Architectural Geometry* a typical approach to classify surface patches are in three categories, namely planar surfaces, single curved surfaces and in general double curved free-form surfaces [5]. "*An interesting class of double curved surfaces, so called ruled surfaces, comprises developable surfaces and share their property of being generated by a continuously moving straight line.*" [6]. (Fig. 1)

In the context of the current experimentation and fabrication strategy presented in this paper, these straight lines map the movement of the hot wire attached to the end effector of the robot [7]. Furthermore, the movement of the robot itself needs to be considered from the early stages of component design in order to prevent any possible collisions of the pre-built end effector with the built-in-place jig holding the EPS block.

Thus, the design exploration of components and final assembly starts with a set of important constraints elaborated above. A custom-devised algorithm built in Grasshopper, graphical algorithm editor embedded in Rhinoceros 3D, initially generates variations of doubly-curved ruled surfaces that are appropriate for hot-wire cutting for individual modules.

During the initial stage of the workshop, students were divided into 6 groups to investigate and explore means of generating a global form from the aggregation of modules with inbuilt attributes to address the specified constraints in design, fabrication and assembly process. Students were informed on the design constraints, and these included minimum waste, time and material efficiency in the fabrication of each component, structural stability of the final form, and an efficient assembly process.

At the end of the design phase, each group proposed a design option by highlighting their important design intentions. Every option signifies a different approach to the final assembly, ranging from an emphasis on the overall form via creating more complex components by cutting an EPS blocks several times consequently, to various assembly techniques, as well as the introduction of a joinery system between components.

Fig. 2 illustrates one of the design options whereby students have explored multiple cuts within each EPS block and simultaneously utilized all pieces in the formation of the global assembly in order to reduce material waste.

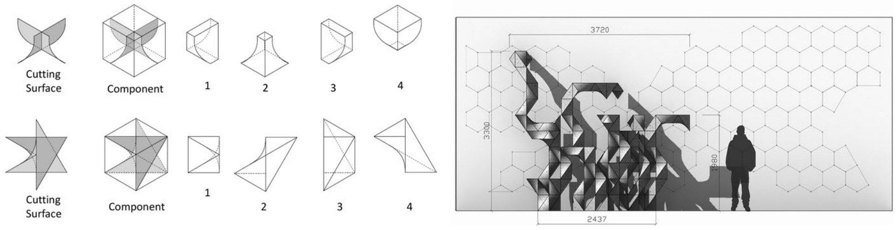


Fig. 2. Design alternative 1.

Fig. 3 demonstrates an alternative approach towards a multi cut scenario of an EPS block. Students have attributed the assembly logic of the final form into their cutting process. Consideration of an assembly logic have rendered this option more favorable compared to the option illustrated in Fig. 2.

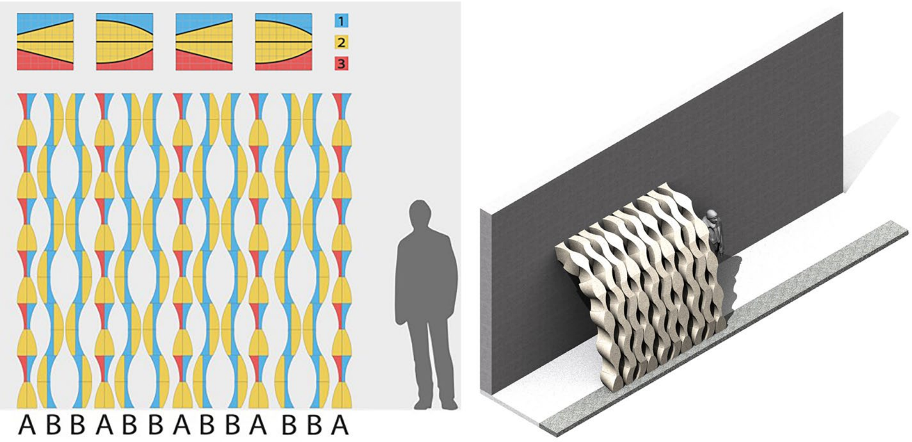


Fig. 3. Design alternative 2.

In contrast to the first two options, Fig. 4 illustrates an option whereby students have imagined the global form being generated by carving out from the stacked groups of EPS blocks in a 3-dimensional grid. This method has created a unique global form but due to the distinctness of each block, the fabrication and assembly time increases significantly.

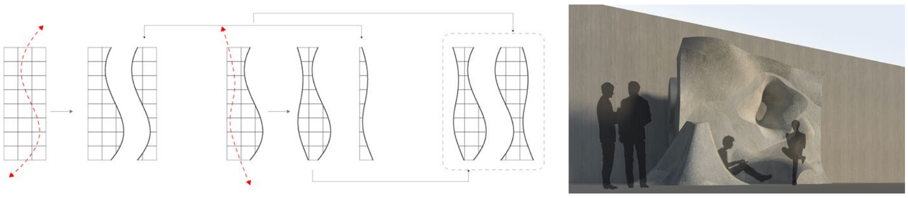


Fig. 4. Design alternative 3.

Similar to the first design alternative described above, Fig. 5 demonstrates an option characterized by the generation of multiple cuts from one EPS foam block and the aggregation of the cut pieces to generate the final global configuration. The structural stability of the form has been a concern for this design option.

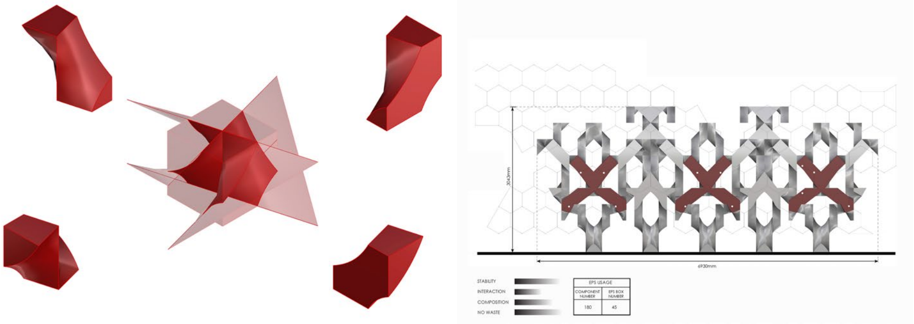


Fig. 5. Design alternative 4.

Fig. 6 illustrates another option outlined by the generation of non-orthogonal components with a single cut from the EPS foam block, yet this proposal has not elaborated on component to component joinery system.

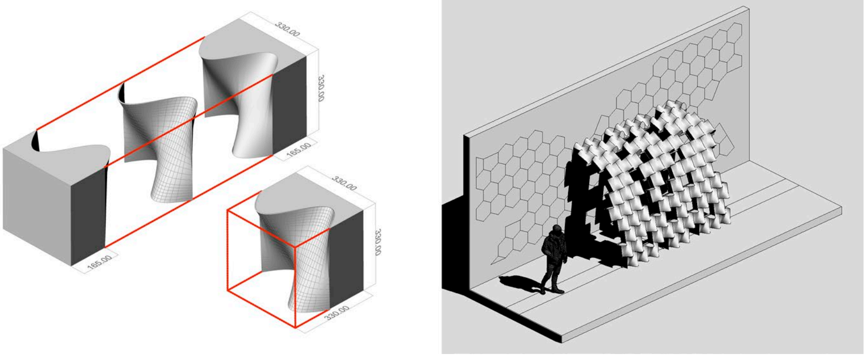


Fig. 6. Design alternative 5.

A collective decision based on time, fabrication, structural stability, and assembly efficiency has been made to carry forward with one design option. Along with the design proposals, each design team presented the estimated fabrication time for each block and for the entire proposal. Structural stability of the proposals was observed via scaled mock-up models presented by each group. Each team developed the robotic toolpath and tooling required to fabricate their modules. A key consideration was the complexity presented by multiple cuts to one foam block, and the type of frame necessary to hold the blocks in place for cases of multiple cuts. In order to avoid a complex frame that would potentially increase fabrication time, a single cut for each block was opted for. The selected design option, illustrated in Fig. 7, comprises modules generated with a single cut from the modular EPS foam block, and the global form is defined by a gradient of morphological variation.

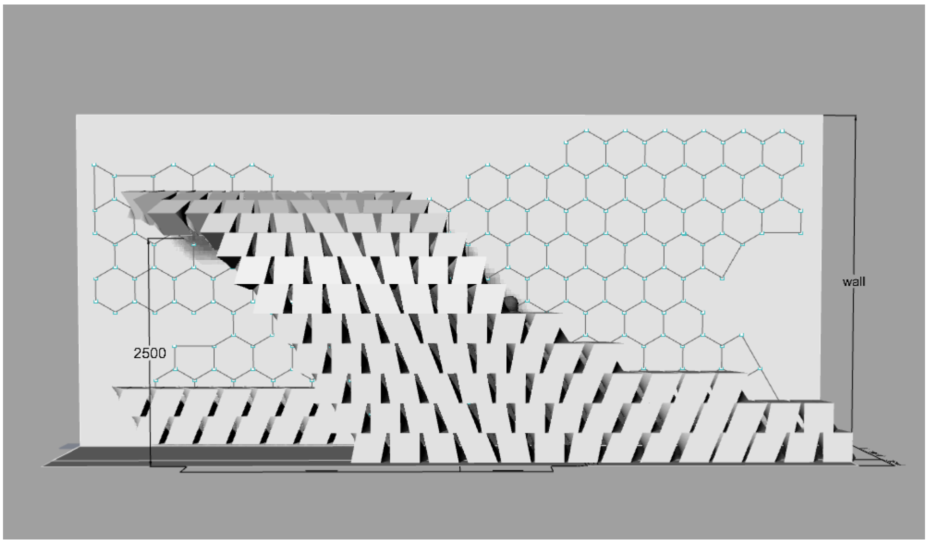


Fig. 7. Selected design option for fabrication and assembly.

Each component of the selected proposal is made up of a set of two unique volumes which are generated by cutting a single EPS block via RHWC. Both generated pieces are part of the global formal configuration of the assembly, thereby generating no waste material. The algorithm then distributes all the pieces according to a global configuration system where all pieces share overlapped surfaces (Fig. 8).

The assembly information and sequence are also embedded in the algorithm by means of creating unique tags and spacers for each module to map the spatial relationships to its adjacent components (Fig. 9). Finally, all the unique pieces are produced with a KUKA KR-20 robot and assembled on site.

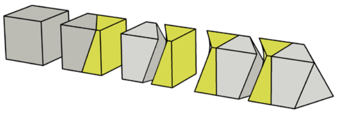


Fig. 8. Computational form-finding for a single EPS block.

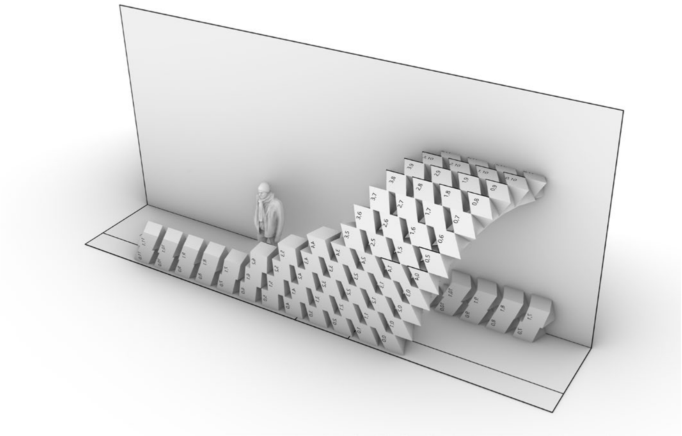


Fig. 9. Visualization of the final global assembly, including assembly information.

3 Robotic Fabrication

Following the key design principle of material efficiency, different materials for the form-work have been considered. Several composite materials made of plastics have been evaluated based on their strength, mechanical properties, chemical properties, and cost. Due to the manufacturing method, RHWC, the melting point of the material and the mechanical properties have been essential factors to maintain the efficiency of the fabrication process. Expanded Polystyrene (EPS) has been preferred as the most convenient option, with its melting point for wire cutting being at 100 °C and its elastic modulus of 5 Mpa [8]. These two properties, in addition to being a lightweight material (20 kg/m^3), have been key considerations for the 3 phases of the manufacturing process, namely robotic wire cutting, form-work assembly, and concrete deposition.

3.1 Robotic Manufacturing

Wire cutting is a widely used subtractive manufacturing method for low melting point plastic in the construction industry. It is generally used to process blocks from raw production into commercial sizes, usually leaving a high amount of waste material. In order to improve this method, a robotically actuated wire cutter with reduced tolerances has been employed to produce more precise cuts from base blocks. Reduced tolerances around cuts mean that all parts that yield from the cuts can be used in the design to achieve the zero-waste material goal of the research. Since every form-work element is different and optimized, the robot arm is essential to obtain unique cuts according to each block.

3.2 Tooling

Hot Wire Cutting is a technique based on using a hot element (wire) to melt for cutting a material. A bespoke wire-cutter, with dimensions of 790 mm. by 530 mm., has been assembled, and a 0.4 mm. diameter, 80% Nickel / 20% Chrome wire has been attached to the wire-cutter. This wire has been selected due to its durability, its resistance over 24 ohms/meter, and its melting point which is close to 1400 °C. For the power source, a 24V 10 A variable power source has been used to operate the wire cutter. This current can heat the wire till 750 °C.

3.3 Tool Operation and Constraints

The setup for the robotic arm was not spatially limited, yet the EPS blocks and the framework that stabilizes the EPS blocks have been designed keeping in mind the possibility of collision of the end effector with the frame that holds the blocks. The blocks have been elevated by a wooden frame for about 200 mm to avoid any collision and increase the safe working area (Fig. 10). The optimal routes have been calculated concerning the robot arm's flawless movement and any singularities that might occur during the cuts. Furthermore, the cutting position for each block has been designed to avoid excessive stretching of the wire and its potential failure. The power supply has been calibrated to never exceed the thermal expansion rate, 45 W/M, of the alloy. Furthermore, a spring-loaded system has been attached to the wire-cutter to absorb the expansion of the wire and keep the length within an acceptable tolerance.

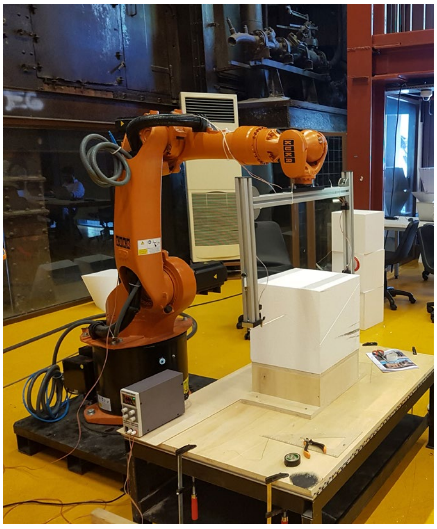


Fig. 10. Robotic set-up.

3.4 Performance

The robotic fabrication setup comprises a KR20-2 robot mounted on a transportable platform, assisted by a fixed table that is calibrated as part of the robotic environment. The robotic toolpaths are generated in Robots, an add-on for Grasshopper. Several constraints have been added to the robot program creation to compensate for constraints related to wire-cutting. One of the main constraints has been to avoid the collision of the wire cutter and the blocks by limiting the rotation angles along the cutting path. Secondly, the program has been optimized to ensure that the entry and exit points to each block are in the right position ensuring that the cuts are generated correctly. Finally, excessive rotation in target planes has been avoided in order to overcome excessive heating of the material and the potential imprecision to the cut. Planes and zone parameters are adjusted to limit the axis rotation to the minimum to avoid this potential imprecision.

Robot programming has been a collaborative process with the students. As every design team developed different design proposals, with their own strategies for material efficiency and time optimization, all the proposals were tested with RHWC. Data pertaining to toolpaths and fabrication time were collected and analyzed. This process concluded with the selection of the definitive protocol for fabrication in line with the zero-waste concept and time efficiency. For the selected process we achieved a rate of 1 whole block cut every 3 minutes, including the preparation and removal of the piece.

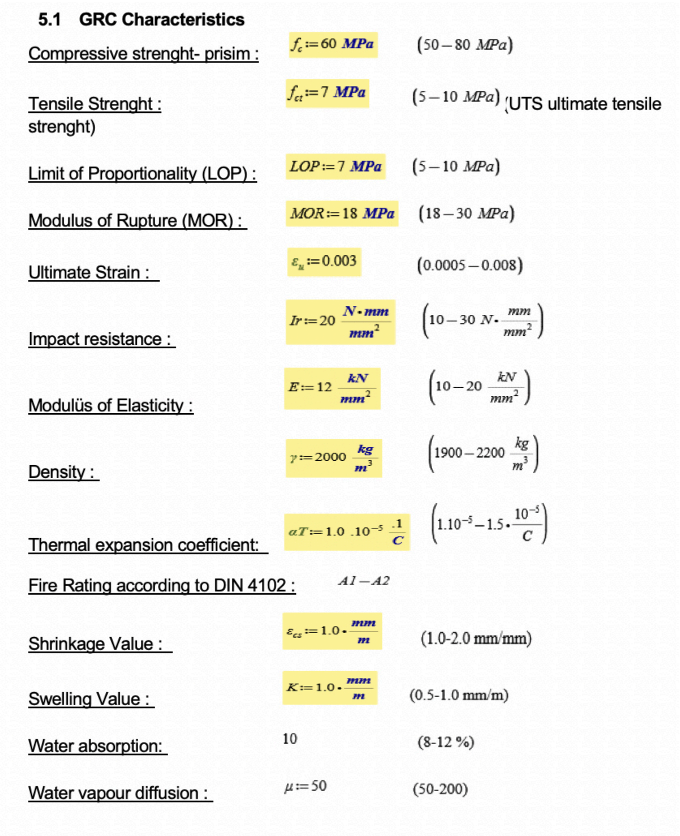
4 Material Technology

The objective to minimize material waste in production to develop computational and fabrication workflows for a spatial structure has led to the initiation of the material tests prior to the workshop. The focus has been to obtain a clear understanding of constraints and potentials of both materials, namely EPS blocks and GRC. The tests began with working on EPS blocks, which is a lightweight and rigid material commonly used in constructions for its insulation properties. EPS blocks, supplied by the industry partner, has a density of 20 kg/m3 with the standard dimensions of 330 mm. by 330 mm. by 330 mm.

Three main areas of exploration were specified to develop a module for the GRC application test. The major ambition of this material test was to establish a relationship between the degree of surface curvature and the applicability of GRC with precision. Other considerations included the integration of a joinery logic to the modules' geometry to prevent using extra adhesives while trying to maintain optimal surface area for connection. Furthermore, a major design consideration was to generate a global assembly that is defined as a porous system both for lighting properties and overall weight concerns. Lastly, testing the capacity for high surface resolution of the final form was critical for its potential design inputs. In order to test these parameters, an optimal form that has varying double curvature was proposed and shared with the industry partner to be tested with GRC. GRC (Glass Fiber

Reinforced Concrete) is a construction material that is commonly used in facade cladding (Table 1) [9].

Table 1. Material properties of Glass Reinforced Concrete (GRC).



5.1 GRC Characteristics

Compressive strenght- prisim :	$f_c := 60\ \mathbf{MPa}$	$(50 - 80\ MPa)$
Tensile Strenght :	$f_{ct} := 7\ \mathbf{MPa}$	$(5 - 10\ MPa)$ (UTS ultimate tensile strenght)
Limit of Proportionality (LOP) :	$LOP := 7\ \mathbf{MPa}$	$(5 - 10\ MPa)$
Modulus of Rupture (MOR) :	$MOR := 18\ \mathbf{MPa}$	$(18 - 30\ MPa)$
Ultimate Strain :	$\varepsilon_u := 0.003$	$(0.0005 - 0.008)$
Impact resistance :	$Ir := 20\ \frac{N \cdot mm}{mm^2}$	$\left(10 - 30\ N \cdot \frac{mm}{mm^2}\right)$
Modulüs of Elasticity :	$E := 12\ \frac{kN}{mm^2}$	$\left(10 - 20\ \frac{kN}{mm^2}\right)$
Density :	$\gamma := 2000\ \frac{kg}{m^3}$	$\left(1900 - 2200\ \frac{kg}{m^3}\right)$
Thermal expansion coefficient:	$\alpha T := 1.0\ .10^{-5}\ \frac{.1}{C}$	$\left(1.10^{-5} - 1.5 \cdot \frac{10^{-5}}{C}\right)$
Fire Rating according to DIN 4102 :	$A1 - A2$	
Shrinkage Value :	$\varepsilon_{cs} := 1.0 \cdot \frac{mm}{m}$	(1.0-2.0 mm/mm)
Swelling Value :	$K := 1.0 \cdot \frac{mm}{m}$	(0.5-1.0 mm/m)
Water absorption:	10	(8-12 %)
Water vapour diffusion :	$\mu := 50$	(50-200)

The standard method of application, used by the industry partner, starts with building a mould (materials and techniques varies based on the specific project) and the preparation of the mould's surface before the spraying application of the first layer. Here, the initial layer has a thickness of 2-3 mm., and this layer does not contain glass fibers in order to achieve a smooth finish. This first layer in direct contact with the mould forms the outer layer of the final product.

Subsequently, the spraying application of three consecutive layers of GRC, each with 3-4 mm thickness, is implemented. An analogue rolling process is necessary after the application of each layer to compress the deposited material for a homogeneous distribution. After the final rolling process, the curing time for the GRC changes between 24-48 hours.

The proposed production method of using the EPS blocks as positives required the GRC application sequence to be reversed as the last layer would form the final surface, hence resulting in the spraying of the non-fibred layer and subsequent rolling as the final process. At this stage, tests were made in collaboration with the industry partner before the workshop to understand how this reversed sequence of application affected both the construction process and the final design. Having the non-fibred layer applied last, with the aim to create a smoother finish, and the need for analogue rolling to compress the deposited material resulted in the effect of a heavily textured surface, which was then implemented as a design parameter. A further adjustment carried out was the refinement of the GRC mixture (Table 2) [9] in order to minimize the thickness of each layer to optimize the overall weight.

Table 2. Mixture ratios for Glass Reinforced Concrete (GRC).

Material	Weight (kg)	Percentage (%)
CEMENT CEM II 42,5R	45,00	36,87%
SILICA SAND	50,00	40,97%
WATER	16,00	13,11%
MINERAL ADDITIVE	5,00	4,10%
GLASS FIBER	4,27	3,50%
POLYMER	1,65	1,35%
PLASTICIZER	0,12	0,10%
TOTAL	122,04	100,00%

The outcomes of the tests (Fig. 11) defined constraints such as the minimum thickness needed to prevent breaks on the EPS after the application of GRC, surface properties and overhang limits to prevent drooping or unwanted accumulation of the material, the maximum degree of surface curvature and necessary gap distance in between modules considering the hand-reach for analogue application, the overall weight, and surface resolution. The limitations and potentials learned after the material tests were then integrated into the final fabrication process (Fig. 12).

Fig. 11. Initial material experimentation on a complex form with varying double curvature.

Fig. 12. The application of GRC on the final prototype.

5 Assembly Process

The production and assembly of the prototype required various tasks to be carried forward simultaneously. New working groups were formed by participants and led by tutors in order to complete the tasks related to fabrication and assembly. While each group worked on their tasks, attention was kept on coordinating and collaborating with other groups to avoid conflicts that could have arisen during the process.

5.1 Analogue Fabrication Setup for Component Fabrication

The first step of the fabrication process has comprised constructing a wooden jig to fix the EPS blocks in place to be cut by the robot. The model of the jig is implemented in the 3D environment so that the robot codes can be generated with the model of the cutting space in Grasshopper. Double-sided tapes were used to fix the blocks on the wooden jig rather than a mechanical system due to their sufficiency and were renewed for every 10 blocks. As the cut pieces were detached from the robot, they were tagged by their unit codes and ordered accordingly at the assembly area next to the robotic fabrication setting.

One of the key parameters in this process has been the cutting time of each component and to shorten the fabrication time consumed per block. The curved portion of the prototype requires tapering the original 330x330x330 mm blocks with 15-degree angles on a single side after the RHWC process. Hence, besides the unique cuts generated through RHWC, almost quarter of the components were required to be cut twice. A repetitive cut with a static angle with the industrial robot would be time consuming and contradict the versatility of an industrial robot arm. Therefore, a manual cutting jig was developed during the workshop with the participants to ensure precise tapering angles (Fig. 13). The jig aims to reduce the total cutting time by creating a parallel workflow with manual labor while removing the burden of the repetitive cutting action from the robot. The optimization of the RHWC process by adding a simultaneous and manual cutting process reduced the cutting time to roughly 4 minutes per component. This collaborative fabrication process between digital fabrication and analogue fabrication unfolded a seamless workflow.

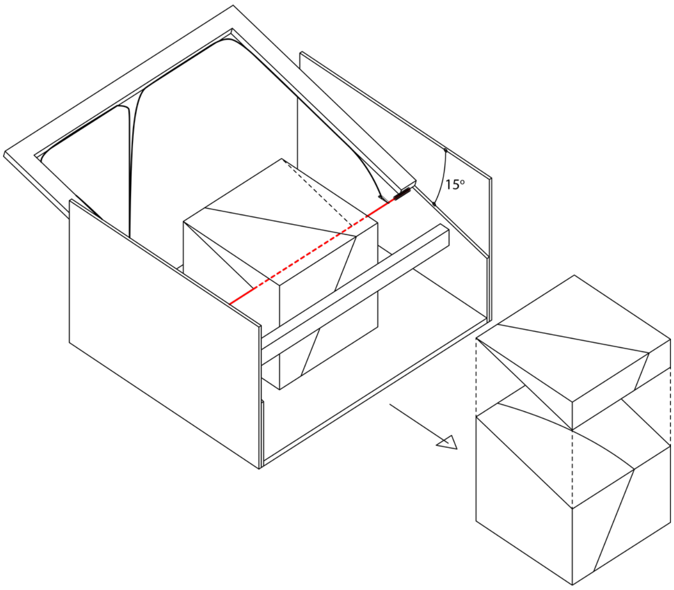


Fig. 13. Manual cutting jig.

5.2 Assembly Process and Workflow

The connection of the prototype to the ground and to the load bearing wall were crucial parts of the assembly process. The prototype's base was designed to sit on the gravel-filled border between the building pavement and the main pedestrian axis. The wall connection was designed so that the semi-vault would sit on an L-beam supported by 4 L-sections (Fig. 14).

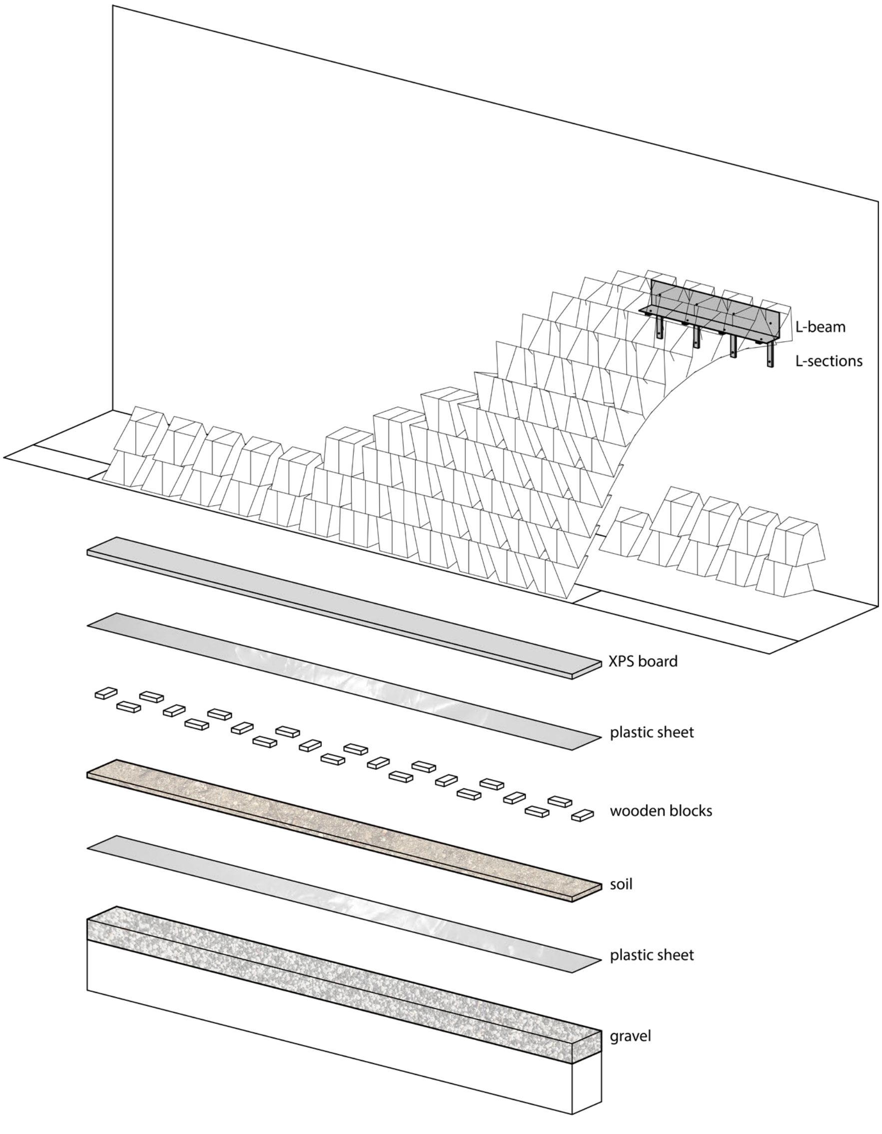


Fig. 14. Exploded perspective of the prototype's connection details.

Assembly process of the EPS form-works has been coordinated in three consecutive stages. The first stage included gluing two pieces that result from cutting a single block back to back. The second stage involved gluing newly formed pieces together as columns using unique spacers, whereby the curved and straight portions of the installation were brought together separately. Finally, all the columns were glued together on site (Fig. 15). Polyurethane-based adhesive and thin wooden dowels, aimed at holding the pieces together until the adhesive cured, were used in the gluing process. A one-to-one scale application template, demonstrating the column locations in plan, was laid out on the ground and straight columns were glued to the previously constructed base. Steel L-brackets were fixed at intervals between the pieces and the base so that the whole structure would not tip over when the curved portions were assembled. The most challenging part of the assembly was to put curved columns on top of the straight ones and the L-beam with the correct angles. The absence of a temporary scaffolding prolonged the assembly process. After the whole structure was completed, the EPS formwork was let to dry and cure for 10 hours before GRC spraying commenced.

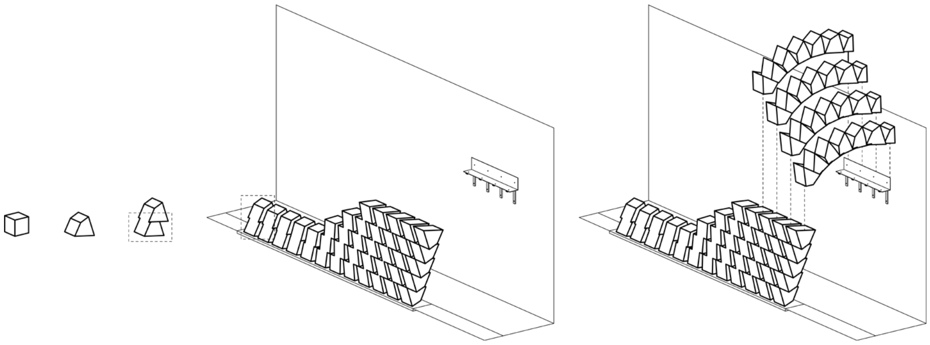


Fig. 15. Assembly process.

5.3 Application of Sprayed GRC on Form-Work

The following tasks are carried out with the GRC machine: The concrete mixture is prepared, long fiberglass threads are cut into small pieces and mixed with the concrete, and the final mixture is sprayed with a spray gun. The whole process needs to take place at the construction site; therefore, GRC machine was brought on site and set up so that it could be moved back and forth around the installation, facilitating easy access for the spray gun over the entire structure.

The spraying process was performed in three iterations (the mixture ratios for each layer can be observed under Section 4 - Material Technology). In the first and second iterations, the mixture contained fiberglass particles (hence GRC) and the entire structure was sprayed on. A roll press application after each round tightened the surface connection between EPS-GRC and subsequently GRC-GRC. The last iteration contained only a cement mixture without fiberglass for a smoother finish.

This layer was applied on the straight portions of the installation and only on the outer surface of the curved portions (Fig. 16).

Fig. 16. Application of GRC on stay-in-place form-work.

Lighting design of the installation was aimed to emphasize the plasticity and surface characteristics via light and shadow interplay during dark hours. An RGB LED strip along the L-beam and another one along the ground connection were installed (Fig. 17).

Fig. 17. Final prototype with lighting design.

6 Discussion

The driving ambition of this research project was the development of complex formwork generation with no material waste and concrete application via advanced computational and robotic methods. During research, a computational workflow for producing only positive modules as stay-in-place formwork elements aimed at various structural configurations was devised. This workflow was directly governed by the geometric rules of hot-wire cutting.

There is an underlying challenge in all complex three-dimensional assemblies of components, and that is the degree of spatial precision that needs to be achieved during the assembly process. As our computational tools advance towards greater accuracy, we need to be conscious of the tolerances that might arise due to local stresses or imprecision in component sizes. One method of overcoming this issue during the construction process would be to employ temporary scaffolding to verify the exact location of components and the angular variation between them. As the section of the designed vault is consistent throughout the structure, a CNC-milled scaffold, made of thin MDF or plywood, would be sufficient in maintaining the accuracy during the assembly process. The production of a scaffolding system may at first be regarded as contradictory with the initial ambition of generating a zero waste material fabrication and assembly system; however, parameters such as recyclability, installation time and precision should also serve as key parameters for the production sequence. Hence, further research can take into consideration the integration of a collaborative robotic fabrication process to aid with the assembly process for increased precision.

One of the key considerations throughout the various stages of the research has been the correlation of geometric complexity and fabrication time. Further research will address varying degrees of geometric complexity in relation to fabrication time with RHWC. This area will be investigated through various parameters, particularly the employment of two industrial robotic arms instead of one, as well as the re-evaluation of stationary versus moving elements during the robotic fabrication process. Moreover, further research will investigate methods of inducing variable thickness of the sprayed GRC during the construction phase in relation to the structural performance and load-bearing capacity of the global configuration.

The adoption of material and fabrication parameters coupled with the geometrical freedom and constraints of a selected research agenda has the potential to address multiple performance criteria embedded in the high level of complexity of design processes. The research presented in this paper addresses this objective through the careful correlation of data pertaining to GRC material properties, the integration of the geometrical principles of doubly-curved ruled surfaces with RHWC, and the introduction of an efficient fabrication process as design drivers.

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