Expanding the Material Possibilities of Lightweight Prefabrication in Concrete Through Robotic Hot-Wire Cutting

Form, Texture and Composition

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In recent years, digital fabrication technologies have enabled renewed explorations into traditional materials, with innovative results. This paper focuses on concrete and on the potentials of a specific technology: robotic hot-wire cutting for the production of expanded polystyrene (EPS) formwork. Academia and industry have explored this process recently but the number of works built with this technology is reduced and the general concrete prefabrication industry has been slow to adopt it. In this context, this paper analyzes the use of EPS in the production of concrete formwork by reviewing its application in contemporary examples. In order to develop a clear assessment of the possibilities of expanding prefabrication in concrete using robotic hot-wire cutting, this paper also documents a set of practical experiments developed in the laboratory, addressing three material challenges: form; texture and composition. This research involved the design, formwork production and casting of concrete elements to explore the limits and characterize the process of robotic hot-wire fabrication in the context of concrete prefabrication. By recognizing the different approaches present in contemporary examples and in the explored practical experiments, we point out the advantages and limitations of using hot-wire cutting, and develop the reasons behind its limited application in practice.

Keywords: *Digital Fabrication, Concrete, Hot-wire cutting, Prefabrication, Formwork*

INTRODUCTION

A case for concrete digital prefabrication

Concrete is largely regarded as the most consumed, man-made material today. Its availability, mechanical properties and ability to take on any shape desired has enabled its use for almost any kind of structure. For this reason, in 2013, 4 billion tons of cement were produced for an estimated consumption of over 33 billion tons of concrete, worldwide [1].

Concrete construction technologies are traditionally based on the repetitive, undifferentiated and labor-intensive fabrication of formwork elements, which correspond to a large part of the construction costs related to this material (Johnston 2008). This not only contributes to the general waste production and natural resource consumption of the concrete industry, but has also been a relevant limiting factor to the realization of complex shaped elements in concrete architecture.

The development of pre-fabrication in concrete, in the early 20th century, addressed the problem of formwork costs by applying the industrial principle of standardization to the production of concrete elements. By placing the fabrication in a controlled environment where variation is reduced and reusability is assured, it became possible to reduce costs and production times with the effect of further limiting formal possibilities. During this time, the austere aesthetic and rational logic of the modern movement found traction with the formal restraints and efficiency of prefabrication and by extension, standardized formwork. For this reason, although the plastic character of concrete was one of its main features, this was not apparent in most of the architectural practice for a large part of the last century.

In this background, the contemporary emergence of digital design and fabrication processes and its introduction in concrete construction represents one of the biggest prospects for renovation of our built environment. These processes present a particular opportunity to reconsider the sustainability of our construction technologies and their impact on the development of architectural aesthetics.

While there have been several successful results of the use of digital fabrication technologies for the production of cast in-situ concrete structures, the concept of mass customization that characterizes the emerging digital condition, suggests the prefabrication in concrete can be an exciting alternative. Furthermore, mass customization, driven by digital fabrication technologies, can be a solution to the problem of repetition inherent to pre-fabrication, while simultaneously maintaining all other aspects that make this technique desirable in concrete construction.

In the foreword of the 2011 Design Modelling Symposium Proceedings, the editors name one of the introductory chapters "Digital Fabrication means prefabrication" (Gengnagel et al. 2011), citing the cost, size and fragility of the necessary equipment. In the case of concrete construction almost all examples using digital fabrication hold this statement true to some extent. The usual products of digital fabrication for concrete (moulds) are prefabricated, but more often than not, used for on site monolithic casting of concrete. As such, the interesting notion of precisely fabricated and accurately assembled components that can be equated with the use of digital fabrication technologies in architecture is lost in the translation from process, to construction and architectural expression.

It is our understanding that there is a specific relation of complementarity between the digital design and fabrication technologies, and the prefabrication of concrete that should be further explored regarding its feasibility and architectural potential.

The present paper follows a previous research into the overall impact of digital fabrication technologies in concrete (Martins P. and Sousa JP 2014) and focuses on exploring robotic hot-wire cutting as an architecturally expressive solution to the production of formwork for concrete prefabrication.

BACKGROUND

Traditional approaches for complex concrete constructions

In order to develop a clear view of the problem of materializing complex shapes in concrete, it is relevant to consider the historical exceptions to the rationalized use of concrete described earlier. Relevant examples can thus be found in the design and construction of thin shells structures, pioneered through the works of architects and engineers such as Eduardo Torroja, Felix Candela, Pier Luigi Nervi and Heinz Isler. What makes theses constructions relevant in the scope of this research is their structural dependence on complex curved geometries, the material behavior of concrete and the construction techniques developed, which allowed for the creation of very large spans with very light concrete structures.

Traditional construction techniques employed in the production of such complex surfaces in concrete commonly used wood formworks produced from straight beams, fitted with bent wood boards, either interpolating or rationalizing a general curved surface or describing the actual surface in case of ruled surfaces. After metal reinforcement was placed, a high viscosity mix of concrete was poured and troweled into place, defining the finished concrete surface. Such was the case for the Palmira Chapel, designed by Felix Candela, and built in 1959, featuring a hyperbolic paraboloid shell with 4 centimeters of overall thickness (Basterra et al. 2001).

A substantial different technique was developed by Nervi, which used lightweight, prefabricated ferrocement components as lost formwork for concrete casting. The components were prefabricated on-site and assembled to define the casting surface, becoming embedded and part of the finished structure after a final layer of concrete was poured.

The method of prefabrication and assembly of components used by Nervi and defined by Iori and Poretti (2005) as "structural prefabrication" depended on the subdivision of the surface and overall structures into manageable components, which could be built simultaneously and assembled on-site. Because of time, economical and fabrication restrictions at the time, these components were limited in variability and complexity (Iori and Poretti 2005).

While both methods can be regarded as labour intensive, it is clear that in the case of the works of Nervi, lightweight prefabrication enabled a considerable reduction in material consumption, waste production and construction time, with the clear drawback of geometrical repetition, limiting the possible design space.

The traditional techniques described in the case of the Palmira chapel are still much in use today and in some cases, have been integrated with digital fabrication technologies. Examples can be found in the construction of the Mercedes Benz Museum and the Rolex Learning Center [2]. Nevertheless, the lessons of Nervi, in time and material economy, as well as in the use of lightweight prefabricated components in large, complex assemblies are still relevant today, more so, with the emergent possibilities of digital fabrication and their applicability for greater diversity of form, precision and efficiency.

EPS moulds for prefabricated and in-situ concrete in current practice.

One of the first cases for the integration of digital fabrication technologies in concrete construction can be found in the pioneering works of Frank Gehry. The Neue Zollhof building, in Dusseldorf, Germany, was built in 1999 and featured an innovative solution for the problem of formwork production for freeform concrete surfaces, through the use of CNC milled moulds for concrete casting. Although it was also used for in-situ casting, of particular interest was the development of this process for the production of large prefabricated wall segments with ruled geometry.

At the time, a significant time reduction of the milling processes was needed to achieve the economical viability necessary for construction industry. This was accomplished through the high speed, rough milling (5cm tool bit) of expanded polystyrene (EPS) blocks (Shelden 2002). The wall components were cast off-site into open, one-sided moulds, with standard steel reinforcement. One face was cast against the mould and the other troweled into shape, causing the transference of large tool marks from the milled formwork to the exterior concrete surface.

This process resulted in an overall low quality of the surface of the concrete that was subsequently finished with other materials. However, it is possible to imagine the difficulties of using other traditional formwork systems for the construction of the desired geometry, despite of being, predominantly composed of ruled surfaces.

CNC milled EPS formwork was similarly used for the in the construction of the Spencer Dock Bridge, by Amanda Levete Architects, built in Dublin, in 2008, although in this case, the majority of the concrete was cast in-situ, creating a monolithic structure.

For the design of the formwork, the double curved surface of the underside of the bridge was subdivided into a rectangular grid, taking into consideration standard sizes of EPS blocks. The formwork material was milled with a 5-Axis router in consecutive passes with increasing resolution, resulting in a smooth finish of the surfaces as compared with the previous example.

In order to ensure a correct demoulding and an acceptable finish for the apparent concrete surfaces, further work was necessary on the formwork with the addition of multiple sprayed impermeabilization coatings and sanding. The EPS moulds were then assembled on a plywood and steel falsework, their connection joints were sealed and false rebates created with a desired geometry

At the same time, the more complex lateral elements (double curved, with non-parallel opposing faces and connection joints) were precast off-site, using EPS milled moulds with epoxy and fiberglass coatings for reusability. (Dempsey 2008).

The case of the Spencer Dock Bridge demonstrates the feasibility of building large-scale structures with this formwork system but also the difficulty in obtaining high quality finishes, without incurring in substantial labour and production time increases.

In the time span between both examples, CNC milling and EPS formwork systems have been incorporated into the construction industry through formwork specialized companies which offer it as part of integrated systems for in-situ concrete formwork (e.g. PERI)[3] and other specialized large scale CAM (computer assisted manufacturing) industries [4].

Nonetheless, milling time in the production of EPS formwork for smooth, apparent finishes is currently measured in hours for each piece of formwork, corresponding to months for full structures. Therefore, fabrication time is a large factor in the CNC milling of EPS formwork, greatly increasing costs and relegating the use of complex freeform in concrete to exceptional buildings.

It is therefore relevant to find other, more economically viable processes that can democratize the use of complex forms in concrete. We believe that although it is an inherently limited process, Robotic Hot-wire Cutting (RHWC) can bridge this gap to become not only a viable technology, but also capable of enabling future explorations into the architectural potentials of concrete.

MATERIAL EXPERIMENTS

Precast MSE Panels

In order to assess the technical and architectural potential of RHWC, we developed a set of practical experiments, addressing specific material challenges for prefabricated concrete elements.

This work builds upon previous experiments with RHWC such as the RDM Vault (Matthias Rippmann and Silvan Oesterle), the Automated Foam Dome (Thibault Schwartz), the Light-Vault (Yuan et al. 2014), or the Opticut prototype (Feringa and Søndergaard 2014) by shifting focus from design to the particular material implications of concrete cast with hot-wire cut EPS formwork.

For these experiments, three material challenges were identified, taking into consideration their relevance to concrete and RHWC and each was addressed through the production of one or more prefabricated components:

Figure 1
MSE wall construction with precast concrete panels. Specific panel geometry differs by manufacturer, situation and design.

1. Double-curved components (form);
2. Textured components (texture);
3. Variable materiality components (composition).

The first challenge addressed the overall problem of complex curved geometries, which in the case of RHWC, are limited to ruled surfaces, with the objective of determining the geometric constraints and limits of the technology in the production of formwork for concrete.

The second is focused in revisiting past examples of textured concrete and exploring the specific architectural possibilities for textural effects emerging from the hot-wire cutting process.

The third challenge is aligned with current interests in non-homogenous materials. It addresses the concept of a variable materiality in concrete elements, by which different zones of a single element can have different material performances, either functional or aesthetic, by using different concrete mixes with sequential castings.

The exploration into three different problems allowed us to stress different aspects of the fabrication technology to ascertain its overall relevance in diverse prefabrication scenarios.

Component design and robotic simulation

The overall design concept used for the experiments was based on the geometry of precast panels for mechanically stabilized earth (MSE) (Figure 1). MSE is a technology used for the construction of retaining walls capable of sustaining heavy loads, generally used in highways or bridges. A distinctive characteristic of this construction technique is the use of prefabricated modular concrete panels as exterior facing for the system. These are commonly quadrilateral or hexagonal, with or without interlocking joints,forming continuous, planar surfaces.

As it was not the objective to devise a new panel system for MSE, we used the geometric and modular concept of these panels, without taking into consideration their specific technical function.

The geometry of the 3 panels was modeled in Rhinoceros and achieved by vertically projecting the standard panel design onto two (or three, in the case of the third panel) parallel double curved, ruled surfaces. In order to further stress the geometric constraints for the fabrication, we ensured that the edges of the panels were not parallel to the surface ruling lines, creating 4 curved edges in each panel.

The bounding box dimensions for the three fabricated panels were 308x385x385mm, 308x385x445mm, 220x555x390mm and the overall panel thickness was 40mm, defined in accordance with the available EPS blocks (1000x500x350mm) and also taking into consideration a necessary surrounding margin of 50mm to withstand the pressure of the concrete pour. The components were orientated in the stock material regarding these needs and the objective of reducing material waste.

The robotic simulation and toolpath generation for the hot wire cutting of the EPS moulds was done in the Grasshopper plugin for Rhinoceros, using the KUKAprc software, developed by the Association for Robots in Architecture.

As stated before, the possible geometrical space of this technology is limited to ruled surfaces. These are determined by the movement of the hot-wire, akin to the concept of a line (generatrix or ruling) moving through space, along a curve (directrix). Using similar methods to those mentioned in previous works in RHWC, the movement of the hot-wire was programmed in the KUKAprc software by extracting two points from each ruling of the surface, plus a third outside point to respectively position the hot-wire line correctly in space and define the angle of the hot-wire bow in relation to the cut, throughout the entire sweep. The geometric design of the textured surfaces of panel 3 was obtained directly in the Grasshopper and KUKAprc definition, by alternately shifting in the y-axis, the reference points along one of the directrix curves that describe the original ruled surfaces.

Formwork design and Fabrication Process

Because of the proposed geometric complexity, we decided to use closed moulds for all of the castings. The moulds for panels 1 and 2 were designed with three separate parts: one for each front and back facing and one internal piece defining the negative space for the concrete casting. The third panel was designed with an intermediate subdivision that enabled the two castings required.

The RHWC setup at the DFL laboratory consists of a stationary Kuka KR 120 R2700 industrial robot, mounted with a 100 cm wide and 0,25mm thick hot-wire end-effector (Figure 2).

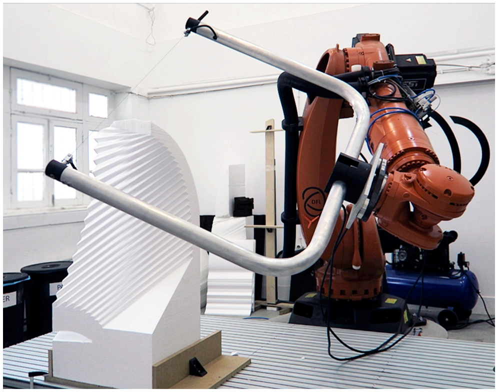


Figure 2
Robotic hot-wire setup and fabrication process (panel 2, beggining of sweep 3)

Using this setup, the cutting routines consisted of 4 cuts for panels 1 and 2 and 5 cuts for panel 3. The first cuts carved the front and back general ruled surfaces from the EPS stock block (sweep 1 and 2), followed by the cutting of the central void in the remaining piece (sweep 3). The entrance and exit trajectory for this cut became the concrete pouring channel. After re-assembling the previously cut parts, a final horizontal cut (sweep 4) trimmed and separated all the parts of the mould. (Figure 3)

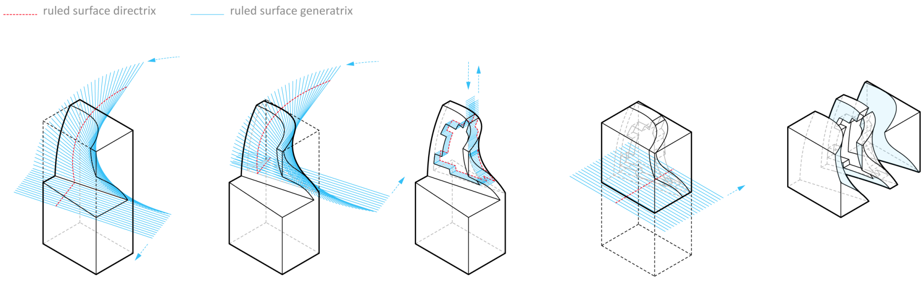
The fabrication process was successful, with a few practical problems, related to the hot-wire calibration. With this technology, one of the most critical parameters is the relation between cutting speed and temperature. A base line for this relation was established through trial and error after initial runs. In order to increase the accuracy of the cutting process, a relatively low overall speed (10cm/s) and temperature setting was used. Furthermore, because the wire temperature was not included in the KUKAprc definition, it was closely monitored in the final cuts, aiming at achieving a constant cut, despite of the diversity of cutting situations and their respective speeds.

Concrete Mix and Casting process

Regarding the materialization of complex geometries in concrete, one critical aspect of making these processes viable, which is not frequently mentioned, is the design of the concrete mix. The same reasons concerning geometric complexity that frequently justify the use of digital fabrication technologies for concrete production, often require custom concrete compositions to become viable. In the case of this experiment, the difficult accessibility of the moulds and the problems that would arise from using traditional metal reinforcement were taken into consideration to define a mix of self-compacting white concrete, reinforced with polypropylene fibres. For the third panel, a similar mix was used, with grey portland cement and fly ashes.

Although the material variability in this exercise was purely aesthetic, other performative changes could be explored in the same manner. For example,

Figure 3
Robotic cutting routine (panel 1).



changes in weight, mechanical resistance, thermal or acoustical behaviour could be achieved with the introduction of different material elements in the concrete matrix. (Table 1)

Table 1
Concrete composition for mix 1 and 2

Mix 1 - Materials	Quantities (kg/m3)
C ement (CEM II/B -L 32,5 R (B r))	630,6
Limestone filler	283,8
Fine sand	622,7
Medium Sand	622,7
Water	198,6
Super plasticizer (Viscocrete 3005)	6,0
Fibres - Meyco Fib SP 630 (BASF)	6 ,0

Mix 2 - Materials	Quantities (kg/m3)
Cement (CEM I 42,5 R)	630,6
Fly ashes	244,4
Fine Sand	622,7
Medium Sand	622,7
Water	198,6
Super plasticizer (Viscocrete 3006)	16,0
Fibres Meyco Fib SP 630 (BASF)	6,0

For the casting process, the moulds were treated with a demoulding agent and a lateral bracing was applied to ensure no buckling would occur. A conscious decision was made to avoid the use of time-consuming coating applications, as was observed in earlier examples. It was our understanding that it would defeat the purpose of developing a time efficient process for formwork creation. Furthermore, it was an opportunity to study the textural quality of concrete, emerging from this process.

Panels 1 and 2 were cast and set for 60 hours, before demoulding. In the case of panel 3, we followed an iterative process for the cast of the two layers of concrete. An initial cast of the first layer, followed by a partial demoulding after 24 hours, opening of the second interior void and re bracing the mould. The casting of the second layer with the different mix of concrete followed and the final demoulding was done after 72 hours (Figure 4).

The casting phase revealed that the precision of the RHWC process as well as the fact that all parts of the moulds were cut from a single block (which would not be the case for milling) had a large impact on the accuracy, correct fit and ease of assembly of the moulds (Figure 5).

DISCUSSION

During the execution of the described experiments, several constraints and characteristics of the process of Robotic hot-wire fabrication became apparent that should be taken into consideration for future research.

Geometrical constraints. One major geometrical constraint of this technology in surface description, especially when compared with the established freedom of other subtractive processes, is its restriction to the creation of ruled surfaces in the movement of the hot-wire through space. This unavoidable fact is

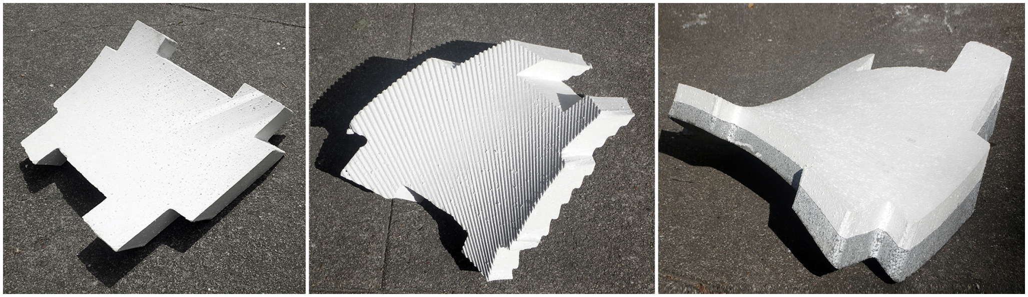


Figure 4
Finished concrete panels: Standard panel (left), textured panel (center) and variable materiality panel (right)

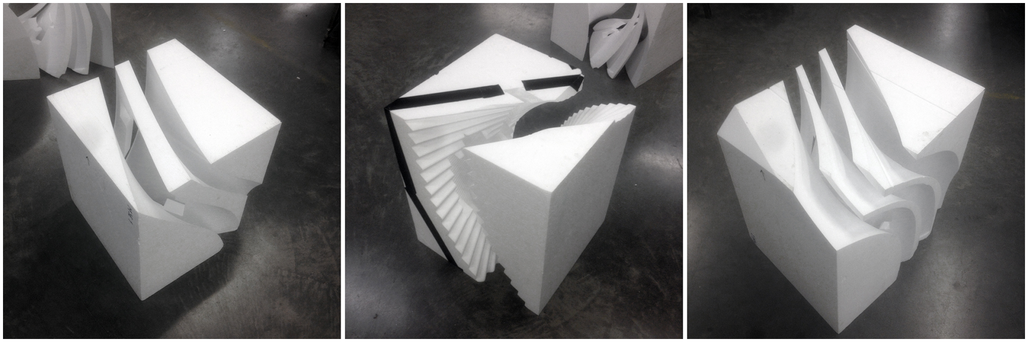


Figure 5
Fabricated EPS formwork assemblies before closing and bracing (panels 1, 2 and 3)

the clearest limitation of RHWC. On the other hand, ruled surfaces encompass a great diversity of forms, which have a clear historical relation with architecture as discussed in the previous examples. Furthermore, the increasing tendency for freeform buildings in concrete has prompted developments into rationalization strategies for double curved surfaces, using strips of ruled surfaces, with a very high accuracy, greatly increasing the relevance for these geometries (Flory and Pottmann 2010).

Size restrictions. Taking into consideration that the size of uncut EPS blocks does not prevent the scaling of this technology to construction-scale elements, the major size constraint is clearly in the available length of the hot-wire. Nevertheless, a design problem was detected that further constrained the size of components. Because the borders of the proposed elements were not parallel with the ruling lines, the hot-wire described a diagonal movement through the blocks. This meant that the seemingly large length of the 100 centimetre wire was used in all its extension for the production of the otherwise relatively small components.

Precision. The gap left in the hot-wire cutting path that results from the melting of the EPS foam, is a function of the cutting speed and the wire temperature. For a set speed, an increase in temperature represents an increase in the cut width and for a set temperature, a decrease in cutting speed also represents an increase in cutting width. For this reason, a ruled geometry that implies a stationary point in space within the movement of the ruling line (ex. the vertex of a conic surface) results in an unwanted increased cutting gap representing a local loss of precision. These situations were mitigated by reducing the temperature below what would be overall necessary for the surface, resulting in an increased cutting time.

A similar problem was encountered when cutting surfaces at sharp angles with other cut surfaces. Because of the low thickness of the foam in these sections, it melted much easier, resulting in uneven edges, which were also compensated with low cutting temperatures and speeds.

Optimization. A usual solution to the problem of optimizing material usage when producing multiple components from large stock material, such as EPS blocks, is packing the desired elements using nesting techniques. In the case of the production of formwork components for concrete casting, depending on the selected casting process, we found that a balance must be struck with regard to the relevance of determining horizontal sections for concrete pouring. Although the concept of closed moulds was successful in reproducing the desired panel geometry, we concluded that the casting process would have been more efficient, with no loss of precision, if the moulds had featured one open side for the concrete pour.

Speed. Considering the conservative cutting speed used in the experiments (10cm/s), the four cuts necessary for each complete formwork took on average approximately 7 minutes. According to our early experiments in CNC milling and in line with other literature (Feringa and Søndergaard 2014), this represents a 25 fold decrease in production time directly related to the robotic fabrication process. During production, no significant practical aspects were found that reduced this difference.

Surface Quality. One of the most relevant issues regarding the acceptance of these techniques in the concrete industry is the perceived poor surface quality of the finished elements. In the case of this experiment, we found an obvious loss of smoothness in the finished surface when compared to concrete set with traditional steel and plywood formwork, that can be traced to the porosity of the untreated EPS foam. Nevertheless, most notably in the case of panels 1 and 3, we found that the resulting surface had not only an acceptable quality (Figure 6), when compared with wood board formwork, but also revealed a similarly interesting textural pattern of the hot-wire rulings that was further emphasized in the design of panel 2. We concluded that the process of RHWC, although optimized for speed of production can also yield positive results, worth of architectural exploration.

Figure 6
Surface quality for standard EPS formwork with demoulding agent.

CONCLUSIONS

In light of the practical experiments conducted for this research, the advantages of the robotic hot-wire cutting process are clear. The drastic decrease in fabrication times and the material economy in comparison to CNC milling make this technology a viable solution for the production of concrete formwork. While its geometrical constraint is a significant issue, we believe that the use of ruled surfaces is still relevant today as architectural expression and as a rationalization solution for general double curvature surfaces.

From our comparison of production technologies and formwork systems, we conclude that the reasons for the slow adoption of robotic hot-wire cutting as a solution for the production of concrete architecture are two-fold: the reality of the construction industry and the interest of designers. When comparing CNC milling and RHWC, although the latter is

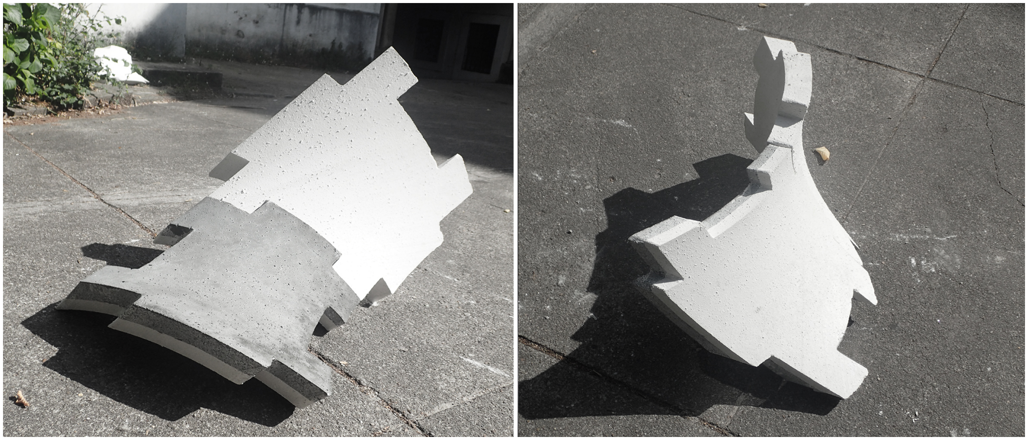


Figure 7
Prefabricated panel assembly (panels 1 and 3)

in most cases much more geometrically constrained, we believe that this is not reason enough for its inadequacy.

One possible cause can be found in the fact that CNC milling processes have been used for a longer time in manufacturing industries before being adopted by architecture and the construction industry. As such, tools, software and the knowledge of their application is much more widespread and its integration and understanding in the architectural environment more profound.

From the perspective of the designer, facing the current alternative methods of formwork production, the eventual design rationalization of a general curved surface to ruled surfaces poses a minor problem when compared to the issue of smooth surface quality, which seems to be the standard goal in the architectural practice today. When considering the general use of EPS and digital fabrication technologies for formwork production, the limiting factors are clearly the material conditions of EPS and not the technology employed. As such, other paths should be explored in the future, that assume these limitations and explore different textural qualities for concrete, while maintaining the advantages of the digital fabrication workflow.

Finally, when considering the relation between technology, materials and architectural expression, we found that in the explored case of concrete there was an interesting emergent architectural vocabulary that linked the prefabricated and assembled components to the fabrication technology. This visual and conceptual link created a specific tectonic quality (figure 7) that we intend to further explore in future experiments with prefabrication in concrete.

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