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An industrial application of Robotic Hot-Wire Cutting in concrete construction: Geometric, technologic and material implications

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Abstract. In recent years, digitally driven concrete fabrication has focused on traditional mold-making with 3D milling and advancements in 3D Construction Printing (3DCP). Both methods face challenges in efficiency, sustainability, and practical application. In this context, Robotic Hot-Wire Cutting (RHWC) has emerged as a promising alternative for concrete formwork, offering potential cost and sustainability benefits, though its use remains limited. This paper presents an industrial application of RHWC in constructing a geometrically complex canopy—the port-cochère—at the W Algarve hotel in Portugal. It details the design-to-production workflow for Glass-Fiber Reinforced Concrete (GRC) molds, addressing construction challenges and showcasing RHWC's potential to support complex architectural designs. Developed by a team connected to the DFL (CEAU/FAUP), the project exemplifies successful technology transfer from academia to industry.

Keywords: Digital fabrication, Robotic hot-wire cutting, Ruled geometry, Concrete architecture, Robotics

1 Introduction

The relevance of concrete as a construction material today is defined on multiple levels in terms of its general use in our industrialized society and as a vehicle of architectural expression. Concrete is one of the most ubiquitous materials in construction, dominating the human-built environment. Successive EU reports highlight the steady increase in concrete usage, driven by cement production, from the early 20th century to the present, with no signs of slowing.

In recent decades, however, there has been a growing awareness of its environmental impact, prompting significant efforts to reassess all aspects of its use in architecture—from material composition to fabrication processes and optimized design strategies. Particularly relevant is the shift towards lightweight prefabrication in concrete, aimed at reducing the environmental footprint of concrete construction systems through material optimization (Sah, 2024).

Over the past 25 years, digital concrete fabrication has advanced significantly, offering a range of tools and techniques for architectural applications. These methods encompass subtractive, formative, and additive approaches for two primary purposes: the production of formwork or molds for both precast and in-situ concrete construction, and the direct digital production of concrete elements. In the first case, more established processes like 3D milling for concrete mold-making are prominent, while in the second, emerging solutions such as 3D construction printing (3DCP) are gaining traction. Extensive literature exists on these and other digital fabrication techniques for concrete architecture (Carvalho & Sousa, 2014; Paolini et al., 2019).

Among various digital fabrication processes, Robotic Hot-Wire Cutting (RHWC) emerged in the early 2010s by integrating robotic systems with hot-wire cutting technologies. This innovation enabled the rapid cutting of large volumes of soft materials, such as EPS, for producing molds for concrete. The architectural potential of RHWC was explored in several pioneering projects by Jelle Feringa, Wes McGee, and Asbjørn Søndergaard (McGee et al., 2013). Since 2012, the Danish company Odico has been a leader in industrial applications of RHWC for architectural projects, including the Kirk Kapital Building, completed in 2018, which extensively utilized RHWC for both monolithic and precast elements (Søndergaard & Feringa, 2017).

While early explorations of RHWC concentrated on its geometric potential, most existing literature—apart from a few exceptions—remains focused on its application in academic or experimental prototypes. Although these studies are valuable, they often emphasize design or technological aspects, overlooking essential material-related challenges, practical implementation issues, and real-world validation (Feringa & Søndergaard, 2014; Søndergaard et al., 2016; Søndergaard et al., 2019).

To address these challenges and clearly assess RHWC's current capabilities, this paper presents a real-world case study of its practical application and industrial integration. Building on previous academic research by the authors, which included the production of the CorkCrete Arch prototype (Figure 1) (Sousa & Martins, 2016) that served as an early validation of the approach, the work introduced in this paper represents a significant advancement. In collaboration with the construction company Mota-Engil, the project utilized RHWC as the primary method for producing a large, double-curved canopy structure for the entrance (port-cochère) of the W Algarve hotel in southern Portugal. To demonstrate the architectural and industrial potential of this strategy and validate it in a real-world context, this paper examines the

specific design-to-production workflow, the procedural challenges encountered, and the final outcomes.



Figure 1. Previous research conducted by the authors involved the construction of the CorkCrete Arch prototype, which featured a combination of cork and GFRC panels, which derived from RHWC produced molds. Source: Sousa & Martins, 2016.

2 Methodology

2.1 Robotic Hot-Wire Cutting (RHWC)

Robotic Hot-Wire Cutting (RHWC) is a digital fabrication technique that combines a multi-axis robotic arm with a linear hot-wire end-effector. With this setup, a robot can perform precise 3D cutting operations on large volumes of foam-like materials, such as expanded polystyrene (EPS). In concrete construction, RHWC is employed for subtractive fabrication of formwork systems or molds, applicable to both in-situ construction and the prefabrication of finished components. Several key features define RHWC processes, which served as a foundation for developing the project presented in this paper. These key features can be outlined as follows:

- geometry
- material optimization
- speed
- finishing quality.

Regarding geometry, the cutting surfaces of RHWC are defined by the movement of a line (the cutting wire) through space. One of the primary characteristics of RHWC is its limitation to ruled surfaces, as the wire's linear motion constrains the cutting path. This constraint is further influenced by other aspects of the robotic setup, such as spatial reach, tool geometry, and stock material geometry.

Regarding materials, RHWC is typically employed with soft foam-like substances, such as high-density polystyrene (EPS) foam blocks. Unlike other subtractive processes like CNC milling, the 3D cutting logic of RHWC does not involve the direct destruction of stock material. As a result, RHWC is a more material-efficient process, enabling the creation of two functional parts from a single subtractive operation.

Regarding speed, the combination of EPS stock material and the linear cutting action of the heated wire makes RHWC a swift process, measured in seconds per square meter of the finished surface. When compared to traditional CNC milling performing similar tasks, RHWC demonstrates significantly higher time, and cost efficiency, making it one of its key advantages (Martins et al., 2015).

Finally, the finishing quality in RHWC processes depends on the specific application. If cutting speed is controlled smoothly, the surface finish can be more consistent and smoother than that achieved through CNC milling. However, for applications where concrete is the final material, achieving a pristine surface finish may require additional techniques to mask the original EPS texture in the final pieces. This was the case in the project presented in this paper, and a specific strategy to address this requirement will be discussed in the following sections.

2.2 The porte-cochère structure

The W Algarve, a luxury hotel from the international W Hotels chain, opened in 2020 in Galé, Algarve. Designed by Divercity Architects, the project posed several formal and structural challenges, with the porte-cochère at the entrance being particularly complex. Intended to be built with Glass-Fiber Reinforced Concrete (GFRC) over a metal substructure, the construction company required customized, precise molds for casting the final components, necessitating a digital fabrication process. This became an opportunity for technology transfer from the University. José Pedro Sousa, coordinator of the Digital Fabrication Lab (DFL) at the Faculty of Architecture, University of Porto (FAUP), assembled and led a team of recent graduates and collaborators -João Carvalho, Rafael Santos, and Nohelia Gonzalez- who founded the startup WAA (We Are Architects) to devise and implement a digital production process for this project.

The project began with a careful analysis of the structure's geometry and its subdivision into discrete components. Noticing the ruled-surface nature of the design, it became evident that RHWC could be employed, building on prior experiments at the DFL, such as the Corkcrete Arch project (Sousa & Martins, 2016). However, this initial assumption needed to be tested against other mold production methods, such as 5-axis CNC milling of foam blocks. Various subdivision strategies were explored to break down the continuous 3D model into individual parts, enabling an evaluation of the efficiency and cost of each

method. As architects, we paid close attention to this stereotomic process, as the subdivision directly influenced the aesthetics of the structure (Figure 2).

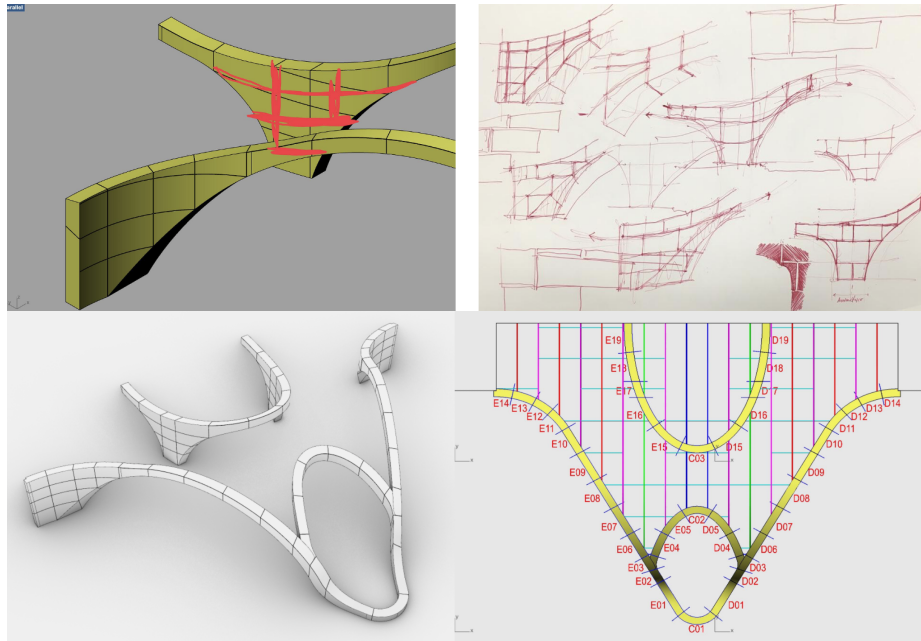


Figure 2. 3D Model of the porte-cochère structure and geometric subdivision studies. Source: authors and Mota Engil.

Despite clear cost and material advantages, RHWC presented a significant risk, as it had not been tested at this scale before. However, trusting in the strong collaboration between the project partners -who were also geographically close- it was decided to embrace the risk and move forward with RHWC as the solution.

2.3 Design Analysis and Mold Design

The porte-cochère structure involved the production of 93 different curved elements of two types:

- Type A: 52 "panel-type" elements that cover the structure where it connects to the ground next to the existing building.
- Type B: 41 volumetric and hollow elements that define the flying part of the structure. With an approximate 50x50 cm square section, they had to be produced in two parts: a U-shaped section and a flat cap.

The ruled-surface geometry of the elements is complex. While all lateral and contact faces remain vertical, the shape curves in both plan and elevation (Figure 3). This complexity demanded a significant volume of stock material to produce the molds, especially for the type B elements. Furthermore, despite the overall bilateral symmetry of the structure, each mold for the GFRC parts had to be uniquely fabricated.

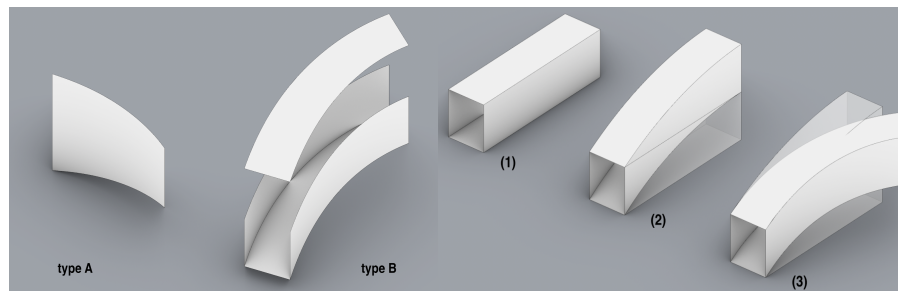


Figure 3. Type of panels - A and B (left). Illustration of the curved geometry of the structure's ruled surfaces (right). Source: authors.

The mold design followed the RHWC parameters outlined in section 2.1. To define the curved geometry, multiple EPS stock blocks were cut to create the negative forms for producing the GFRC components via material projection. For the type B parts, U-shaped molds were assembled from at least three EPS elements per part. In total, including the caps, over 400 RHWC operations were required to produce the EPS molds for all 93 elements.

In this project, it was crucial to prevent the EPS texture from being visible on the final parts. To achieve this, the interior surfaces of the foam molds were covered with 1mm thick thermolaminated panels. These panels were CNC cut according to the digital model geometry, then bent and attached to the EPS molds. Designing and fabricating the panels was challenging, as the lateral sides were vertical (flat) developable surfaces, but the top (cap) and bottom surfaces were non-developable (twisted) ruled surfaces. This required precise geometric subdivision of the sheets to conform to the curved EPS parts. The digital production process, therefore, involved a large-scale, multi-material, and multi-process mass-customization approach for mold production.

2.4 Robotic Setup and Tool

To manage the scale of this project, a dedicated robotic cell was installed at the Mota Engil facilities in Estarreja, featuring a Kuka KR 240-2 industrial robot. In parallel, a custom RHWC tool, measuring 1500mm in length and 1300mm in depth, was developed to accommodate the size of the structural elements. Given its large dimensions, ensuring stability was a critical challenge, as any instability could compromise fabrication precision. The tool's development was

thus informed by a series of design-to-fabrication experiments, which were evaluated through laser scanning to maintain safe tolerances (Figure 4).

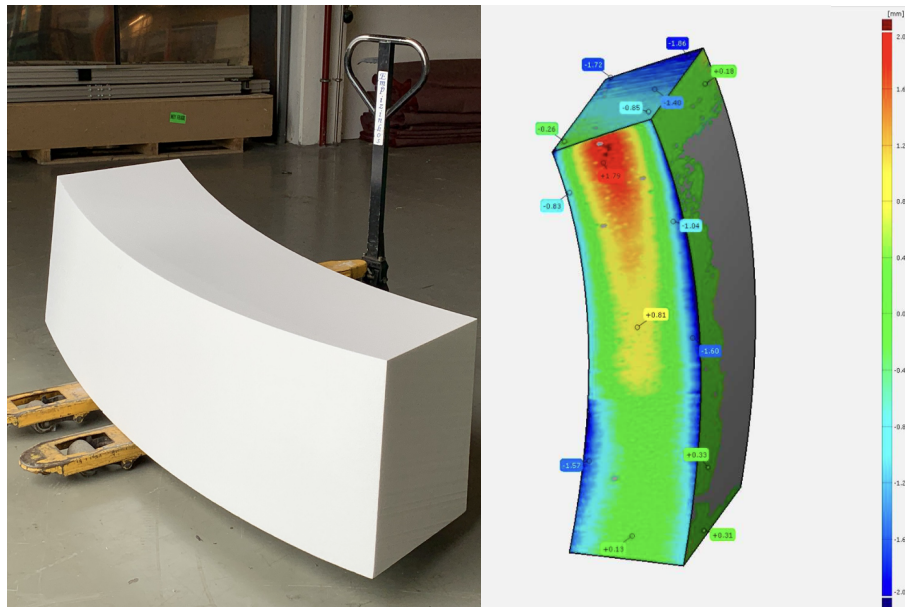


Figure 4. Sample element used to test the accuracy of the RHWC tool at a 1:1 scale through laser scanning. Source: Authors.

3 Results

The fabrication process began in early 2020. Due to COVID-19 restrictions, the production spanned approximately 16 months. The EPS blocks were cut in the factory using the Kuka|prc plugin for Grasshopper, which programmed the robot's spatial movements (Figure 5). By integrating fabrication experience with an analysis of each element's geometry, toolpaths with varying accelerations and speeds were developed to minimize EPS melting and ensure sharp, precise edges.



Figure 5. Robotic programming (left) and fabrication (right). Source: authors.

The finished EPS mold parts were assembled in the factory and completed by attaching CNC-cut termolaminated sheets. The positive EPS volumes, resulting from slicing the stock material, were used as packing around the completed molds, providing protection during shipping to the precast factory. The mold production was scheduled and delivered in phases, allowing the precast factory to begin producing GFRC parts while other molds were still being robotically fabricated (Figure 6).



Figure 6. Cut molds before and after thermolaminated sheet placement and packaged transport. Source: authors.

During this process, the metal structure that would support the GFRC parts was being installed on-site. Unexpected external factors led to deviations between the digital model and the actual structure, which were detected, confirmed, and documented through laser scanning. As a result, the production of the Y-shaped parts was delayed to accommodate these deviations. By scanning the gaps between the installed structural elements, the digital model for these final pieces was updated to match the new on-site conditions (Figure 7). Subsequent molds were then produced using RHWC with this revised digital information. The W Algarve hotel and its porte-cochère officially opened to the public in May 2022 (Figure 8).

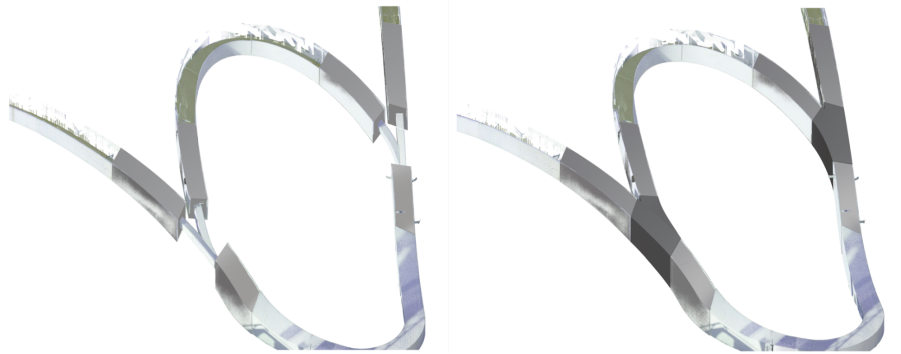


Figure 7. Digital scan of the existing structure represented as a point cloud model (left). Verifying the accuracy of the updated Y-shaped element model by overlaying it onto the point cloud (right). Source: Authors and Mota Engil



Figure 8. Photo of the complete porte-cochère of the W Algarve hotel featuring the robotically fabricated GRC components. Source: W Hotel Algarve

4 Discussion

The pioneering use of Robotic Hot-Wire Cutting (RHWC) in the porte-cochère of the W Hotel highlights its transformative potential in architectural mold production. The project's complex ruled surfaces were ideally suited to RHWC, showcasing the technology's ability to handle intricate designs with high precision. However, the process also exposed areas for improvement, particularly related to heat-induced wire relaxation and surface melting, which led to minor tolerances. Future advancements, such as the integration of abrasive cutting techniques, could mitigate these issues and further enhance the precision of RHWC.

In the broader context of emerging 3DCP technologies, RHWC offers distinct advantages, particularly in mold production, surface quality, and integration with existing workflows for ruled geometries. But RHWC and 3DCP can also complement each other - RHWC can fabricate molds for complex, non-planar 3D-printed concrete structures. While 3DCP revolutionizes the creation of concrete components, RHWC remains a highly effective technology for applications where mold-making and material efficiency are essential. The choice between these technologies should be guided by the project's specific requirements, including geometry, scale, cost, and production speed.

A final note to emphasize the significance of this experience as a prime example of successful technology transfer. It highlights the critical role of bridging the knowledge developed within academic institutions with its practical application in the industry. Fostering these connections is key to address contemporary challenges and shaping the future of both fields.

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