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# Segmental Ceramic Hollow Structures: Prefabricated posttensioned columns for ecological urban infrastructures.

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## Abstract

This paper presents the structural concepts and manufacturing methods implemented to produce segmental ceramic hollow columns for the design and construction of ecological urban infrastructures. The research objective is to harness the potential offered by ceramic materials and robotic manufacturing methods to produce hollow building components that combine structural and ecological functions endowed with elegant aesthetics.

The proposal takes reference from the work developed in the 1960's by the Spanish architect Miguel Fisac in collaboration with the civil engineer Ricardo Barredo. Together they invented and patented a series of posttensioned hollow concrete beams inspired by the morphology of animal bones. The resulting sectional beams, so-called "bones" by Fisac, integrated structural requirements with functional aspects such as water collection, thermal isolation, or solar protection. Following this conceptual approach, the proposed structural system is based on segmental posttensioned columns composed of hollow ceramic components. These components are produced by the combination of conventional extrusion manufacturing processes and subtractive manufacturing methods harnessing the potential offered by robotic technologies to generate non-standard hollow structures that incorporate ecological functions. In this regard, the proposed structural application works both as a column and a water collector integrating aspects of climatic control and water storage.

**Keywords**: conceptual design, structural design, ceramic structures, hollow structures, posttensioned structures, ecological building infrastructures, subtractive manufacturing methods, robotic manufacturing.

## 1. Introduction

Within the Engineering domain, hollow structures emerge as a consequence of optimizing load-bearing components to remove less effective material in order to reduce weight and cost. This operation generates, in turn, lighter and more efficient structures. This position was effectively described by the structural engineer Pierluigi Nervi as "the method of bringing dead and live loads down to the foundations with the minimum use of materials" (Billington [1]).

Similarly, the French engineer Robert le Ricolais asserted:" The art of structure is where to put the holes." (Bendsøe [2]). Among the multiple and outstanding engineering examples worldwide, this position was focal in the works of the Spanish architect Miguel Fisac. He, in collaboration with the civil engineer Ricardo Barredo explored innovative solutions based on the concept of structural hollowness using prefabricated and posttensioned systems, describing concrete as "the only petreous material that works correctly in lintel structures" (Asensio-Wandosell [3]). Based on the analysis of the limitations of standard concrete structures, Fisac developed his investigations of lightweight and hollow concrete beams inspired by the morphology of animal bones, specifically through the series of posttensioned beams that he named "huesos"(bones in Spanish). By hollowing out the beam sections, the aim was not only to reduce the self-weight of the structure but also to provide shading and thermal insulation, to collect rainwater, and to incorporate natural light into the architectural space (Gonzalez Blanco [4]). In addition, the posttensioned solution was conceived to cover large structural spans conferring spatial flexibility for potential architectural implementations.

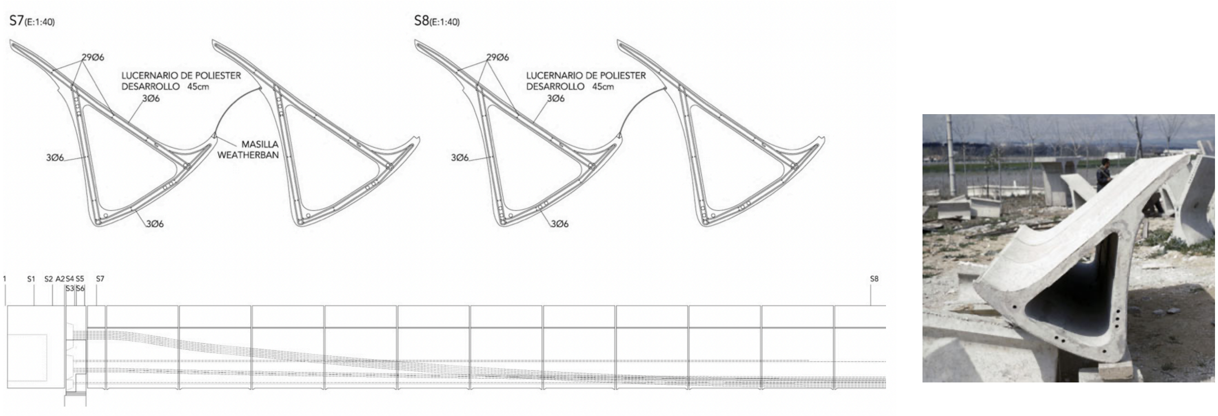

Figure 1: "Cedex" piece and post-tensioned system for the Center of Hydrographic Studies (1960-63), longitudinal section, cross section, and image of the final piece. [source: F.Blanco, *Miquel Fisac: Huesos Varios*, Fundacion COAM, 2007 ]

The Center of Hydrographic Studies completed in 1963, was the first project in which Fisac introduced his innovative structural solution, in this case referred as "Cedex" piece [Figure 1] which, in turn, set the ground for a novel approach to structural design. The structural system, developed in collaboration with Ricardo Barredo in the form of posttensioned structural beams, not only meets the structural demands but integrates, both, rainwater collection and sun shading to achieve a diffuse and homogeneous internal lighting condition (Arques Soler [5]). Additionally, the hollow beam is conceived to provide thermal insulation to the architectural space. This holistic design approach confers, as result, great formal expressiveness to the structure [Figure 2] as well as architectural and environmental qualities to the resulting space.

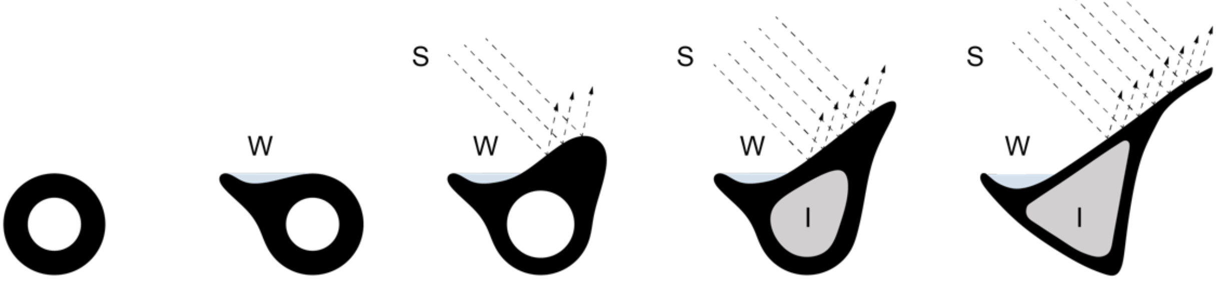

Figure 2: Graphic speculation of a generative process and formal transformation of the Cedex piece cross-section responding to water storage (W), sun protection (S), and thermal insulation (I) criteria.

## 2. Design Concept: Segmental Ceramic Hollow Structures. "Stem I" piece.

Inspired by the works of Fisac and Barredo, this research explores the potential of segmental ceramic hollow structures, as an alternative to reinforced concrete solutions, harnessing the potential offered by the combination of ceramic materials and robotic fabrication technologies to generate non-standard hollow structures that integrate ecological functions such as rainwater collection and heating and cooling systems, and combining their structural function with their potential activation as thermally active surfaces (Castellón et al. [6]).

Following the Roman and Arab tradition in the use of ceramics for the design and construction of water infrastructures, the proposed hollow ceramic pieces act as structural elements conforming the post-tensioned columns, and as ceramic pipes for water collection and storage. Therefore, the "Stem I" piece [Figure 3], developed in collaboration with industrial partners in Catalonia (Spain), was produced through the combination of two main manufacturing processes: extrusion and robotic cutting.

Accordingly, the form of the hollow piece results from an extrusion process of the ceramic mixture through a custom-made metal template under constant applied pressure, producing a homogeneous structural section. This is followed by the precise cut to the final length of the piece using a cutting wire system mechanically controlled as part of the extrusion process. Consequently, the final hollow piece [Figure 3] is 50cm. long, and 18cm. wide.

Nonetheless, these dimensions are decided based on the human scale to be easily handled, shipped, assembled, and disassembled by one or two people. After that, a robotic arm was employed to solve the interlocking mechanical connection (positive and negative) through a subtractive operation on both ends of the piece. Taking advantage of the soft condition of the ceramic mixture, and before firing it into the kiln, the robot was supplemented with a metal wire extension whose movement can be precisely controlled through computer-aided software to remove the parts of the piece that make possible the interlocking connection. The resulting piece generates a modular system that is flexible and able to adapt to different heights (Castellón [7]) and includes a 1cm. EPDM rubber joint to guarantee a flexible assembly and avoid friction between pieces. These joints were precisely fabricated following the exact section of the hollow piece using waterjet cutting technologies.

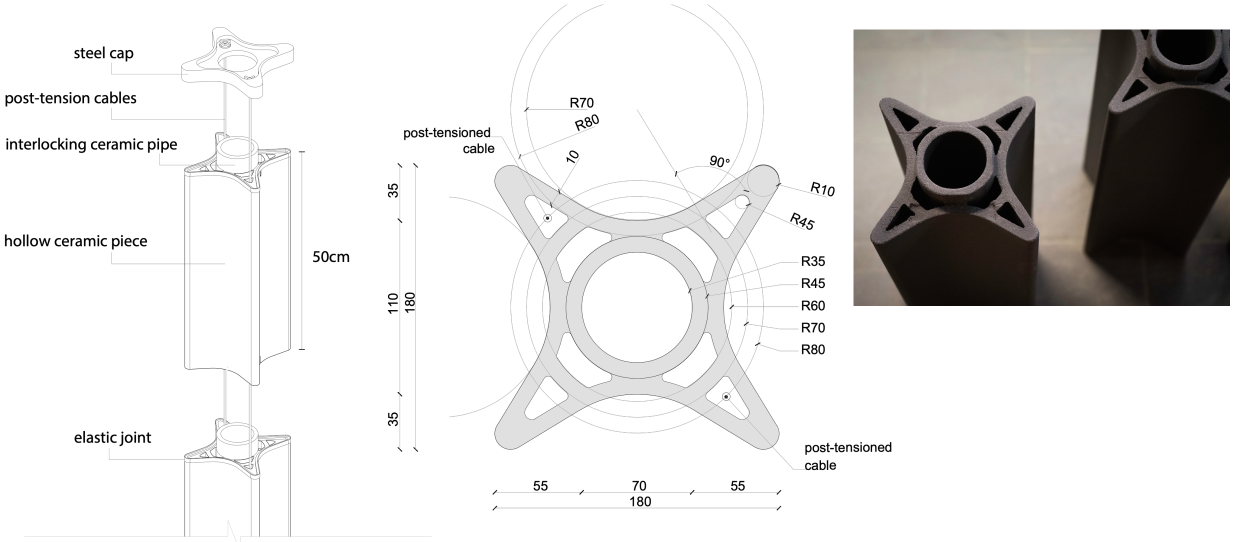

Figure 3: "Stem I" piece. Left: axonometry of column assembly, center: cross-section and geometry of the final piece, right: image of final piece [drawings: Beixi Zhu and Silvia Fernandez Diaz, photo: Frau Recerques Audiovisuals].

## 3. Structural Tests and Mechanical Characterization

Following the fabrication of the “Stem I” piece, the next step was to determine the mechanical properties of the prefabricated ceramic piece to study the potential implementation of posttensioning solutions for the segmental modular columns.

In this regard, the final piece was fired at 1250 C° resulting in a stoneware structural component. Stoneware is a clay-based ceramic material that, due to its relatively high firing temperatures, presents better mechanical properties and lower porosity than earthenware materials such as terra cotta (Cruz et al. [8]). More generally, ceramic materials obey an elastic and linear constitutive equation when temperature and pressures are not very high. The most common criteria to determine the material failure usually include the resistance to compression and bending loading.

Accordingly, a series of tests were conducted at the Barcelona Tech Materials Lab to determine the average bending strength (Figure 4, right), 26,4 MPa, with a deformation module of 56,4 GPa, and the average resistance to compression (Figure 4, left), 148,6 MPa, with a deformation module of 59,3 GPa.

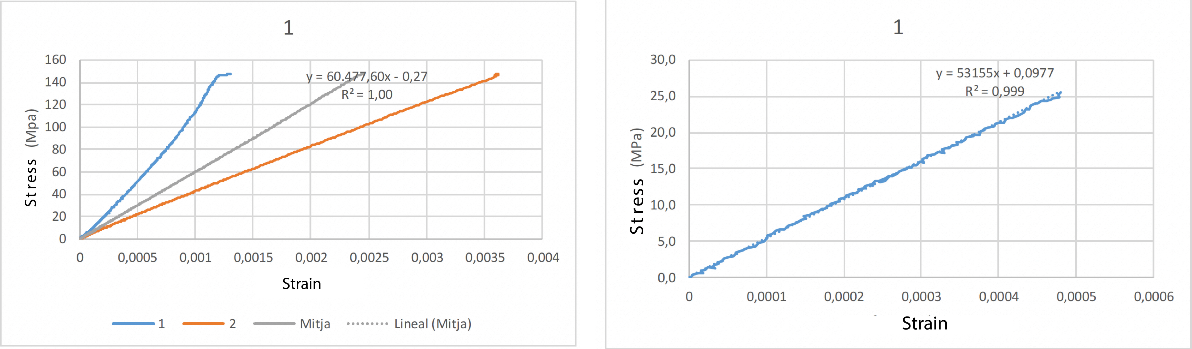

Figure 4: Mechanical characterization of the piece. Left: diagram to determine the average resistance to compression. Right: average bending strength, [Barcelona Tech, Materials Lab].

A second series of tests focused on testing the compression strength and load-bearing capacity of the cylindrical section of a singular piece. Using the modulus information provided by the Barcelona Tech Materials lab, a loading test was conducted in one ceramic piece adding a rubber material on top of the piece to distribute equally the forces throughout the piece (Figure 5, left). From this experiment, the stress-strain diagram was obtained (Figure 5, right). According to it, the maximum value the column withstands was 12,327 psi (85 MPa). While this first test helped estimate an approximate value, the following tests will use a complete segmented column composed of 5 ceramic pieces.

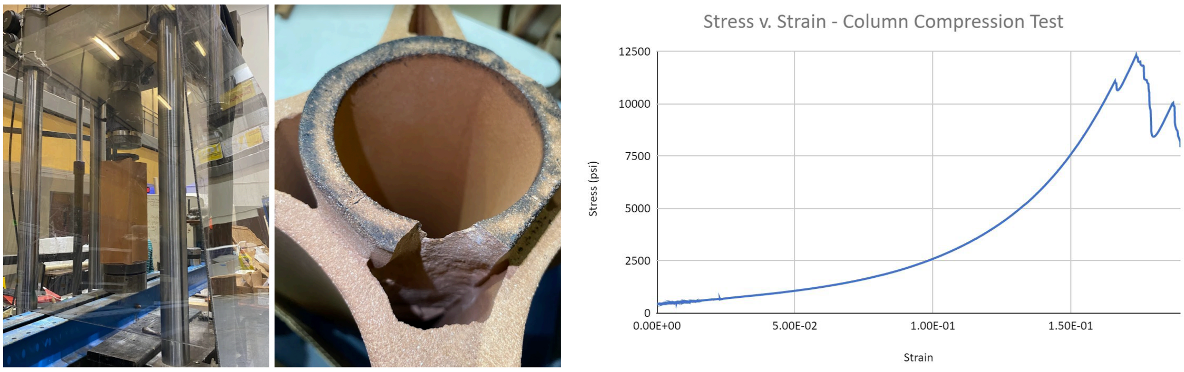

Figure 5: Compression test. Left: “Stem I” piece ready for the loading test, and image of the piece after running the test. Right: Stress v. Strain graph [images: Alyssa Jordan, Neha Singh, Aidan Weindel].

## 4. Topological optimization and subtractive operations.

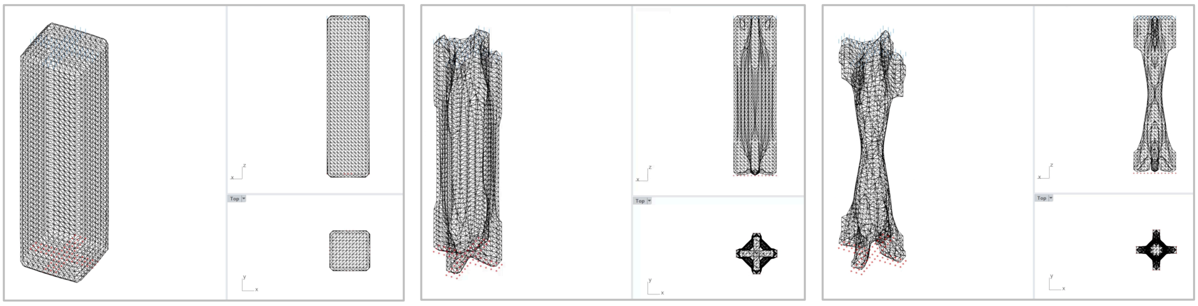

Figure 6: Form-finding process of the piece using topology optimization software [images: David Chen]

While the structural tests provided promising results in terms of mechanical behavior, the ultimate design objective is to optimize the structural capacity of the ceramic piece using a minimum amount of material and explore the formal and load-bearing potentials of this hollow ceramic component. This is achieved through the combination of a topology optimization process to figure out the parts of the piece that could be further removed, in combination with a design methodology to produce this stereotomic prototype as a result of subtractive operations (Castellón and D'Acunto [9]). In topology optimization of continuum structures, the shape of external and internal boundaries and the number of inner voids is optimized simultaneously with a predefined design objective (Eschenauer and Olhoff [10]). Alternately, the implementation of subtractive operations to achieve a similar design objective was applied as an iterative approach to integrating architectural and structural parameters.

According to this, the topology optimization process was unfolded using Millipede, a structural analysis and optimization component for Grasshopper (plugin for Rhinoceros 3D Modeling software). Based on specific loading (cross-like cross section in compression) and design constraints, the optimal form of the piece emerged. The results of these digital explorations defined the targeted design for the "Stem II" piece evoking, as in the case of Fisac, the form of an animal bone (Figure 6). However, the final form was not a literal materialization of the topological optimization process but a balance between the optimum form, the design aesthetics, and the specific manufacturing method (Figure 7).

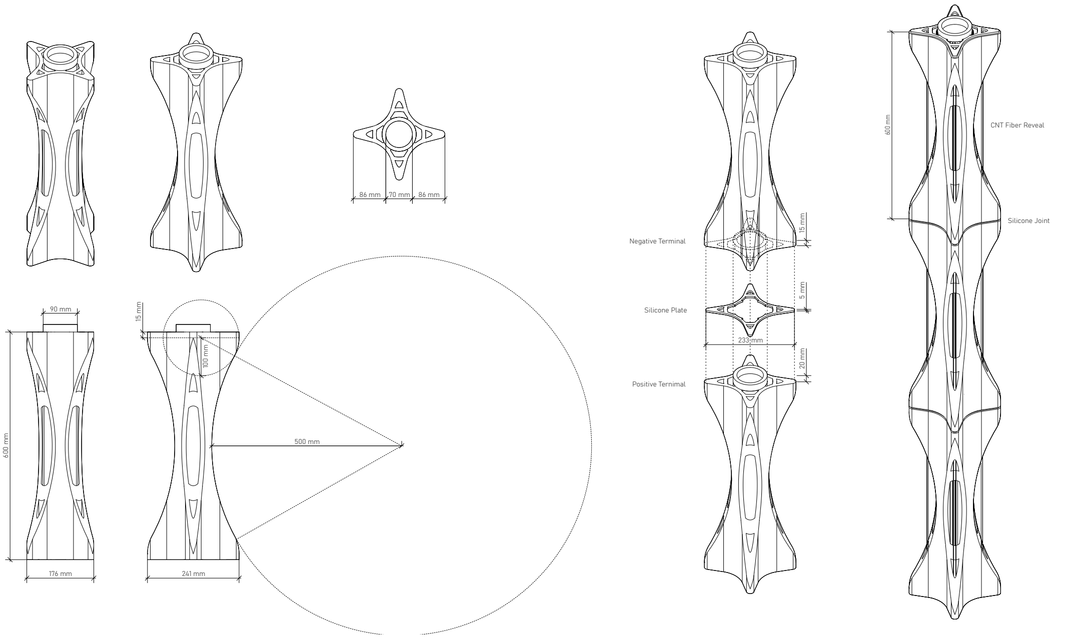

Figure 7: Drawings of the "Stem II" piece. Left: Individual piece, right: Axonometric drawing of the piece, and segmented column combining three pieces [drawings: David Chen]

## 5. Post-tensioning concept and design implementations

The research and development of this segmental ceramic hollow column is part of an ongoing research collaboration for the design and construction of ecological and collective urban infrastructures (Castellón et al. [6], Castellón [7]). As a result, the "Stem I" piece has been used for the construction of two previous installations: one exhibited at the Seoul Biennale of Architecture and Urbanism 2021 (Figure 8, left) and another one at POST Houston (USA) in 2023 (Figure 8, right). In both cases, the installations were presented as proof of concepts for future developments of the research.

The project lends itself to operating as a prototypical flexible module, with the potential to be deployed onto any pre-existing urban rooftop or public area. Consequently, it integrates structural and material strategies to optimize construction aspects related to transportation, assembly, and disassembly of building components, as well as thermodynamic properties related to heat transfer and water cycles, while helping to foster a sense of community and social interaction as well as ecological culture and awareness.

Figure 8: Design implementation using the "Stem I" ceramic pieces. Installations exhibited at the Seoul Biennale of Architecture and Urbanism 2021 (left) and at POST Houston, USA, 2023 (right).

While the two previous prototypes were instrumental in demonstrating the architectural, material, and structural potentials of this holistic concept, in both cases, the anticipated posttensioning system for the segmental columns was replaced by a steel tube inserted inside the cylindrical ceramic pipe.

In this regard, a new design implementation and prototype are currently under development using the "Stem II" piece for the segmental columns. The intention is to build the columns using the new "Stem II" pieces and incorporating the posttensioning cables for the assembly and structural integrity of the hollow columns that supports a folded membrane for rainwater collection and sun protection. Furthermore, the subtractive operations executed in the design of the new piece convey the organic nature of the proposed structural system while exposing the posttensioning cables as part of the aesthetic expression of the modular structure.

Accordingly, a scale model was built using 3D printing technologies to materialize the new "Stem II" hollow pieces conforming to the segmental hollow columns that support the folded membrane (Figure 9, left). The model includes the hypothetical placement of the posttensioning cables (Figure 9, right). The model recalls the forms of animal bones and tendons as well as the forms of stems, fibers, and trunks inspired by the works of Miguel Fisac, and Antoni Gaudí, in the search for a balanced and harmonic dialog between our built and natural environment.

Figure 9: Scale model of the new prototype. 3D printed segmental columns with the folded membrane for sun shading and water collection (left) and detail of the segmental hollow column with the post-tensioning tendons (right). [Images: Tammy Feng, Liufei Zhu]

## 6. Segmental Hollow Ceramic Piece: Manufacturing Process. "Stem II" piece.

Once the geometry of the "Stem II" piece was decided and the conceptual framework consolidated, the next step was to develop the manufacturing methodology to produce the new hollow component.

While relevant examples have been published in the field of additive manufacturing and robotic fabrication technologies to produce structural columns both in concrete (Burger et al. [11], Anton et al. [12]) and in clay (Seibold et al. [13]), this research explores the use of subtractive manufacturing methods using robotic fabrication.

Following a similar setup as the one described in Chapter 2 (in which a robotic arm was supplemented with a metal wire extension whose movement can be precisely controlled through computer-aided software to remove the parts of the ceramic piece), this time the challenge was to produce these precise cuts responding to the smooth and symmetric geometry of the hollow piece.

Therefore, the first test was conducted, placing the extruded piece in a vertical orientation, while the robotic arm was moving around it and subtracting the excess clay according to the targeted form described in Chapter 4. However, slight deviations in the base produced irregular and non-symmetric cuts. Therefore, the decision was to place the piece in a horizontal orientation and rotate it along the axis to, on the one hand, control the exact position and, on the other, facilitate regular and symmetric cuts of the piece. Consequently, an auxiliary metal structure was fabricated to insert the piece into a horizontal metal tube taking advantage of its cylindrical hollow section to receive the supporting and rotating mechanism. The precise horizontal position of the piece was guaranteed using a laser level while rotating the piece 90 degrees for each of the robotic cuts operated to generate the final piece (Figure 10).

This fabrication methodology was conceived in collaboration with the industrial partner, Ceramica Cumella, with a base in Granollers, Spain. The final steps to manufacture the final piece included the production of the mechanical connection (negative and positive) at the end of the pieces, the glazing finishing (applied manually), and the firing process at 1250 C° to complete the stoneware structural component.

Figure 10: “Stem II” piece placed in the auxiliary structure for the precise robotic cuts and rotation [image: Frau Recerques Audiovisuals]

## 7. Conclusions and further developments.

This research demonstrates the potential of ceramic materials and subtractive manufacturing methods to produce non-standard structural components. While the method was applied to produce a singular piece, further developments of the project include the design and fabrication of multiple parametric variations.

The combination of conventional extrusion processes and the iterative application of subtractive operations generate a hollow piece that reduces significantly the weight of the structural component and facilitates the integration of environmental aspects (water collection) as well as the assembly and disassembly of the structural components following the principles of circular construction.

The objective for the final prototype is to incorporate post-tensioning cables as an integral part of the segmental ceramic hollow column. Accordingly, preliminary tests (including mechanical characterization and loading test for one piece) showed promising results in developing the solution. However, additional tests, such as the loading tests for one complete segmental column and the consideration of second-order effects such as buckling, will be conducted before analyzing and calculating the most suitable solution for the actual posttensioning system.

Finally, the goal is to build the design implementation described in Chapter 5 as a full-scale installation conceived to promote the design and construction of ecological urban infrastructures for social interaction and in harmonic balance with our natural ecosystem.

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