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3DCP PREFABRICATION FOR COMPLEX TOPOGRAPHICAL CONTEXTS: A CASE STUDY OF ROCKY PONTOONS

João Ribeiro[1,2]
João M. Silva[1]
António Morais[1]
Bruno Figueiredo[1,2]
Paulo J.S. Cruz[1,2]

[1] EAAD — School of architecture, Art, and Design of University of Minho| Portugal
[2] Lab2PT — Landscape, Heritage, and Territory Laboratory| Portugal
Corresponding author: bfigueiredo@eaad.uminho.pt

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Abstract
This article explores the potential offered by 3D Concrete Printing (3DCP) through the analysis of a practical application case: the qualification of rocky pontoons in marginal areas with spaces for recreational use and protectors of marine biodiversity. The purpose of the work is centred on the production of a set of platforms, divided into prefabricated concrete modules, which fit perfectly into the complex geometry of marine rockfills, generating new uses for these areas of difficult access and appropriation. The paper focuses on questions related to the manufacture of a prototype, accompanying the process from the design phase to its execution. For this, a methodological division into five sections is followed: (1) a literature review with a view to production and application in a real context; (2) the design of the architectural object; (3) the preparation the object for printing; (4) the production in laboratory environment; and (5) assembly and fastening on site. In conclusion, the work presented demonstrates a case of application in a real context where 3DCP technology allows generating more efficient and sustainable solutions to design and build architectural elements adapted to highly complex contexts, such as rocky pontoons. We anticipate that the results of this study will provide an impetus for further exploration and utilization of technology in other intricate contexts.

1. INTRODUCTION
Coastal erosion is becoming an ever more pressing issue in coastal cities across the globe. A variety of direct and indirect human activities, such as the construction of seawalls, and natural phenomena, such as wave force and rising sea levels, are responsible for the erosion of coastal areas. To combat this, architects, designers, and engineers have been creating larger structures, such as pontoons, to break the power of the sea and contain it, preventing it from claiming the land of our cities. Unfortunately, these structures often obstruct prime beach and riverfront areas, resulting in people attempting to traverse them and risking injury due to their chaotic arrangement. The construction of any type of structure in these locations is a complex challenge. However, recent advancements in technology, such as computational design, drone photogrammetric surveys and 3D Concrete Printing (3DCP) manufacturing, have allowed for the creation of complex forms which would have been thought impossible in the past [1]. 3DCP has enabled mass production and reduced the need for formwork, as adjustments to the equipment are no longer necessary for each new geometry. Furthermore, it is also possible to print hollow structures which use less material, as well as employing optimization algorithms to further reduce the number of structural elements.

This paper focuses on the use of 3DCP to create a system of platforms which can be placed on the irregular surface of the pontoons. The goal is to create a system that allows for the construction of walkways, leisure areas, fishing spots, and viewpoints for the sea. Currently, photogrammetric technology enables the accurate digitalisation of complex geometries like those of the pontoons, which can then be replicated digitally. This process allows for the generation of a digital model with the intricate cut-outs of the rocks. 3DCP is a technology that demonstrates its capability to fabricate complex geometries of this kind. Furthermore, since the structure will not be permanently attached to the site, it can be retrieved during the wintertime, when the sea is stronger, and put back in place during the summer months.

Another problematic of the ocean, is about the rising water levels and temperatures that threatening the survival of many marine species. AM processes can offer solutions of added value regarding the creation of new micro-habitats or refuge for native species. In this project, the infill of the slabs is configured with two main objectives in mind: increasing the strength of the prints to resist to the force of sea waves and creating void, possible with various textures and measurements to promote the local marine life growth, both fauna and flora. Image 1 summarizes the proposed uses.

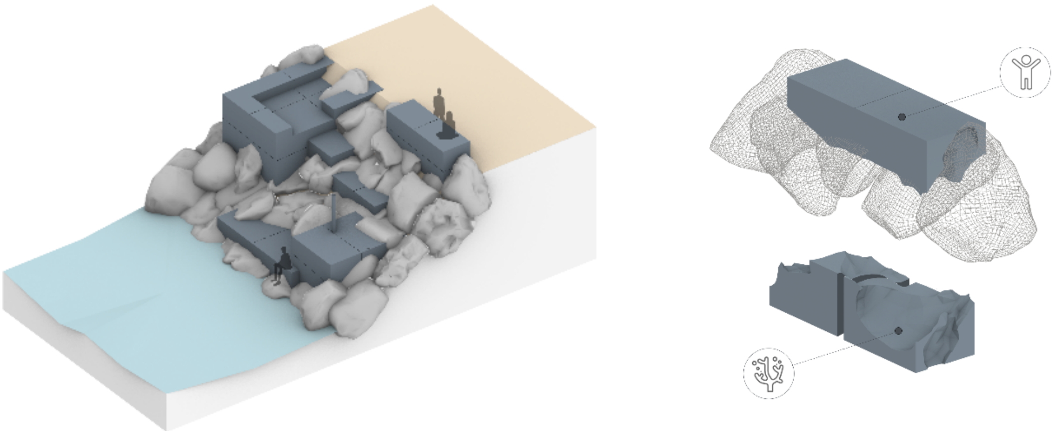

Figure 1. Schema of occupation of the rocky jetties, with custom-fit prefabricated concrete components, which expand public use and marine biodiversity.

Formally, the project starts with a digital survey and reconstruction of the rocky landscape, in this case, a selected maritime pontoon in Póvoa de Varzim. However, the main scope of this paper will only focus on the issues associated with the process of designing, manufacturing and placing the structure on site. In this sense, the work is divided into five sections: (1) a literature review to understand how the object can be placed in a practical context; (2) the generation of the architectural object for the intended use; (3) preparing the prototype for 3D printing in concrete; (4) the robotic fabrication of the object in the laboratory; and (5) the techniques to make the implantation on site. In short, we will methodologically explain the solutions adopted to overcome the challenges inherent in 3D printing in concrete of complex geometries.

2. STATE OF THE ART

In the last years, the continuous development of Additive Manufacturing (AM) technologies in the Architecture, Engineering and Construction (AEC) industry has as its main expression in the advances and applications of 3DCP that have expanded beyond traditional construction systems. Although AM processes have the ability to generate geometries with reduced margins of error compared to the digital models, one of the problems associated with the proposal discussed in this article concerns the ability of the printed prototype to mimic the geometric complexity of sea rockfills, allowing it to fit perfectly into the pontoon. In some parts, such geometric complexity exceeds the constructive limits of the technology, challenging results obtained in previous tests. A strategy to increase the reliability of the printed geometry is the use of accelerated mortars during the extrusion process, namely as explained by Gosselin et al. [2], however, this approach was avoided since it lacks in-depth rheology studies in order to avoid the generation of cold joints between layers [3]. Conversely, using non-accelerated mortars, Ahmed et al. [4] reported favourable results using sand as a support material in the fabrication of a bridge components with high camber angles. This principle will be followed in areas of greater surface inclination to minimize the geometric deviation of the components produced.

With regard to the place of manufacture, in general, two main production practices are recognized: (1) in-situ fabrication, which typically involves building monoliths and using large structures for production, and (2) off-site prefabrication in a laboratory, or controlled industrial environment, which usually involves discretization solutions for components that are compatible with the need for transport and in-situ placement. Recognizing the advantages and disadvantages of both processes [5; 6], and considering the geographical context of our research and the additional value of manufacturing in a controlled environment, we have oriented our research towards a laboratory environment from an early stage. This ideological strategy, in which the geometry to be produced is divided into components that can be manufactured, transported, and assembled, requires the design to be thought of from the perspective of its prefabrication, so that the components not only respond to the production phase and the final functionality, but also to the needs of transport, handling, and assembly on site. Mechtcherine et al. refers to the obligation to develop, in the design phase, effective connections between elements and the calculation of the size of the discretized components according to the handling, transport and assembly capacities of the in-situ structures, factors that, when not foreseen, can have a negative impact on the efficiency of the whole process [6].

If in terms of the size of the components, these must be dimensioned exclusively depending on the existing locomotion capacities and their associated costs, in terms of the connection between produced elements, different interlocking solutions are recognized in the bibliography by juxtaposing the components. One such example is Polybrick 2.0, developed at the Sabin Design Lab, where a set of "puzzle-type" ceramic blocks are produced and, when fitted together, form an undulating wall [7]. Another example is presented by the Emerging Objects in the Quake Column project. This project exposing a column based on Inca bricks where each “stone” fits perfectly with the neighbouring blocks, creating a knurled and twisted structure, optimized to resist seismic vibrations [8]. However, in the case of the proposal presented in this paper, the scale and weight of the components to be produced, as well as the extrusion technology used, have different limitations compared to the Binder-Jetting technology, making it difficult to obtain angular fittings with different directions, as in the examples.

In a maritime context, some types of cast-in-concrete blocks for sea walls, such as the "Stone-Block" [9], also use male-female fittings to prevent the components from moving. In this sense, we believe that we follow logics of interlocking and fitting in the rocks to prevent the pieces from moving horizontally, however taking into account that here we will produce substantially lighter components, we believe that these solutions will always have to be combined with other structural reinforcement solutions.

In this field, the study of structural reinforcement solutions applied to 3DCP processes is widely discussed by Kloft et al. [10]. On the other hand, in terms of reinforcement solutions for prefabricated elements – reinforcements inserted after the material has cured in order to guarantee the connection between different produced elements – we can highlight the External Reinforcement Arrangement system, performed by Asprone et al. at the University of Naples [11], and post-tensioned cable solutions such as the Smart Slab developed at ETH Zurich for DFAB House [12] and the bicycle bridge developed by TU Eindhoven for Gemert [13]. While in the first case it is proposed that the printed concrete and the external steel reinforcements work together, optimizing their behaviour in compression and tension, respectively, in the second a mechanical principle is explored where the additional application of prestressing allows to confer load capacity to elements that would normally also involve traction forces. This last principle will be adapted to the maritime prototype, making it work as a post-tensioned bridge.

3. CUSTOM-FIT PONTOONS DESIGN

The first step of the design process of the platforms was the digitalization of the pontoon through photogrammetry survey technic. To geometrically define each slab of the pontoon extension, a parametric design strategy was developed. This system takes the boundaries of a given area above the digitised pontoon and superimposes a modular grid, in which each cell represents a building module with specific measurements. A computational design model is then used to arrange an 80x80cm rectangular grid in place so that each module is provided with local support from the rocks below. Figure 2 illustrates the project concept.

Figure 2. 3D simulation of part of the platform to be produced.

The aim of these maps was to validate the most suitable sites for module installation by assessing a) the depth of the cavities in the pontoon rocks, b) the roughness of the rocks, and c) the division of the main grid into 0.80 x 0.80 meter grids. In each grid, one of the edges is broken in the middle and shifted 15cm outward to create an interlocking system between the other modules. This system allows for a monolithic structure to be formed from the individual parts. In addition to the connections, another type of fastening was planned. In this case, post tensioning with steel cables was used. The computational design model used to generate the platforms limited the depth of each piece to 1m. The grid outlines each slab, and a volumetric configuration is obtained by projecting points from each module in the z-axis onto the surveyed mesh. Triangulation and quadratic remeshing are then used to correct any imperfections and the mesh is extruded up to its intended height on site. This process was chosen instead of a straightforward boolean operation to prevent tangling, holes, or unprintable meshes.

Each slab is unique, as four objectives must be met: (1) conforming to the geometry of the supporting rocks to latch it in place; (2) interlocking with neighbouring modules; (3) meeting a functional necessity between horizontal circulation, vertical circulation, and resting; and (4) creating a habitat for local fauna by varying the infill pattern. The two modules on which this paper focus on, are represented in the Figure 3.

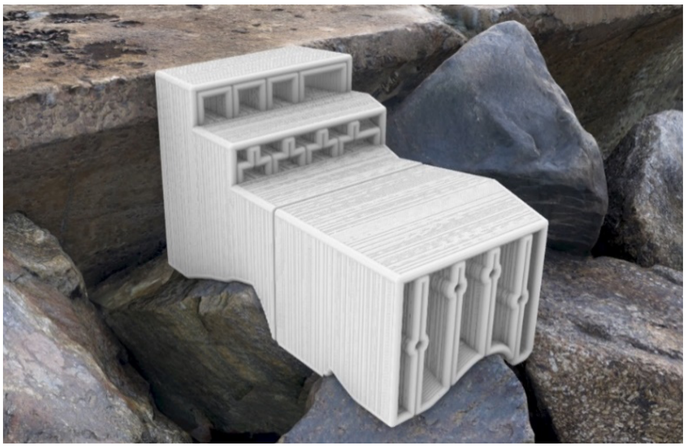

Figure 3. Final prototype to be produced.

The first module that contacts with the pontoon wall is a vertical access module composed of two steps and a small platform. The second module is entirely composed of a circulation platform. To this module, a second variant could be added where a step could be added at its limits, which could be used as a resting place or for activities such as fishing. On the right side of the image, the male joint that allows the interconnection of the different modules with each other is visible, allowing them to act as a monolithic structure. The design of the infill is responsible for defining interstitial spaces that allow marine fauna and flora to inhabit these spaces since the front of the steps and the front of the modules will always remain open allowing the entry of marine animals and plants creating possible unique ecosystems.

4. DESIGN TO BUILD

In order to manufacture the previously designed parts by means of 3D printing, a “preparatory” phase is necessary. This phase is characterized by the design of the paths that serve as guides for the robot to perform the extrusion. Since the geometry of the contact with the rocks of the pontoon is very complex, each piece will be unique, and no two cuts will be the same. Therefore, a small computational model was created in Grasshopper with the objective of automating the production of the extrusion paths. This process is performed in three moments. First the algorithm defines horizontal planes spaced by the height of the printed layer (10mm). It then calculates the intersections between each plane and the slab geometry, resulting in a set of closed curves that define its outer boundary. These curves are then offset by half the thickness of the printed layer, which for a 20mm print nozzle diameter will be approximately 35 to 40mm. An initial evaluation is then required to assess the slope of the rock side and determine whether a different orientation could reduce it in other to be successfully printed.

The next step is the design of the infill structure. The aim was to be adapted to the three typologies of functions: a) stairs, b) circulation and c) bench. The infill adopts an alveolar configuration with three basic purposes: (1) to increase the structural resistance of the printed element; (2) to create voids to help the dissipation of the sea waves; finally, (3) to work with complex morphological structures, with different textures and concavities, that highlight the native marine fauna and flora of these regions. Due to the different needs of the modules to be printed, the infill was divided into three categories as represented in Figure 4.

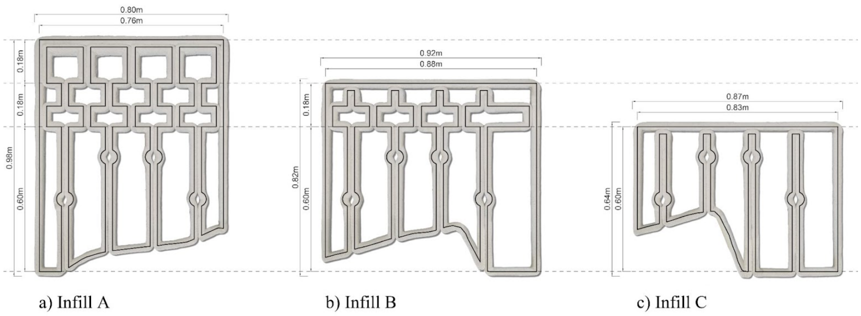

Figure 4. Different types of infill for reinforcing printed components and to ensure support for the upper layers.

Each of these types of infill is adapted to a specific function. A specific infill for the staircase modules and the cells corresponds to the size of the mirrors of the steps (Figure 4 a). An infill that can do both staircase and act like a bench (Figure 4 b). Finally, an infill type for the areas of Platform which is characterized by a simplification of the internal filling (Figure 4 c).

At the same time, it was necessary to define a strategy to connect the different modules during the assembly phase. For this reason, the post-tensioning method was chosen through the passage of steel cables, later tensioned. To this effect a set of holes was designed along the proposed modules. The purpose of these holes is to allow, during the assembly phase, the passage of steel cables to aggregate the different printed modules. These cables are passed and tensioned in a perpendicular direction to the layers using compression forces against the different layers.

Once the infill and the modules dimensions were defined, the last step was to define the printing orientation of the modules. One of the issues conditioning the printing orientation is the need for the printing to be continuous due to the fluid nature of the printing material we are using. Therefore, a careful analysis of the geometry that would be printed was made. The solution found for the print was to project the infill into the print area with the cut-out area contacting the pontoon on the side and printed as a wall. This decision led to the appearance of support issues due to the forced inclinations that will be analysed later in this paper.

5. PRINTING

The main part of the 3DCP process involves using a computer-controlled manipulator system to layer concrete material in a predetermined pattern. Currently, a large part of exploratory projects in this area at medium/large scale are using systems based on industrial 6-axis robots as printhead manipulators. This choice is mainly justified by a particularly interesting cost-benefit ratio, associated with high precision and ease of control resulting from significant advances in hardware and software development.

Based on consolidated models, namely as exposed by Da Silva [14] or Gosselin et al. [2], a printing setup for 3DCP comprises three essential phases, sequential and continuously interconnected: (1) the production/mixing of the material with automated dosage or not; (2) pumping it to the extrusion head; and (3) the deposition of the material in layers, with continuous filaments, according to a certain printing path. The scheme below (Figure 5) illustrates the design of a concrete 3D printing setup, using a continuous supply system comprising a dry premix (Stage 1) before mixing with water (Stage 2), a screw pumping system (Stage 3) and the industrial robotic arm using an extrusion head equipped or not with a helical auger as a manipulator (Stage 4).

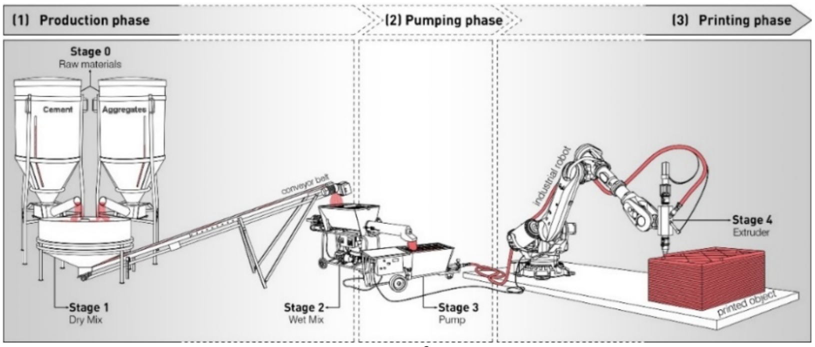

Figure 5. Layout of a 3DCP setup.

Figure 6 shows the 3DCP equipment setup used in this research at the ARENA Robotic Fabrication Laboratory at the School of Architecture, Art, and Design of University of Minho. In our case, dry mixing was replaced by the use of a special mortar mix for 3D printing developed and marketed in bag by Weber, Saint-Gobain – the Weber 160-1. Since the mixture does not require accelerator injection during extrusion, a direct extrusion process (without an auger) was used by attaching to the robotic arm a tubular extruder with a section similar to the concrete hose (25mm).

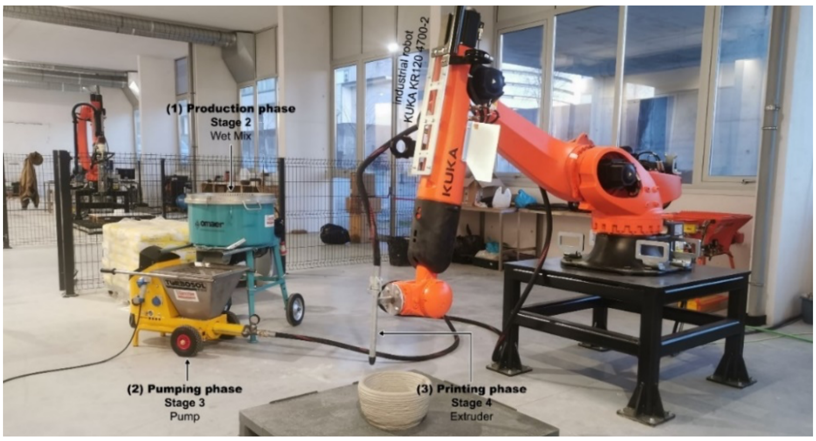

Figure 6. 3DCP setup, ARENA Robotic Fabrication Laboratory at the School of architecture, Art, and Design of University of Minho.

Besides that, for mixing the material with water a planetary mixer was used. As a result of previous tests and to avoid excessive waiting times, a mixture in batches of 2/3 bags at the most was preferred. Furthermore, for a mixture with an adequate ratio between pumping capacity and buildability after extrusion, the addition of 10.8% of water allowed the best behaviour, requiring a minimum mixing time of 5 minutes to acquire ideal workability.

In addition to the characteristics of the extrusion equipment (the mixer, the pump, the robot, etc.) the production quality of any component is deeply dependent on the relationship between the basic printing settings. The components produced for the marine prototype were extruded layer-by-layer through a 20mm thick nozzle and using a layer height of 10mm and a printing speed of 100mm/s. Previous tests have shown that to ensure optimum bearing capacity, a layer width of around 40mm should be sought. For this, the pump's extrusion flow was continuously adjusted to adapt the workability of the material to the defined layer width.

5.1. PRINTING CONSTRAINS

During the printing phase, several problems had to be solved. Some of them made it necessary to make some adjustments to the original design, namely regarding the size of the modules and the way they relate to each other. Although the original design grid predicts a dimension of 0.80 x 0x80 m, it was necessary to reduce these modules to smaller staves due to problems that appeared through the analysis of the cut-out of the modules in contact with the rockfill of the pontoon. These cut-outs often reach inclinations that make the pieces very difficult or even impossible to print due to the amplitude of the angles they create. Thus, the printing strategy was to divide the original modules into smaller staves (between 0.30 and 0.20m), like is showed in Figure 7.

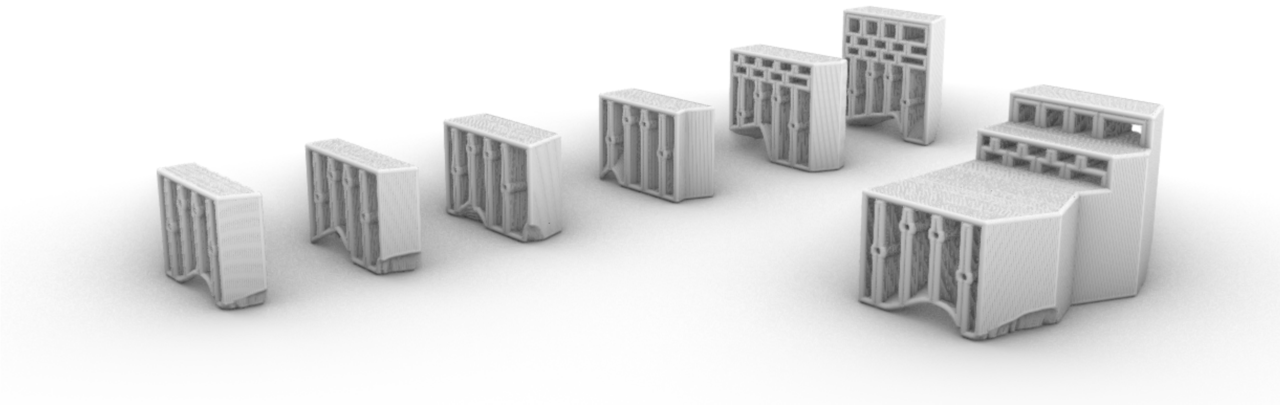

Figure 7. Exploded view of the different sections of the modules to be printed.

This division into smaller pieces had two purposes. The first has to do with the division of the stronger slopes which allows the load exerted by the upper layers during the printing process to be lower due to the lower number of printed layers resulting from the lower "height" of the pieces. Another positive consequence of this division is the simpler handling within the laboratory due to the lower weight of the pieces. The mechanic system that we have in the laboratory, doesn´t enable us to move heavy weights. The weight of the original modules of 0,80cm will be around 700kg and 900kg. With this division the weight of this modules is around 300kg each, which is relatively easier to handle and transport.

At the same time, due to the way the pieces are printed, rotated perpendicularly, coinciding the contact faces with the modules with the face that rests on the pallet, a solution had to be found that allows not only to lift the module from the printing base, but also to rotate the piece on itself 90 degrees to be placed in the position it will assume when placed on the pontoon. For this purpose, a lifting system that allows the rotation of the piece was designed. This system was materialized through the introduction of a 20 mm diameter VD tube placed transversally in the module during the printing, remaining embedded in the piece. After drying of the printing and when the piece has reached its maximum resistance, a 10mm threaded rod is passed through the inside of the tube. At the ends of this threaded rod are applied accessories that allow the coupling of lifting slings that are attached to a forklift. Through this system it is possible to lift the piece and rotate it to its final position. This system not only serves to move the piece during the production phase in the laboratory, but also permits its movement to be placed in its final location, allowing the rod and its accessories to be removed at the end of the lifting operation, so that they can be placed again whenever it is necessary to carry out any movement operation of a module.

Although the division into smaller modules helped in the printing of the sloping walls, due to the degree of inclination they presented, over which we had no control because they reflect the texture and the cut-outs obtained from the geometry of the rocks of the pontoon, a way had to be found to have support during the printing process.

The solution found was to use a neutral material as a support. Sand was the material that suggested as the most viable option. So, the solution found for printing complex inclinations was to add sand around the layer as it is being printed. At this stage, this addition of sand is done through a manual process that presents some problems such as the need to sometimes have to build a box around the object to be printed so that the support material (the sand) does not "leak" with the weight of the print and cause the object to be printed and give way. However, despite the constraints, the solution found allowed for the successful printing of prototypes with very pronounced inclinations, as can be seen on Figure 8. The observed inclination would be very hard to print without the use of support methods. At the end of the printing process, the sand is easily removed from the surface of the printed layers with a brush.

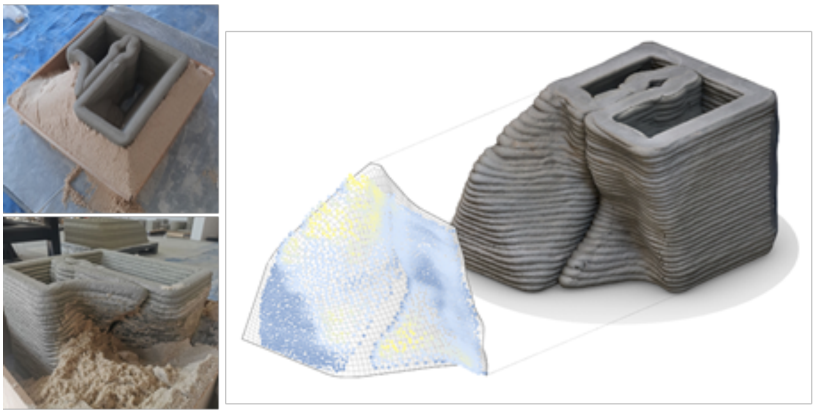

Figure 8. Section print test of one of the prototypes, using sand as support material.

6. TRANSPORT AND POSITIONING

The transport and positioning of the pieces in their final location was planned during the dowel printing phase, where a negative was "built" by placing a 16mm VD tube. The purpose of this tube is to serve as a negative to the passage of a threaded rod to which a set of hooks or fixings can be attached to facilitate the lifting of the stave. This lifting system is intended to facilitate the movement of the stave´s both inside the laboratory and outside when placing the piece on its final location. In the end, the fastening mechanisms and the threaded rod are removed, leaving only the negative on the piece. In a simplified way, for its positioning, the piece only needs to be inserted with the help of a crane and placed in the foreseen position. However, with only its own weight acting as a fastener, each stave is potentially very susceptible to displacement by the impact of waves. For this reason, a post tensioning system was developed using steel cables. The principle of this post tensioning is to crush and aggregate as many staves as possible perpendicularly, as demonstrated in Figure 9.

Figure 9. Schema of the tensioning system with steel cables.

Between each of the stave´s neoprene is placed. This material acts as an energy absorber preventing the forces transmitted between the pieces from creating tensions that could damage the contact faces between the dowels. Through this system, the staves act as a single body, thus acquiring more mass and being less prone to displacement that could damage the pieces.

The stave´s and pre-stressing system offers yet another advantage over traditional systems. The same tools used to place the stave´s on the pontoons, also allow that in the future when these pieces can no longer remain in this place, their removal. Furthermore, given its modular structure, built using discrete elements, if any of the staves suffer any kind of damage, they can easily be replaced. To do this, it is only necessary to undo the pre-tensioning system, remove the damaged part using the same system as before, place the new one and re-tensioning the steel cables. This whole process allows us to think of this type of manufacture as promoting a circular process that allows the recycling and reuse of all the materials used.

7. CONCLUSION AND FUTURE WORK

The printing methodology presented in this paper shows itself as a possibility for the manufacture of complex concrete structures. Using technologies such as photogrammetry, computational design and 3DCP, it becomes possible to design and construct building components that respond to complex geometries and diverse contexts. 3DCP presents itself as an alternative to traditional construction methods based on the use of formwork, which makes the manufacture of customized elements time-consuming and costly. 3D printing opens doors to mass-customization since it makes the customization as easy as mass production through formwork. For future work, the ambition is to print the complete structure with several modules and to place it on the actual site. Through the real implementation in a real context, we intend to evaluate concepts such as post-tensioning, the general resistance of the pieces to wave and salt attacks from sea water. Also, at the level of the implantation of micro-organisms, fauna and flora in the concavities of the modules is expected to be able to evaluate in loco at the time of implantation. The aim will be to follow the evolution and understand what type of geometry can work best to benefit these species. In this way, in the future and through the algorithm implemented for infill design, this can be optimized and will serve as an improvement for future impressions. 3DCP is a manufacturing method with numerous benefits in laboratory/manufacturing pre-fabrication.

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