CELLULAR CERAMICS
Parametric, performative, & free-form

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His research work focuses, mainly, on the integration of digital tools and contemporary design processes with traditional materials and systems, in particular, ceramics.

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1.1. INTRODUCTION

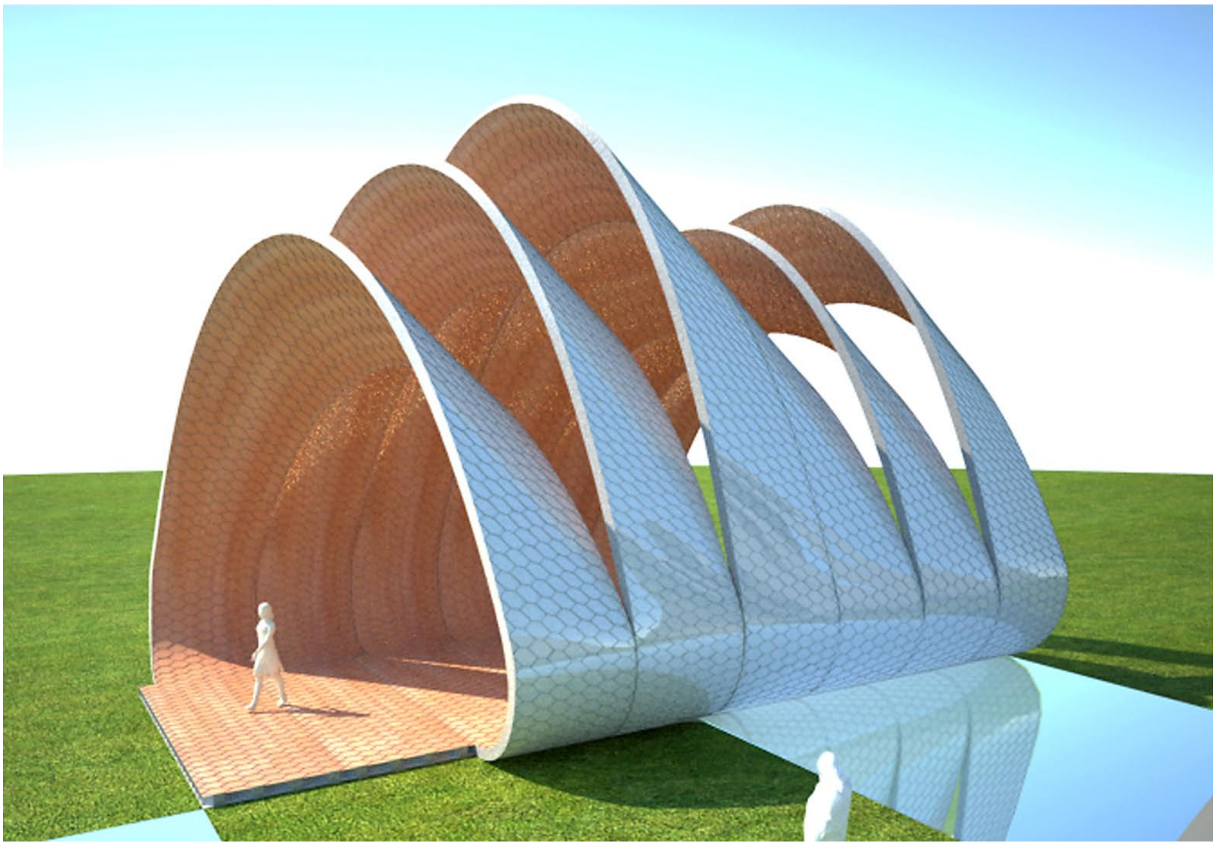


Fig. 1.00 | Reinforced Cellular Ceramics. Virtual Model.

The present document is the result of an investigation that is being conducted in the Department of Structural Design of D-ARCH at the Swiss Federal Institute of Technology Zurich (ETHZ). This investigation, whose first phase was carried out at the Architectural Association School of Architecture (London), is currently in its second phase.

The investigation focuses on the development of a material and geometric system that allows fabrication of structural surfaces with a double curvature by an assembly of ceramic components. In order to do this, the latest parametric design technologies are combined with a manufacturing system based on the Spanish building tradition.

Overcoming the need for standard industrial manufacture, as well as confirmation of the need for an innovative yet responsible architecture that is also aware of social, environmental, and economic factors, opens up a new stage for architects and industrial companies in which it becomes essential to integrate new technologies into techniques and processes inherited from the building tradition.

1.2. PRECEDENTS

Guastavino, Dieste and the evolution of cohesive construction

Fig. 1.01 | City Hall Station. 1900. New York. Rafael Guastavino.

At the end of the 19th century, Valencian architect Rafael Guastavino (1842–1908) developed a construction system based on the traditional technique of the Catalonian vault, which he called cohesive construction[1]. Guastavino distinguished two essential structural types: construction by gravity and cohesive construction. While mechanical construction, or construction by gravity, is based on the resistance that any solid opposes to gravity when it interacts with another solid by friction, cohesive construction uses as structural principle the adhesive strength between different layers of materials (in this case, mortar and ceramics).

Guastavino applied this construction system in the United States in important buildings such as the Boston library, the Cathedral of Saint John the Divine, and the City Hall Station (Fig. 1.01) in New York[2].

His vaulting system was enormously successful and had a great impact owing to the enormous advantages that his cohesive technique provided.

On the one hand, the use of ceramics provided the vaults with excellent non-flammable properties and, in addition to being an economic and aesthetically pleasing material, Guastavino's vaults could bridge spans of up to 30 metres without needing beams or scaffolding, so that the system was fast and, structurally, very efficient.

On the other hand, the technique entailed the disadvantage that it required highly qualified workers and specialised knowledge for design and installation, which is why, despite Guastavino's extraordinary work, the cohesive construction system fell into disuse.

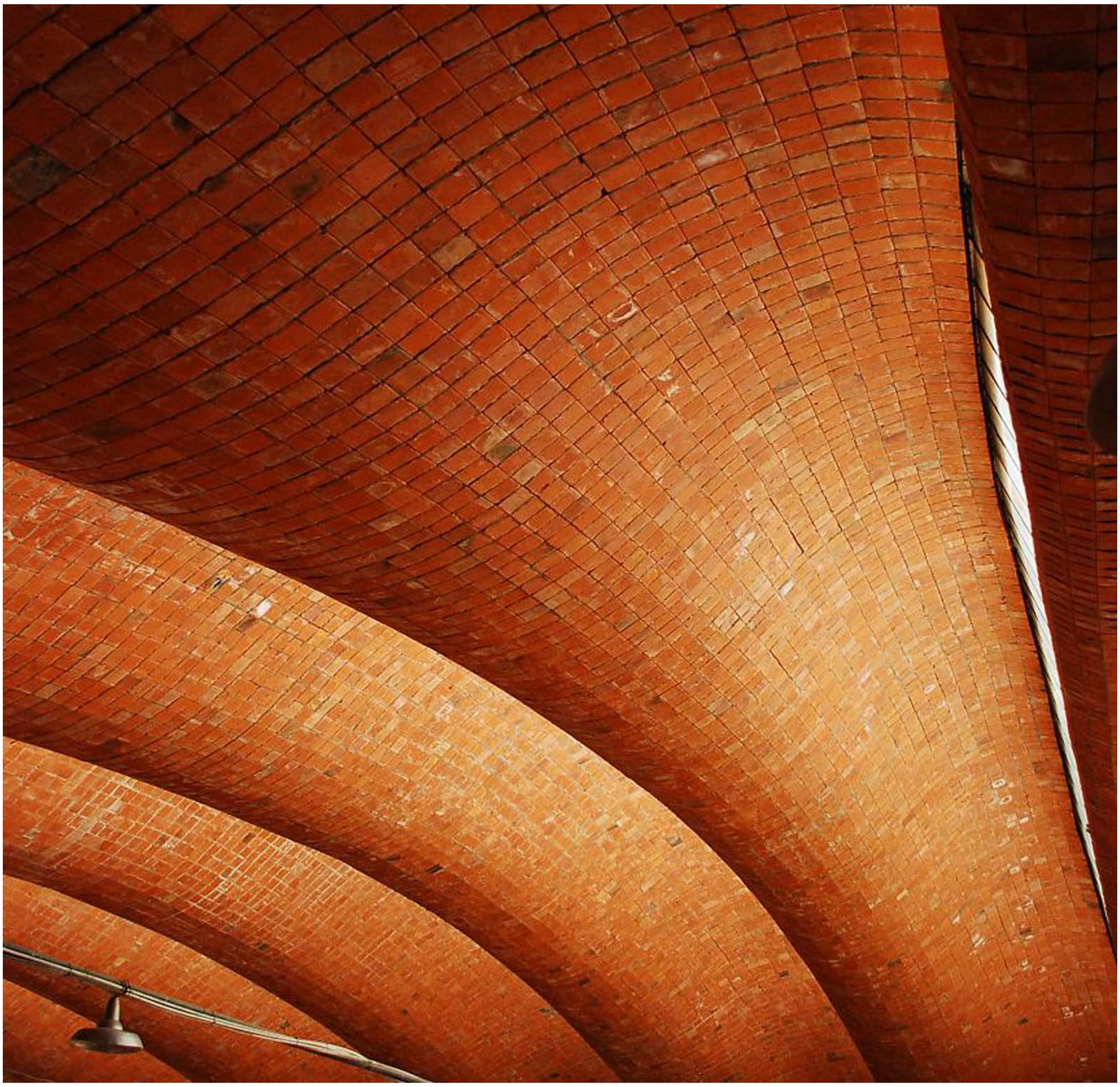


Fig. 1.02 | Durazno building. 1979. Montevideo. Eladio Dieste

Some years later, Uruguayan engineer Eladio Dieste (1917–2000) retook the path initiated by Rafael Guastavino and evolved it, thanks to his discovery of reinforced ceramics[3]. The hybrid technique developed by Dieste combined the traditional technique of bricks with the use of steel strengthening. This combination provided the system with ductility and the mechanical properties of reinforced concrete, while it also offset the poor tensile strength of masonry. A conglomerate of brick, cement, and steel is more heterogeneous than reinforced concrete, so that the tensile stresses are absorbed by the steel while the compression stresses are absorbed by the ceramics and mortar.

In the construction of his vaults, Dieste used hollow bricks arranged in a square grid. Thus, the only way of installing the metal reinforcements was by inserting the bars between the joints following the isostatic lines of the grid. This process was laborious and required considerable installation time. On the other hand, his system was able to bridge spans of up to 50 metres without any columns, with a minimum structural thickness. This was further assisted by the geometric development that Dieste termed Gaussian vaults (Fig. 1.02).

Gaussian vaults are thin double-curvature surfaces, whose geometry makes them extremely resistant. In other words, the geometry of the vault improves its structural performance and, thus, by means of a simple thin layer of reinforced ceramics, Dieste was able to create vaults that combined formal beauty and structural efficiency[4].

The use of structural ceramics was essential to the success of the system, reducing the need for continuous scaffolding during construction and enabling high standardisation and control during the installation. Moreover, the system was based on an optimised use of materials and local resources, and a wise combination of technical efficiency and economic feasibility[5].

2.1. PROCESS PHASE 01

Parametric Design and Cohesive Fabrication

This project seeks to recover the principles developed by Rafael Guastavino and Eladio Dieste and to attempt to develop and update them by using and applying contemporary technologies.

The reinforced ceramics system proved to be an efficient and effective technique in all regards and its development was basically halted for two reasons: the first was lack of qualified workers for the installation and the second was the need for advanced geometric and structural knowledge.

The main objective of this project is, therefore, to solve these two fundamental problems.

The starting assumption was to develop a hybrid, parametric component whose geometry was generated by using new parametric software tools (Grasshopper) and whose embodiment was achieved by combining cement, ceramics, and aluminium honeycomb panels.

The parameters used in the geometric definition of the panels were the angle of twist, panel dimensions (width, length, and thickness), and end curvature (Fig. 1.03). These simple transformations enable infinite configurations to be obtained as a function of the geometry it is sought to construct (Fig. 1.04).

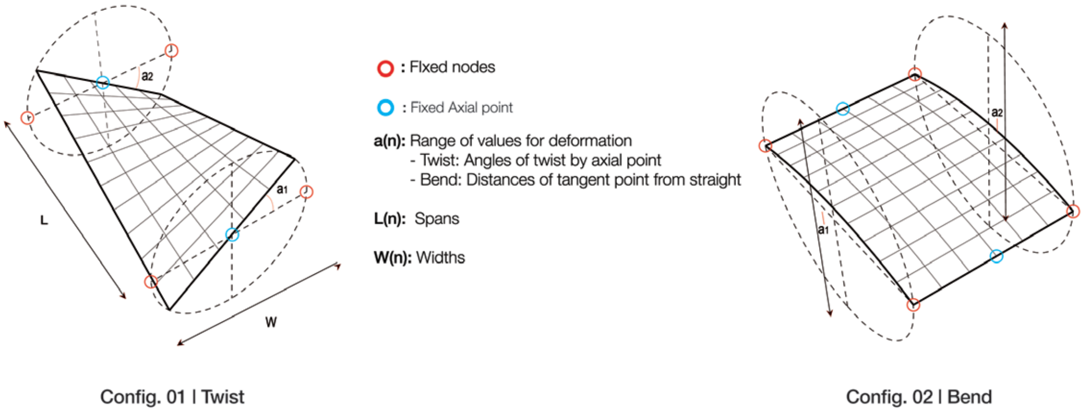


Fig. 1.03 | Geometric Logics. Parameters and Transformations

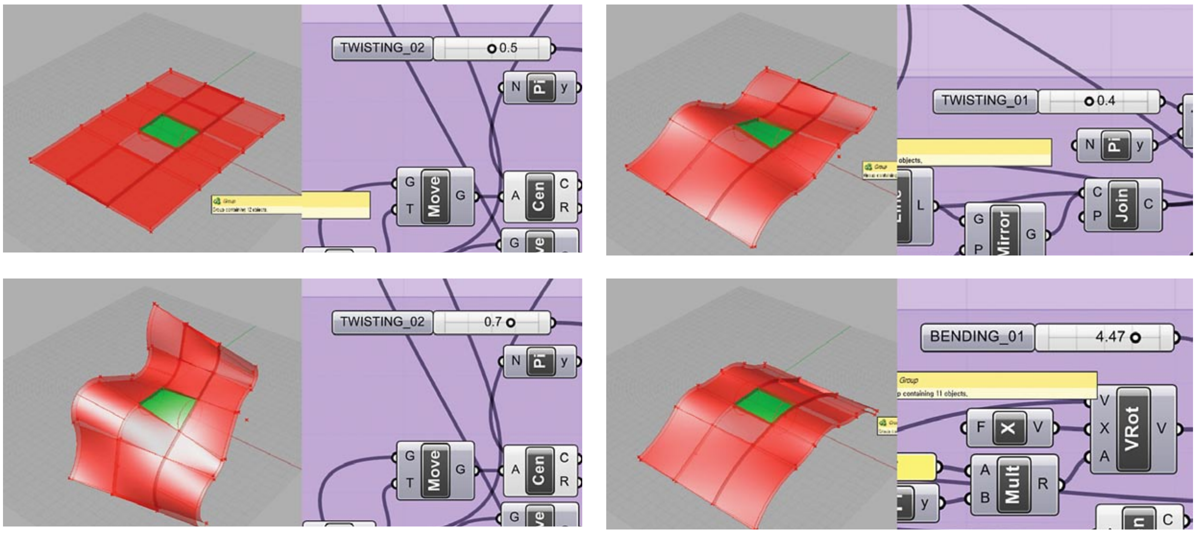


Fig. 1.04 | Parametric configurations generated with Grasshopper

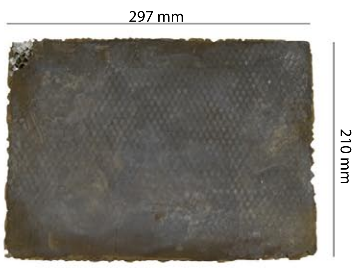
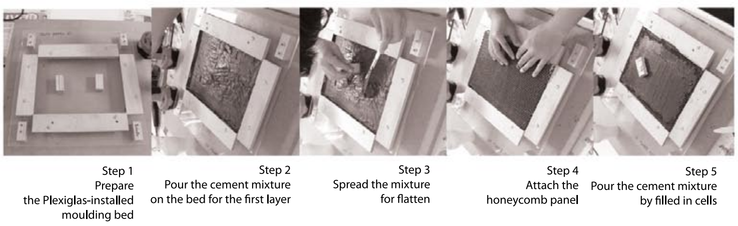


Fig. 3.03 | The sequence of flat panel composite (Honeycomb + Fine Art Cement)



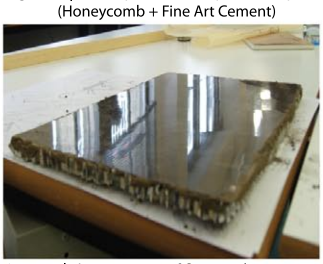


Fig. 3.04 | The sequence of flat panel composite (Honeycomb + Glass Fibre Sheet + Fine Art Cement)

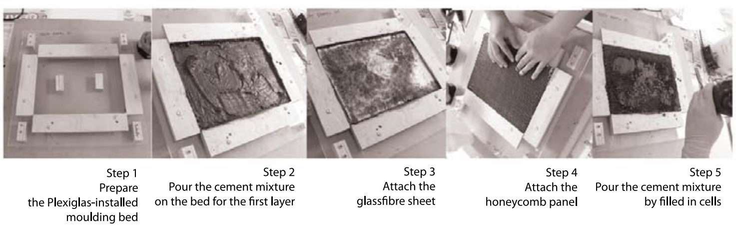


Fig. 1.05 | Test Material. Flat Component Production

In addition, the own shape of the piece increased its strength and its structural performance by following the same principles as those applied in the construction of Dieste's Gaussian vaults.

Once the geometric aspects had been defined, the material embodiment of the new panel needed to be developed. In this case, the concept of reinforced ceramics needed to be interpreted by the development of a composite material that combined the properties of concrete and ceramics with some metal strengthening system.

This is where the idea arose of combining the excellent geometric and structural properties of an aluminium honeycomb panel with those of ceramics. We have called this hybrid system *Reinforced Cellular Ceramics*. First, experiments were conducted with flat pieces that combined cement with honeycomb panels (Fig. 1.05). This was done in collaboration with Alucoat (a company that makes honeycomb panels), which supplied us with A4 size panels that had a cell size of 6 mm and panel thickness of 10 mm.

On the other hand, the possibilities were also verified of incorporating transparency or ventilation spaces in these pieces. For this purpose, experiments were conducted with the piece leaving an area of the honeycomb panel without any material and then adding polyester resin (Fig. 1.06). The result was a piece that was able to incorporate openings and voids, while also displaying the plastic and reflexive properties of the honeycomb panel.

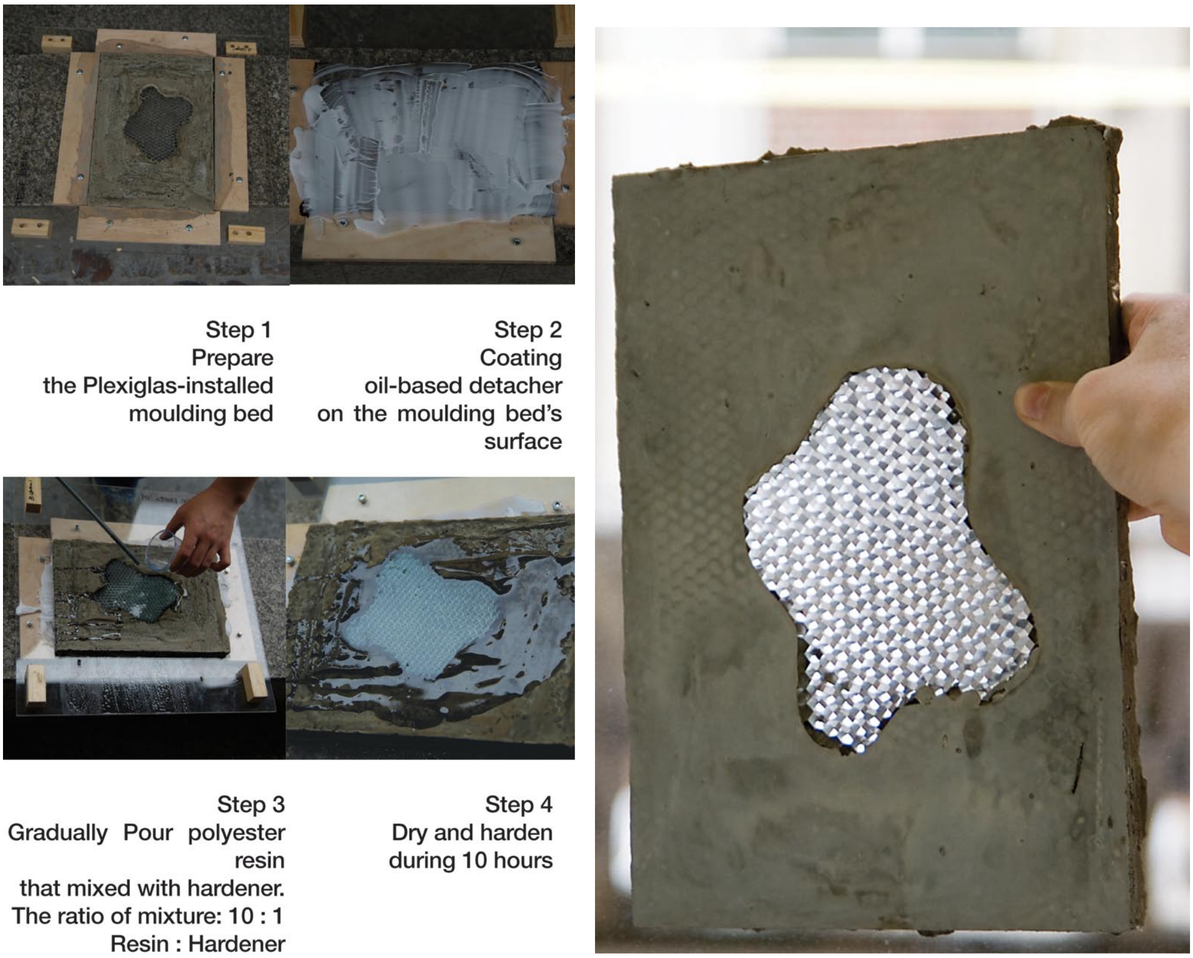


Fig. 1.06 | Test material. Transparency produced by applying Polyester Resin

As a result of this first experiment, it was verified that the combination of the honeycomb panel and cement produced a resistant piece with a potential application as a structural element and transparent or opaque building envelope.

The second experiment focused on making a three-dimensional piece in accordance with the geometric studies developed using parametric software.

For this, a mould system was designed, such that different geometries could be made in accordance with the computer-generated configurations (Fig. 1.07).

The system enables pieces of different sizes and geometries to be made thanks to guides that allow the mould to be adjusted in height and width, as well as the angles of twist and the curvature radii of the perimeter edges of the piece to be controlled. Moreover, the mould system was devised in terms of a three-layer system (Fig. 1.08).

The intermediate layer consisted of a honeycomb panel with a thin latex surface coating. This layer allows the piece to be given a finish while also, thanks to the honeycomb panel, supporting the weight of the poured cement mixture and perfectly controlling the geometry of the finish surface.

The other two layers were those of the fabrication of two symmetrical components.

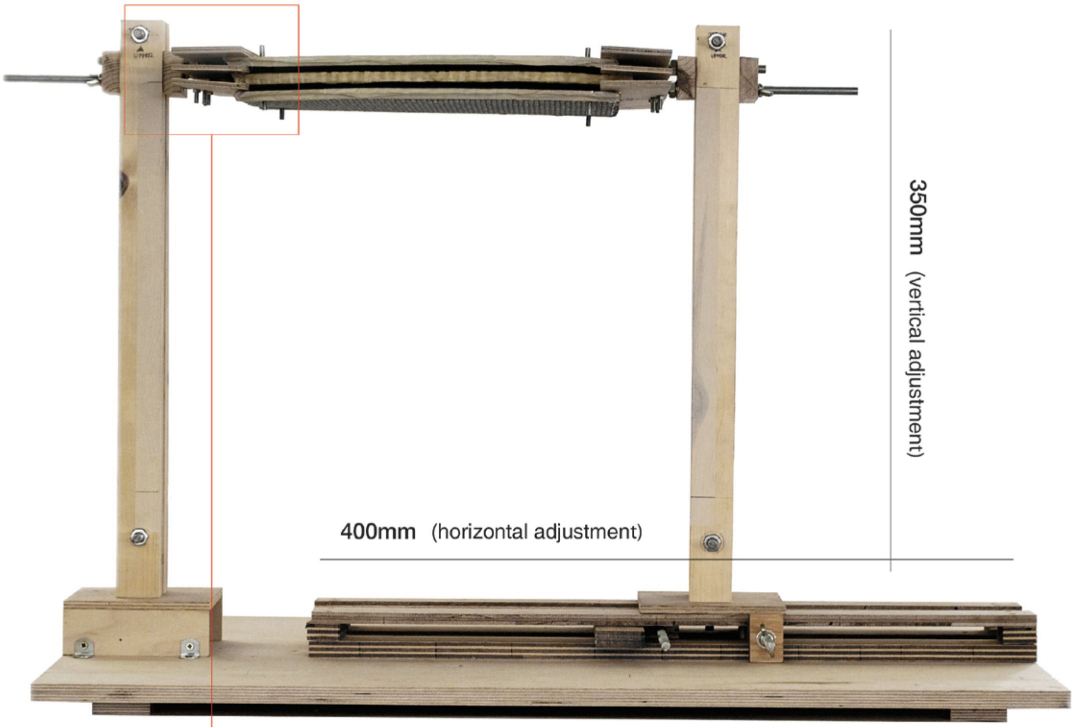


Fig. 1.07 | Prototype of the parametric mould system

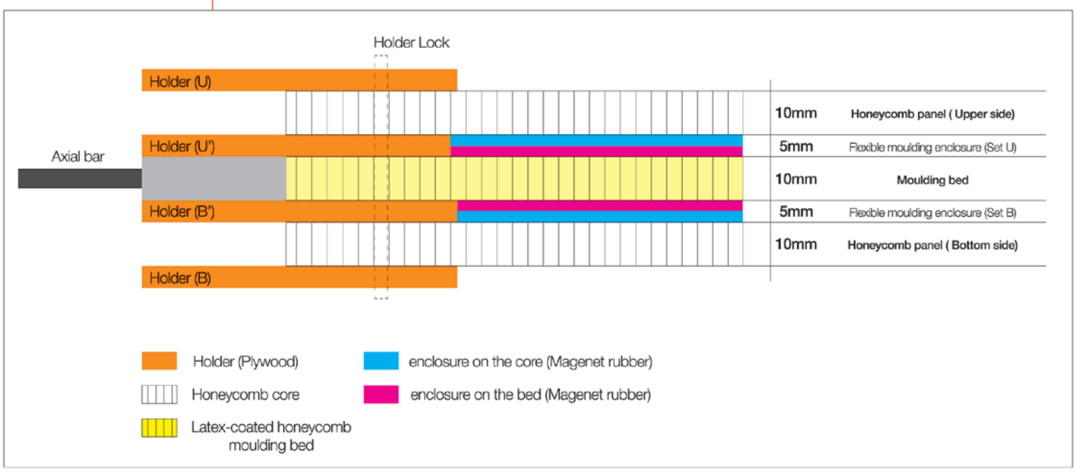


Fig. 1.08 | Cross-section detail of the parametric mould system

To start with, a first layer of cement was applied and the honeycomb panel was adjusted to the geometry of the mould. The geometry was determined by the digitally generated variables in the parametric model. The data were transferred from the computer to the parametric mould system, thus enabling different panel configurations, which could be either curved (Fig. 1.09) or warped (Fig. 1.10). The next step involved applying the cement layer with the final thickness of the chosen panel.

When the panel drying or setting process (depending on whether it was made of ceramics or cement) had ended, the mould was rotated 180º and the same process was followed for the fabrication of the symmetrical piece, thus defining the two faces of the panel in which the honeycomb panel structure was embedded.

The piece produced by this process is a three-dimensional concrete panel reinforced with a honeycomb panel with notable geometric and structural properties (Fig. 1.11), which allows one to envisage the construction of complex double-curvature surfaces by adding and controlling a certain number of three-dimensional parametric components.

The experiments were performed with fast-setting cement and limited technical resources. The development and industrial production of the system are the subject of the investigation being conducted at the Swiss Institute of Technology Zurich (ETHZ).

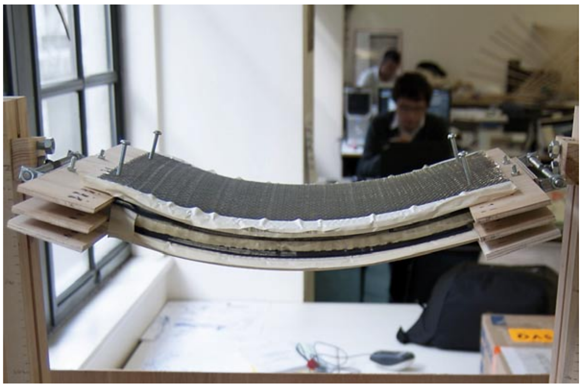


Fig. 1.09 | Mould prepared for a three-dimensional curved piece

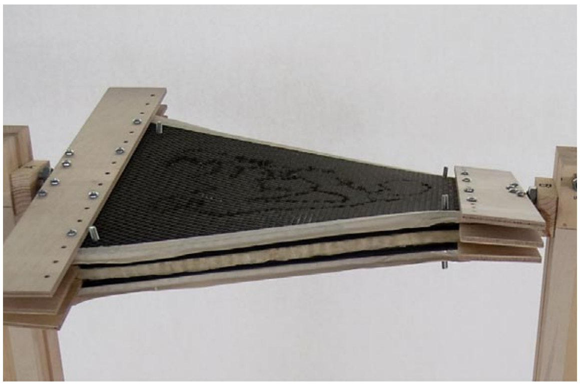


Fig. 1.10 | Mould prepared for a three-dimensional warped piece

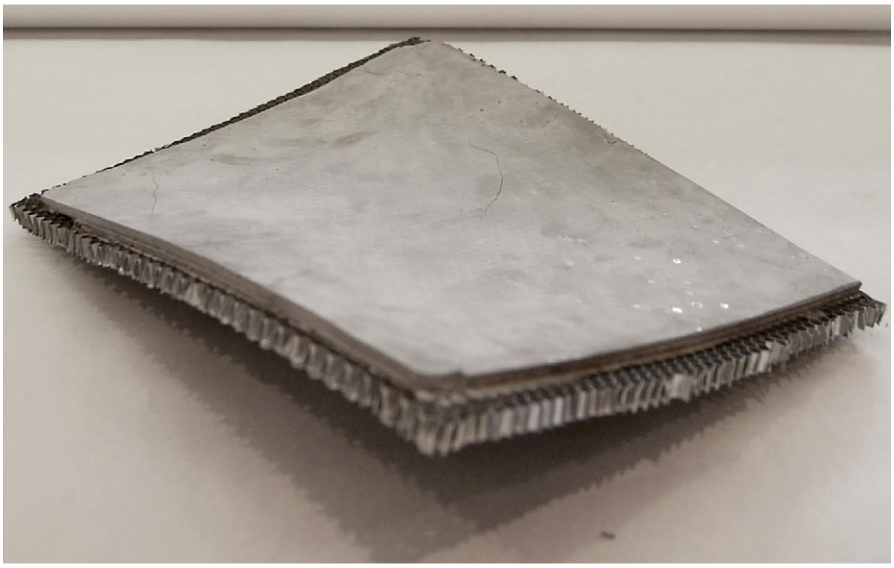


Fig. 1.11 | Three-dimensional panel of reinforced cellular concrete

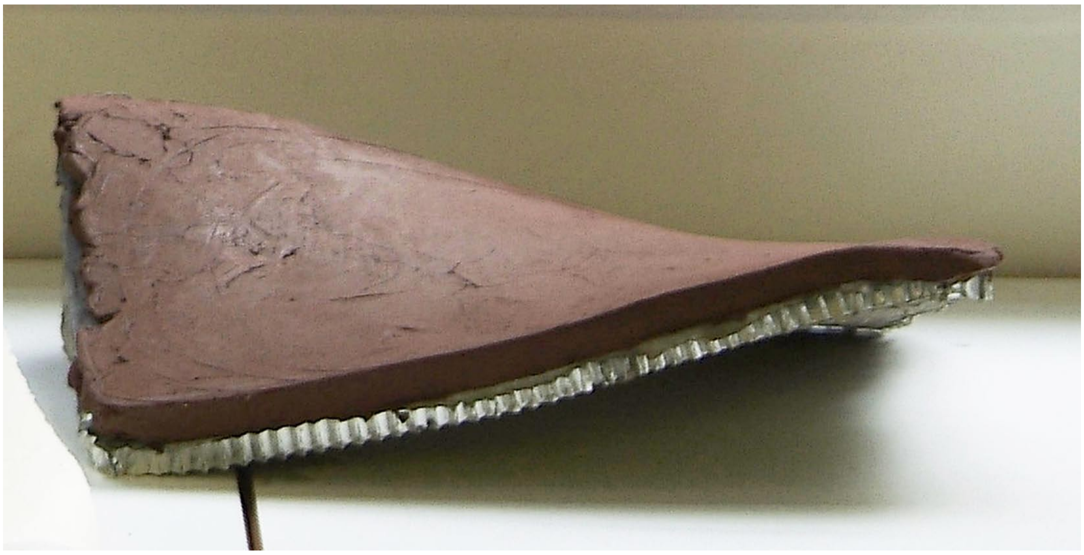


Fig. 1.12 | Model of a reinforced ceramic panel

For the fabrication of ceramic pieces, the parametric mould also adjusted its geometry to the digitally generated parameters and the ceramics layer was applied on the mould. The piece was then put into an oven and, after drying, the hybrid panel of ceramics, cement, and the honeycomb panel was made (Fig. 1.12).

A piece was thus produced that combined the innumerable benefits on a technical, aesthetic, and economic level of ceramics with the structural and geometric properties provided by a cellular concrete panel.

The developed system would allow sequences of three-dimensional components with a double curvature to be made, incorporating variation and geometric freedom (Fig. 1.13). Moreover, the system opens up new possibilities for the construction of architectures generated by means of the parametric design tools that have been developed in recent years and the exploration of their formal and spatial potential.

Fig. 1.13 | Sequence of parametrically generated panels

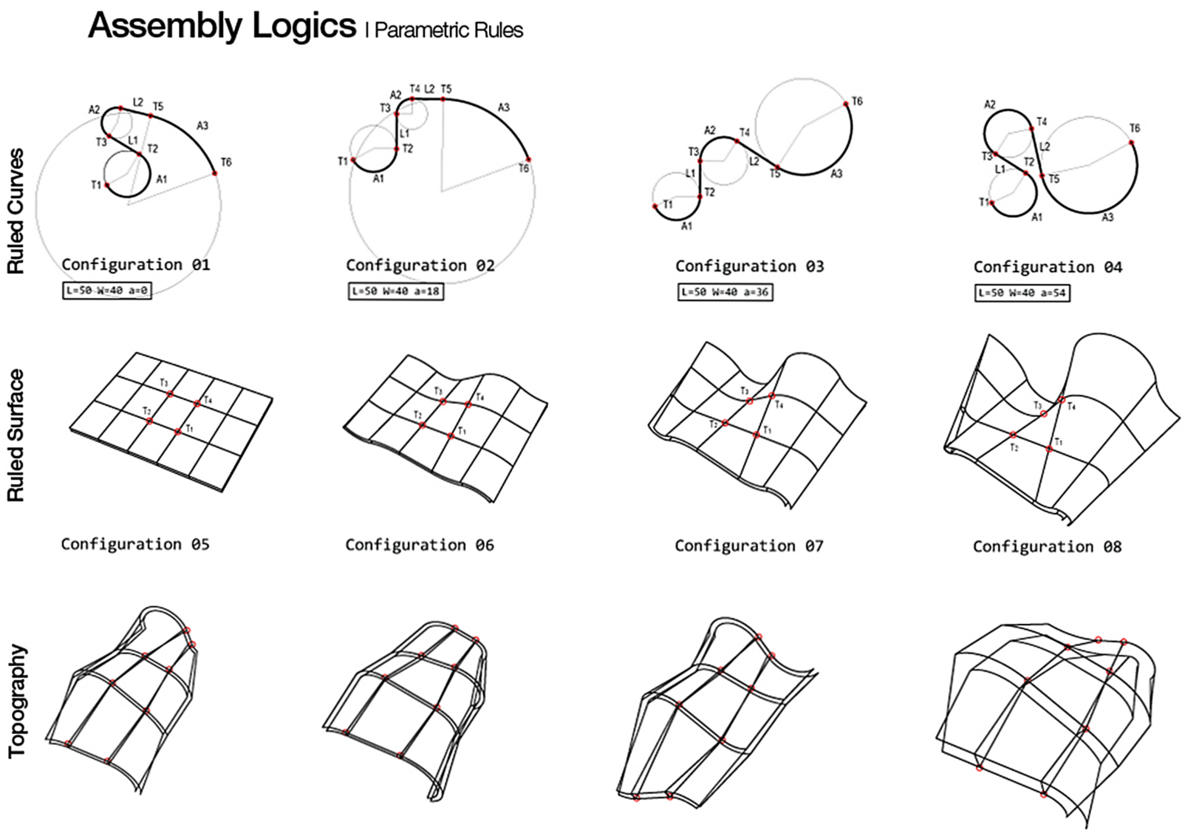


Fig. 1.15 | Assembly Logics. Geometric Principles and generation of surfaces

The main aim was that this system should work without needing to add any further type of structure, in order thus to explore all its architectural, structural, and spatial possibilities.

The next step in the development of the system dealt with the construction and assembly of a given number of three-dimensional panels of reinforced cellular ceramics (Fig. 1.14). The assembly system used geometric principles to assure fabrication control of the components and continuity between the joints generated by the components. On the one hand, geometric principles of tangency were used and, on the other, regulated surfaces and surfaces organised in layers were tested as topographies (Fig. 1.15).

Fig. 1.14 | Assembly of 4 panels according to digitally generated geometry

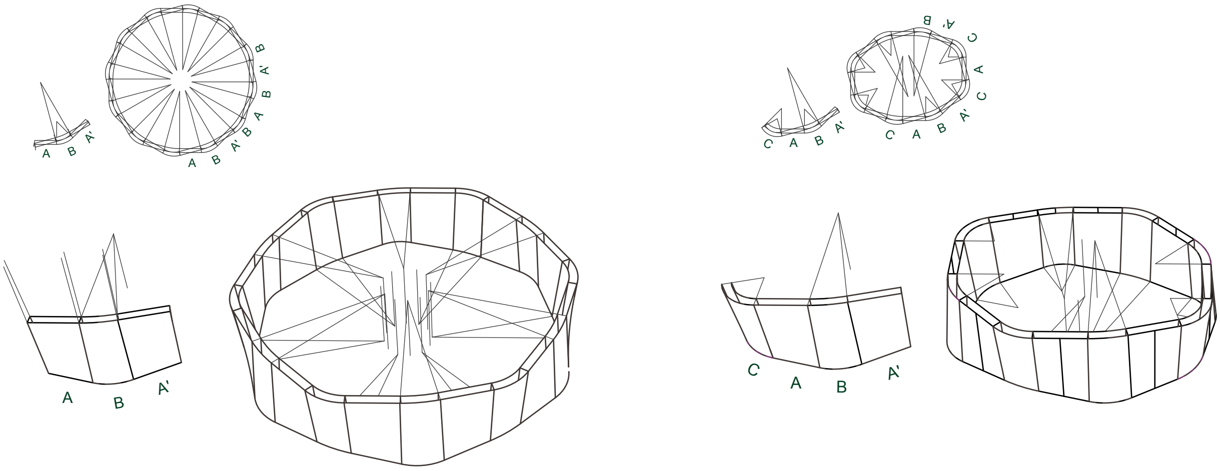
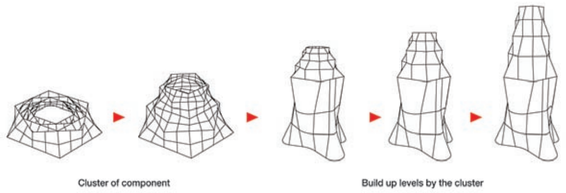


Fig. 1.16 | Additive Logics for the configuration of complex surfaces

In the project, the capability was sought of controlling the geometric complexity of the generated surfaces. Thus, depending on the economic requirements and specific needs of a project, surfaces can be generated from a limited number of components (Fig. 1.16).

Following this logic one can configure, for example, various types of vaulted structures (Figs. 1.17 and 1.18). These structures are parametrically generated and controlled and it is thus possible to verify their structural performance by means of virtual load simulations. The last step in this process phase focused on the construction of a real-scale prototype. In this prototype, the technical solution of the unions was developed, as well as system structural and materials tests.



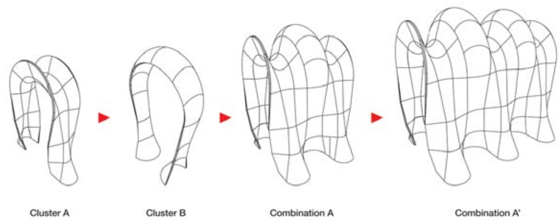
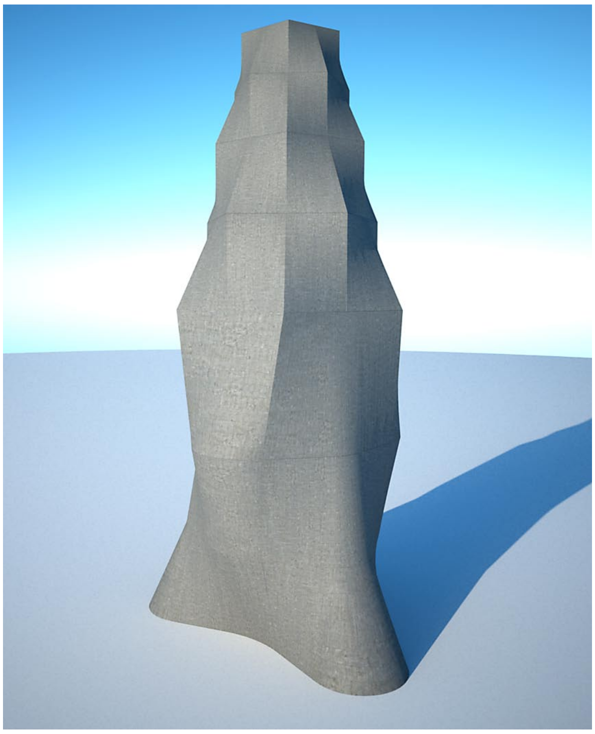
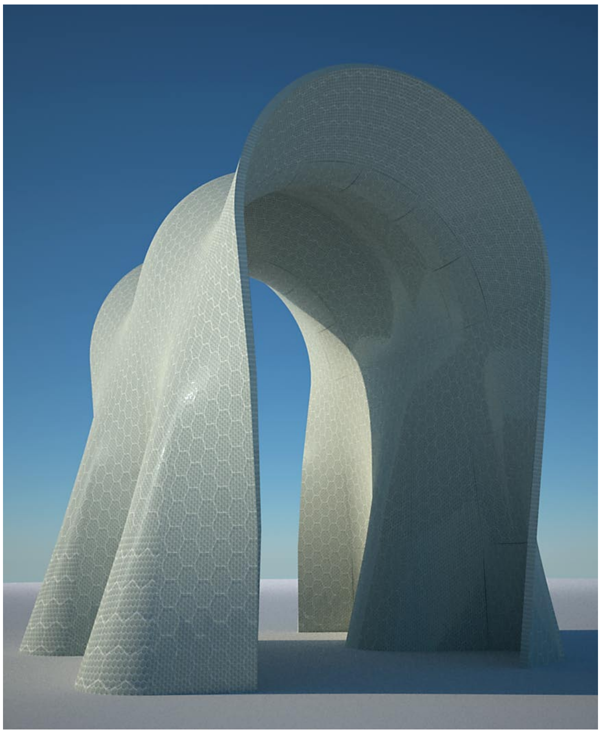


Fig. 1.17 | Parametric Generation of the Vault

Fig. 1.18 | Parametric Generation of the Vaulted structure





2.2. PROCESS PHASE 02

Reinforced Cellular Ceramics

Fig. 1.19 | Sample of NEX Aluminium Honeycomb Panel.

When the first phase of the investigation had been concluded, the second phase began in which the objective was to work with the system on a larger scale. All the experiments conducted in the first phase were based on the use of expanded aluminium honeycomb panels. These panels were supplied by the collaborating company Alucoat, with standard cell dimensions of 6 mm and 420x300 mm format.

However, the fabrication process of the aluminium honeycomb panel begins with a block of aluminium from which a non-expanded slice (NEX) is cut. Before it is expanded, this mesh is flexible and displays an enormous geometric potential (Figs. 1.19 and 1.20). Using the NEX panel as a base, a new investigation phase commenced in which the combination of this NEX mesh and ceramics was explored. This combination was linked to the system of reinforced ceramics developed by Eladio Dieste at the end of the 1970s.

While the mesh is a flexible material that can work well under tensile stress, ceramics are non-deformable components with excellent performance under compression (Fig. 1.21). The combination of these geometric and structural logics was targeted in the definition of a new material system.

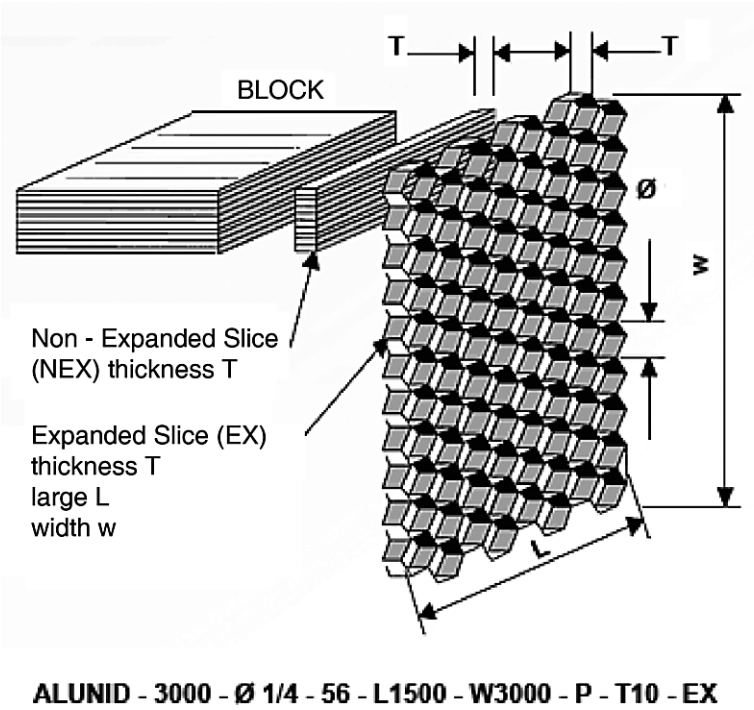


Fig. 1.20 | System of ALUCOID honeycomb panel fabrication

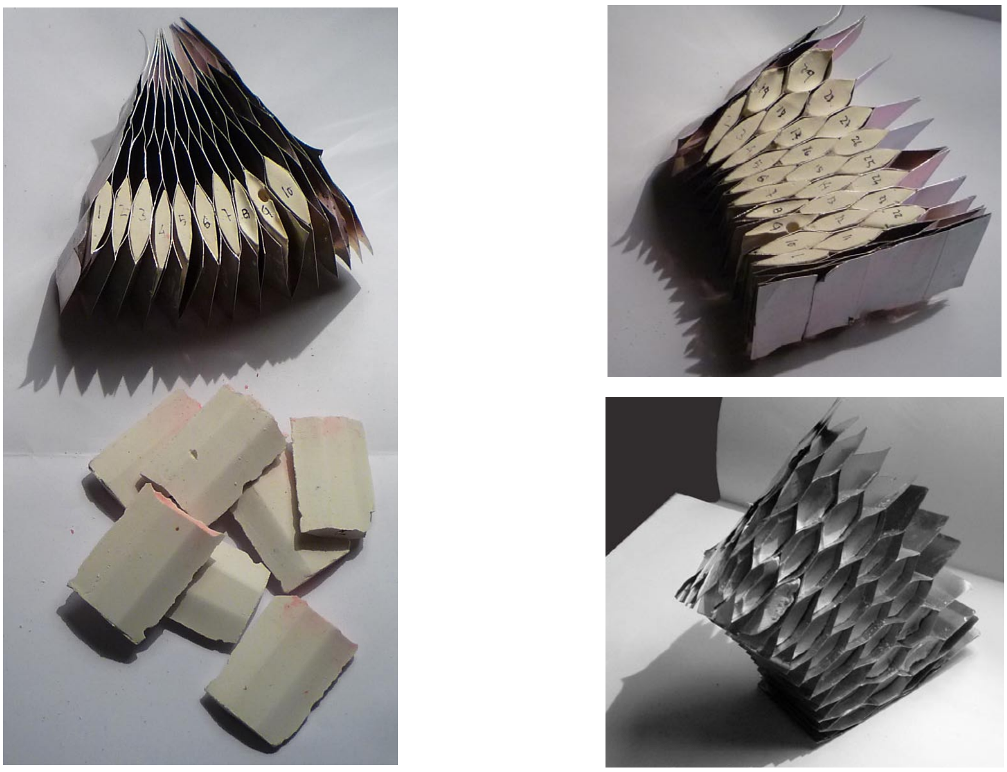
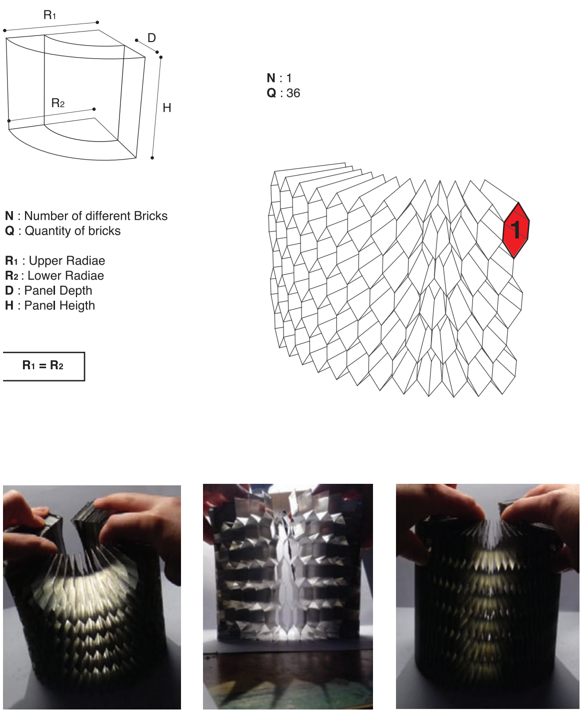


Fig. 1.21 | Cellular Ceramics. Model of the Material System



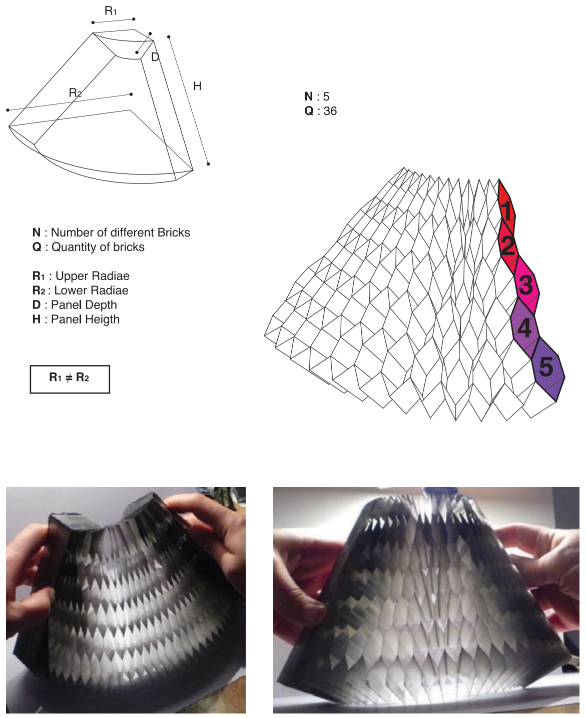


Fig. 1.22 | Geometric System. Cylindrical Surfaces

Fig. 1.23 | Geometric System. Conical Surfaces

Once the research objective had been defined in this second phase, the first step in the process centred on the geometric exploration of the system. It was principally explored how the geometry of the ceramic components (under compression) could define the overall NEX mesh shape (under tension).

In a first case, the definition of cylindrical surfaces was explored by curvature radius using a single component (Fig. 1.22). Secondly, the geometry of the component was varied to generate conical surfaces (Fig. 1.23). It may be observed how complex surfaces can be generated by making a limited number of ceramic components (Fig. 1.24). A dependence was, therefore, established between overall surface curvature radius and the geometry of the ceramic component.

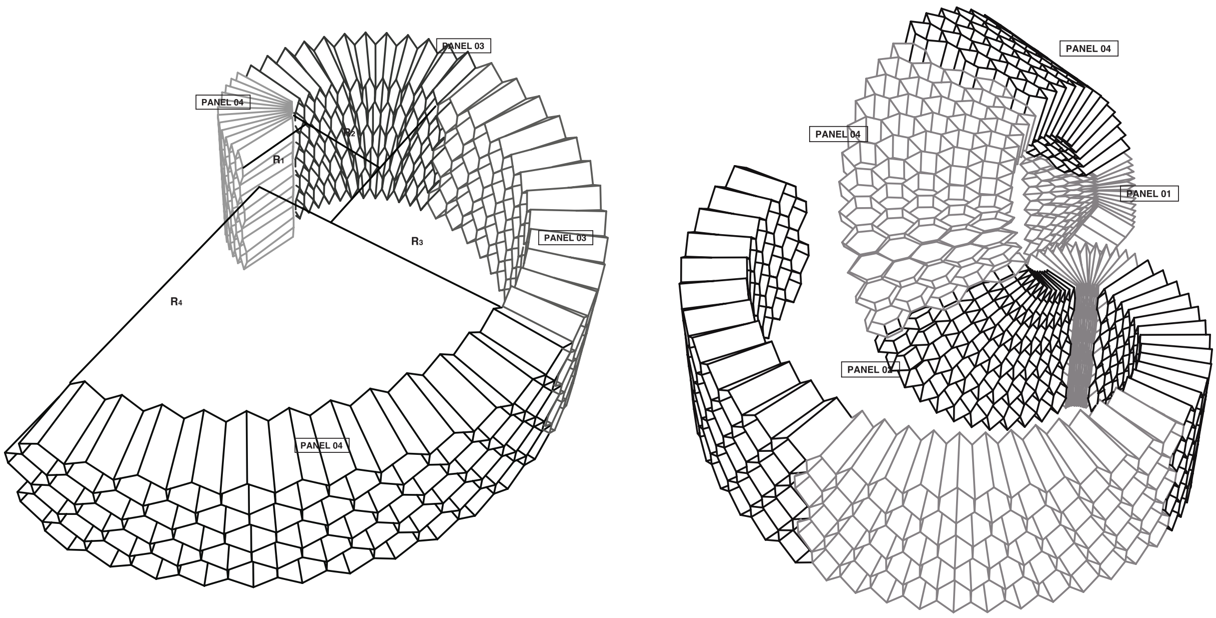


Fig. 1.24 | Geometric System. Combination of cylindrical and conical surfaces

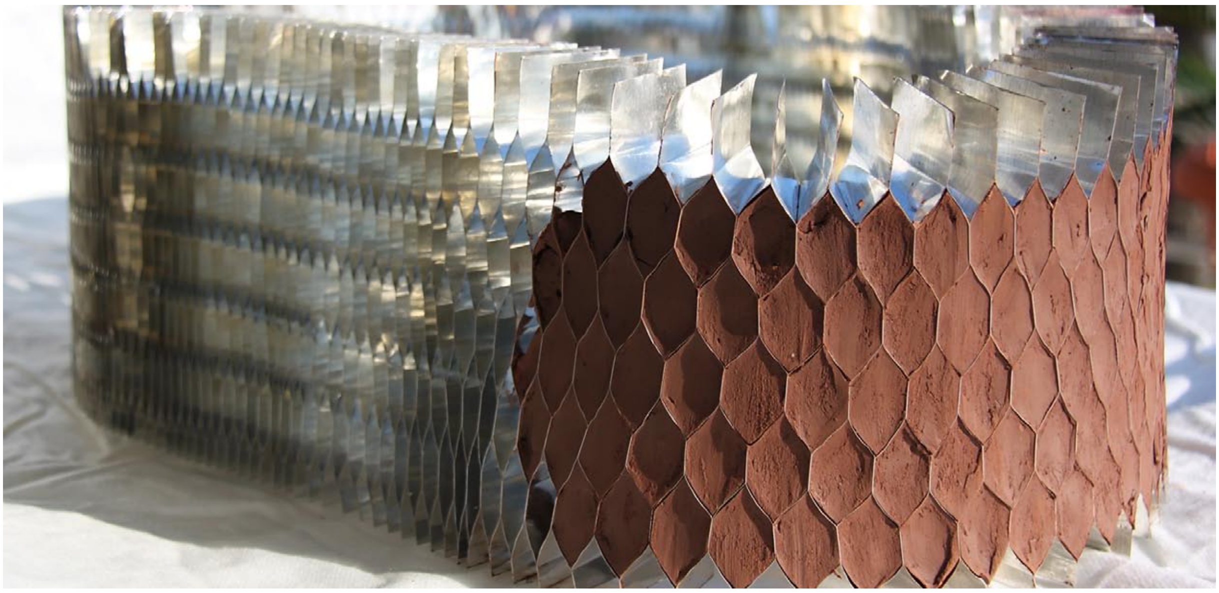


Fig. 1.25 | System test material. NEX mesh + Ceramic pieces

The following step in the process focused on the study of the ceramic component from a performative viewpoint. On the one hand, the material embodiment of the system and its aesthetic potential were studied. The combination of ceramic pieces with the NEX mesh allowed different colour combinations and different degrees of transparency (Fig. 1.25). Furthermore, a system was sought that would adapt to different environmental and spatial constraints. For this purpose, the component was studied as an element that varied according to different parameters.

For example, on a structural level, the system did not have the same requirements across the entire surface, so that varying the ceramic component enabled opacity gradients to be generated, providing different degrees of light and transparency (Fig. 1.26).

A digital, parametric, and performative model was thus developed that reacted to different structural, programme or environmental factors.

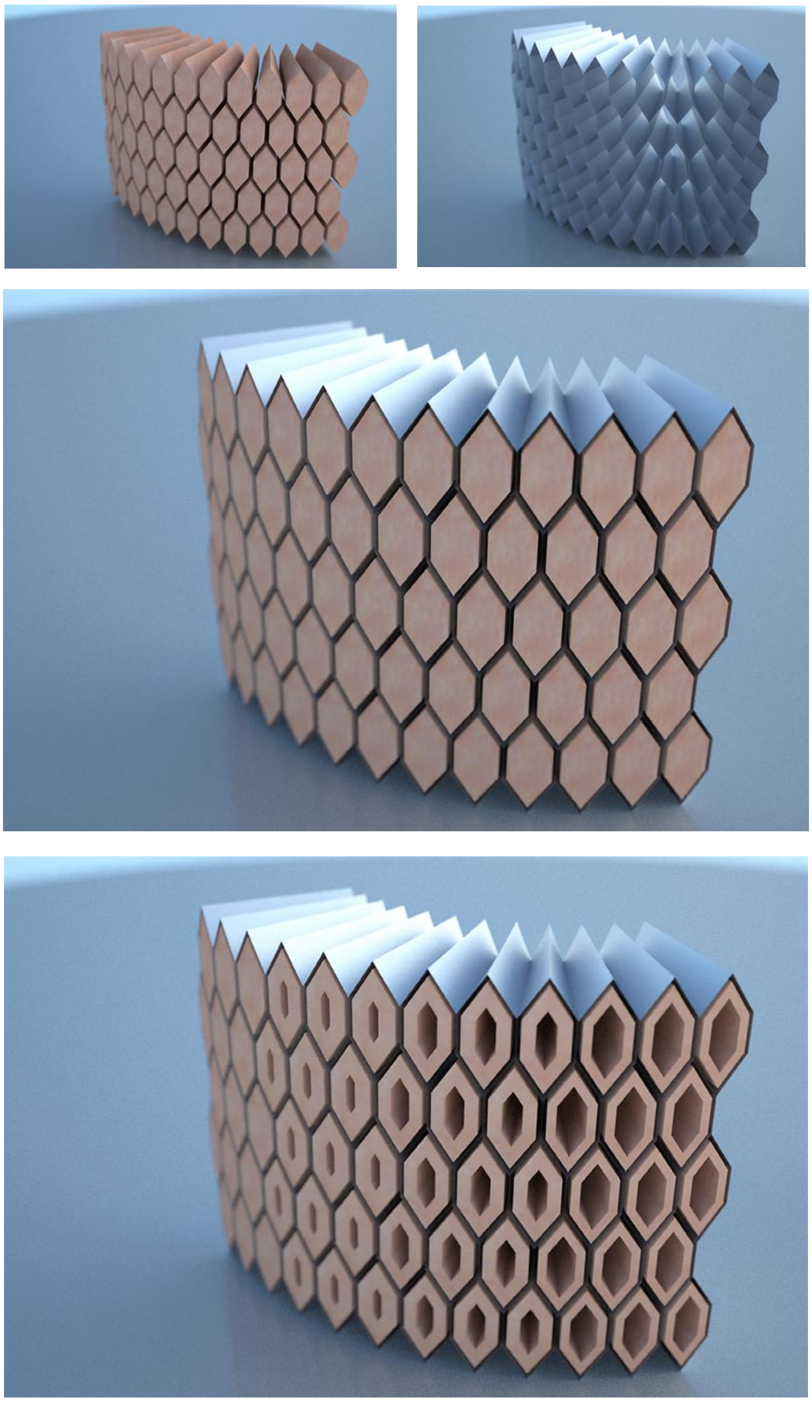


Fig. 1.26 | Parametric Model. Transparency gradient according to structural or environmental requirements

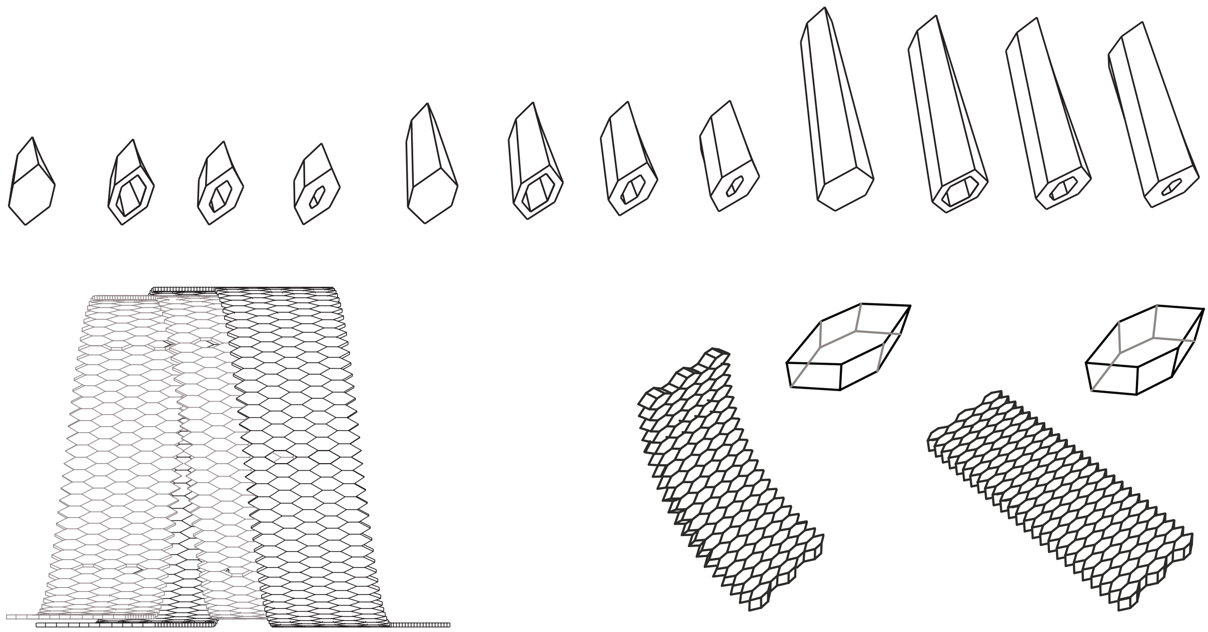


Fig. 1.27 | Construction of loops by means of flat surfaces and simple curvature.

The investigation continued with the study of the possible architectural applications of the system. For this, first, the addition of ceramic components for the construction of flat surfaces and a simple curvature was studied (Fig. 1.27). The assumption was made that, with a single piece for the flat areas and another for the curves, it would be possible to generate loops that organised a continuous architectural space. The parametric model evolved according to these principles (Fig. 1.28) and, with only two ceramic components, it allowed an infinite number of loops to be configured. This system of loops was the basis for the architectural study (Fig. 1.29).

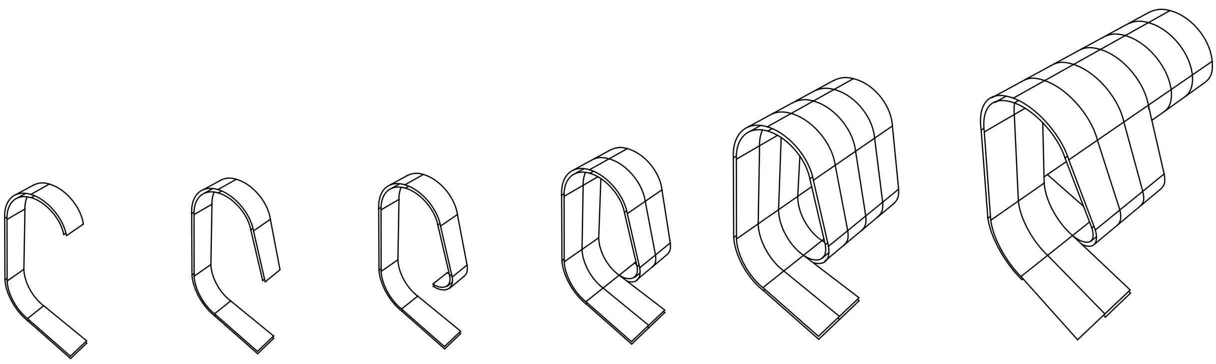


Fig. 1.28 | Example of the evolution of the architectural system. Parametric Model.

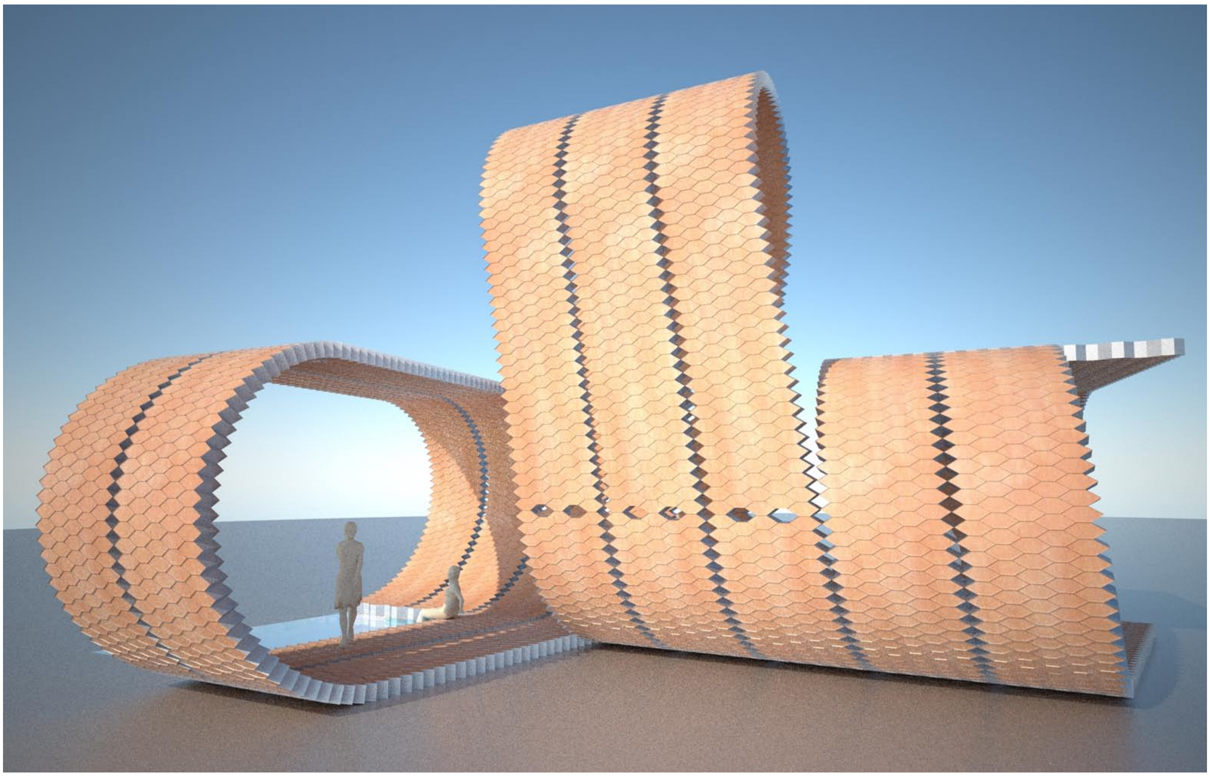


Fig. 1.29 | Possible spatial configuration. Digital Model.

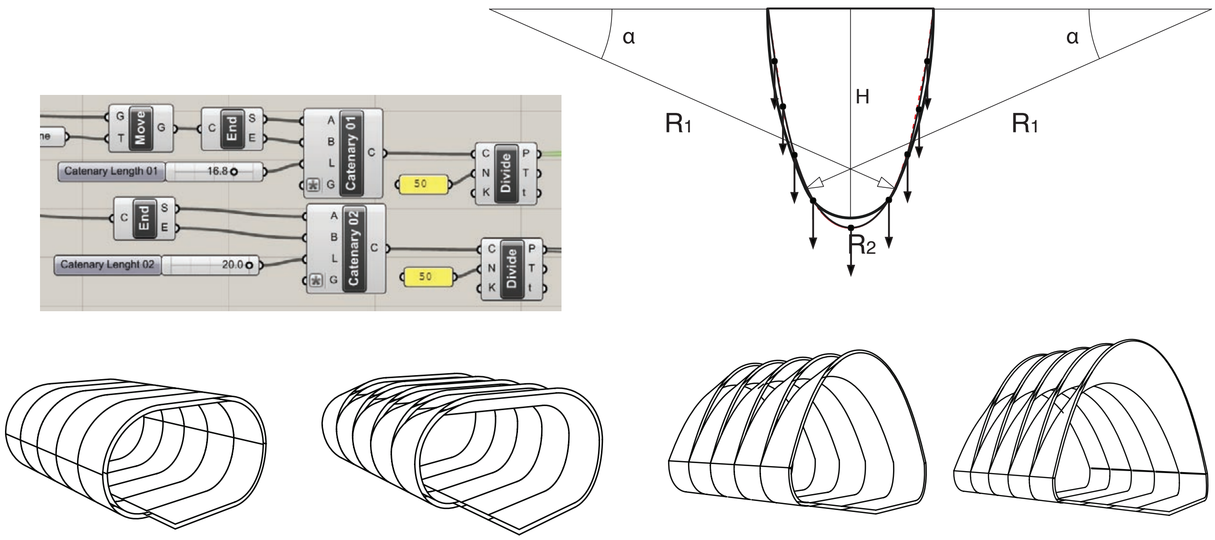


Fig. 1.30 | Parametric Model. Study of Chain Loops

The system of loops was based on geometric, constructive, and spatial premises. However, it lacked the incorporation of structural principles. For this, the parametric model was implemented by a structural principle based on chain curves (Fig. 1.30). This system was used by Eladio Dieste for the efficient construction of his elegant Gaussian vaults and, in this case, they modified loop geometry by incorporating an improvement in its structural performance.

As a result, the surfaces were regulated and a greater variety was required in the fabrication of ceramic components. According to the previously defined principles, it would be necessary to have a piece for each different curvature radius. It was therefore necessary to re-evaluate the fabrication system and to study, in collaboration with industrial companies from the sector, the possibility of producing pieces with a non-linear extrusion. This is one of the issues that are currently being developed for the subsequent study of double-curvature surfaces.

Fig. 1.31 | Architectural application. Access Pavilion to La Alhambra. Digital Model.

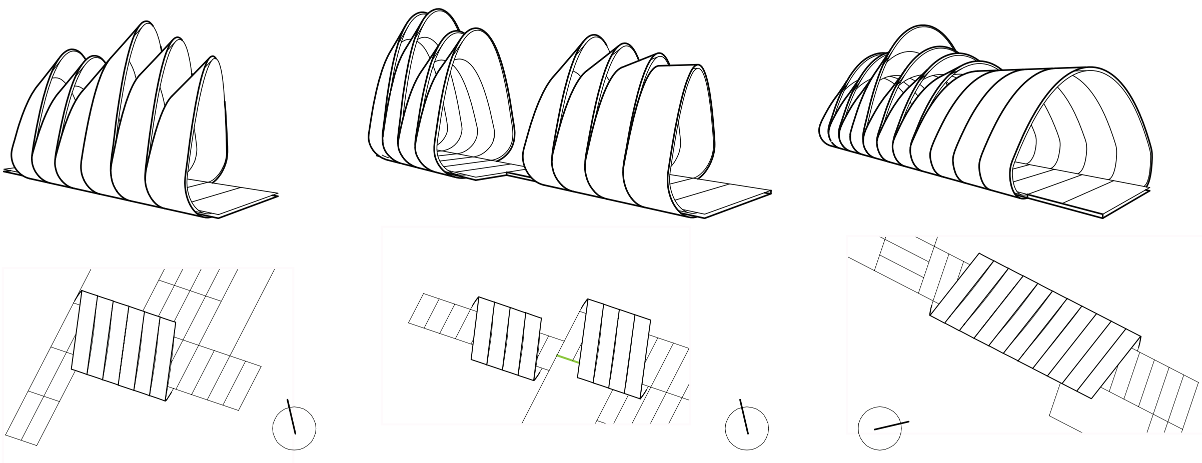


Fig. 1.32 | Parametric Model. Application of Environmental and Programme Parameters.

The project concludes with the application of the system in a particular context, with a specific programme. The construction of a new access pavilion to La Alhambra of Granada is involved (Figs. 1.31 to 1.33). The parametric model must therefore react to environmental and programme parameters. The model reacts to the different orientations and adapted to the programme requirements of the project (Fig. 1.32).

In short, this technique incorporates principles inherited from the building tradition and the benefits of the use of local plastic materials and it opens up an innovative path in the development of new structural applications in avant-garde cohesive construction.

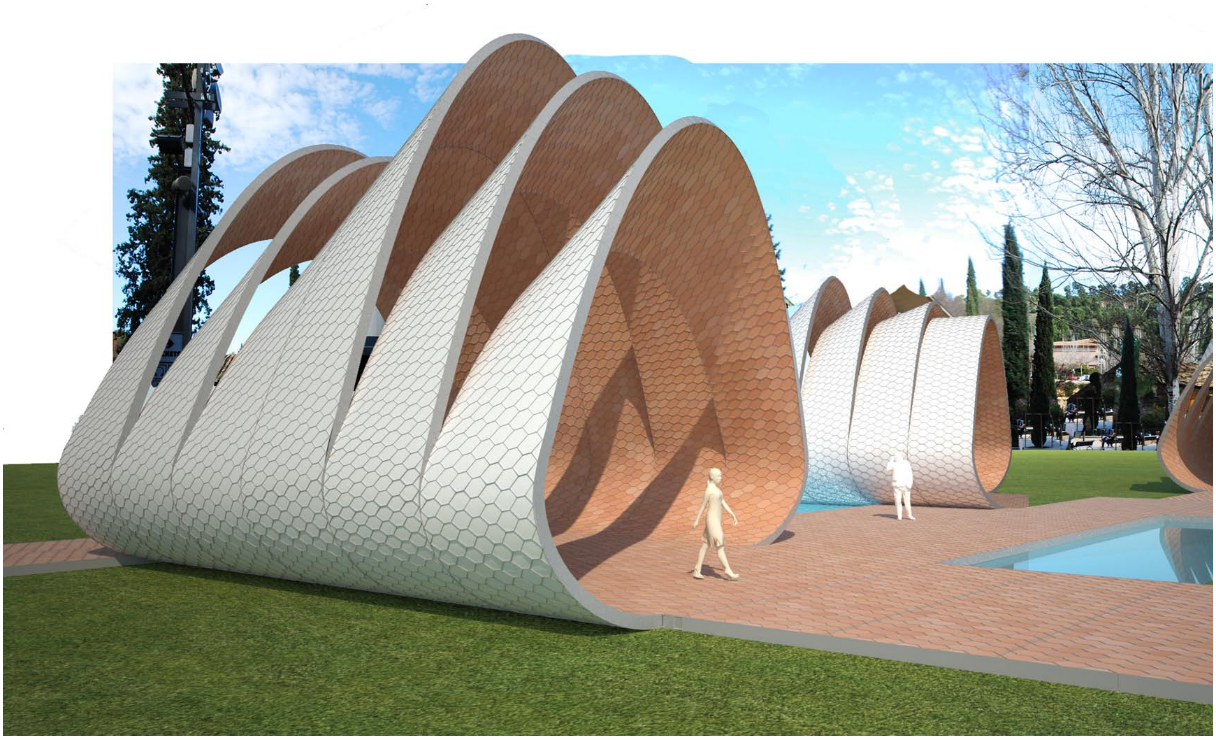


Fig. 1.33 | Architectural application. Access Pavilion to La Alhambra. Digital Model.

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***** All the images were made by the authors of the project, except Fig. 01 by Ryan Budhu and Fig. 02 by Juanitta (source Flickr)

3. CREDITS

COLLABORATORS PHASE 01:

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