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CASTonCAST: Superficies arquitectónicas complejas a partir de componentes prefabricados apilables

CASTonCAST: Architectural freeform shapes from precast stackable components

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Resumen: Este artículo presenta el sistema CASTonCAST para el diseño y la producción de superficies arquitectónicas complejas a partir de componentes prefabricados apilables. Este sistema está compuesto por dos partes complementarias: una innovadora técnica de fabricación de componentes prefabricados apilables y un nuevo método geométrico para el diseño de superficies complejas a partir de baldosas sólidas apilables. Este trabajo describe las dos partes del sistema mediante prototipos físicos y estudios geométricos.

Palabras clave: Técnicas de moldeado, Hormigón prefabricado, Diseño y fabricación, Geometría arquitectónica, Superficies arquitectónicas complejas.

Abstract: *This article introduces the CASTonCAST system for the design and production of architectural freeform shapes from precast stackable components. This system is composed of two complementary parts: a novel manufacturing technique of precast stackable building components and a new geometric method for the design of freeform shapes by means of stackable solid tiles. This paper describes both parts of the system by means of physical prototypes and geometric studies.*

Keywords: *Casting techniques, Precast concrete, Fabrication-aware design, Architectural geometry, Architectural freeform shapes.*

INTRODUCTION

During the last 50 years, the use of freeform shapes in architecture has been an upward trend. However, traditional construction techniques have difficulties to materialise such shapes in a sustainable and efficient manner. This problem has been tackled from two main approaches. The first approach focuses on developing new manufacturing techniques and technology able to efficiently produce geometrically complex large-scale building elements. Among these, it is worth mentioning the novel techniques for casting concrete building elements using flexible formwork[1]; Additive Manufacturing technologies (AM) such as D-Shape[2], Contour Crafting[3], Concrete Printing[4] and Smart Dynamic Casting[5]; Subtractive Manufacturing technologies (SM) such as CNC milling[6] and 3d-cutting; and novel technologies for deforming flat panels into a desired shape such as glass bending technology[7], flexible molding systems[8] and CNC-fabrication of curved steel panels.[9]

The second approach focuses on developing new geometric methods which convert constraints from existing manufacturing techniques into geometric constraints. Some well-known examples of this approach are panelling techniques for modelling freeform shapes from planar quadrilateral panels[10], single curved panels[11] or ruled surface panels.[12] Furthermore, there is also research which seeks to minimise the number of double-curved custom panels in a given shape.[13] Both approaches show that freeform architecture is a multidisciplinary field which demands advances both in manufacturing and geometry.

This paper introduces the CASTonCAST system[14] for the design and production of architectural freeform shapes from precast stackable components (Figure 1), which emerges from a concurrent research in manufacturing and geometry. The main advantage of the system is that it eliminates the need of costly molds, making the production of freeform shapes in concrete more efficient and sustainable. Furthermore, the method has also advantages in the storage and transportation of the components to the construction site. The system consists of two complementary parts:

1. *A novel manufacturing technique of geometrically complex building components which relies on producing a series of components in stacks by using the previous component as a mold for the next one.*

2. *A new geometric method, which emerges from the constraints of the manufacturing technique, for the construction of freeform shapes by the connection of stackable solid tiles.*

The manufacturing technique together with the geometric method create a cohesive system for the design and production of architectural freeform shapes. In this system the geometric method is in charge of simplifying complex freeform shapes into stackable components, while the fabrication technique makes possible the production of stackable components in a sustainable and efficient manner.

The paper is structured as follows: in the first section the concept and basic functioning of the manufacturing technique are described. Furthermore, material requirements for running the manufacturing technique are specified; the second section describes the concept of the geometric method, its application in the stack-to-strip modelling technique and finally it discusses the role of the main parameters involved in this modelling technique for the design of freeform shapes; the third section presents a series of physical prototypes which exhibit the potentials of the system; in the fourth section, the limitations found in the system are briefly discussed; and the conclusions and future research are given in the last section.

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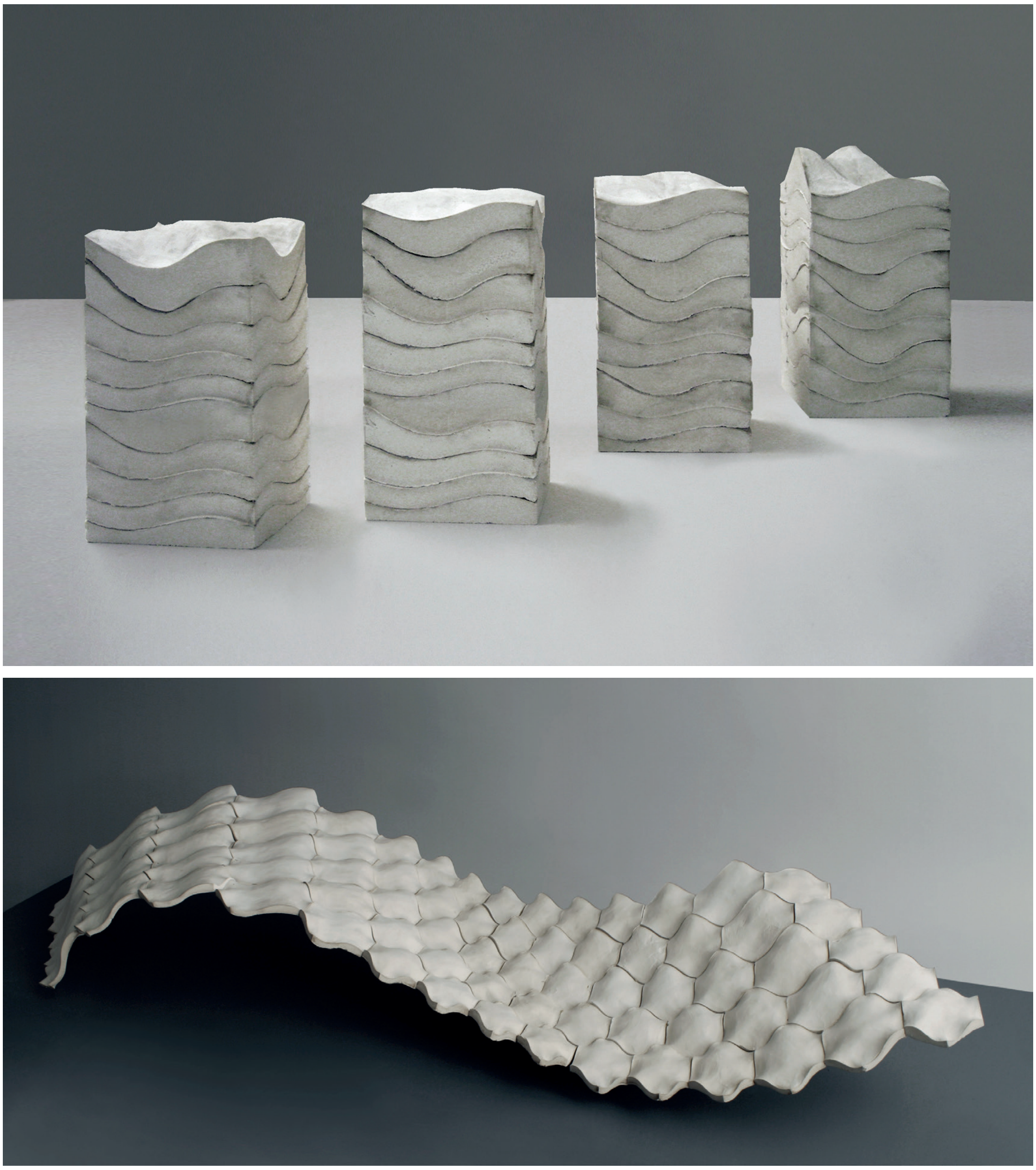

Figure 1. *Prototypes produced using the CASTonCAST system. Above: Components in stacks. Below: Stackable components assembled together giving shape to a freeform shell.*

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FABRICATION TECHNIQUE

Concept and step-by-step functioning

CASTonCAST begins with the ambition of developing a new concept of production whose goal is to produce different building components in an efficient and sustainable manner by reducing the production costs and the material waste. From this ambition, we proposed a chained production system which relies on producing a series of building components always using the previous component to give shape to the next one: component "A" is used to give shape to component "B", then "B" is used to give shape to component "C" and so on. From this concept we developed a manufacturing technique of curved building components which relies on casting a series of components one on top of another in stacks by using the previous component as the bottom mold of the next component.[15] *In this manner, not two but only one curved surface needs to be given shape per component. Different techniques for giving shape to the top surface are later discussed. Once all the components are manufactured one on top of another, they are separated from each other and ready to be rearranged and assembled together in the desired manner.*

This manufacturing technique can be used to produce building components for two main different functions: cladding components with not required load-bearing capacity and structural components for the construction of shell structures. In each of these cases, the scale and materials of the component, as well as the production, transportation and assembly procedures may vary. The main steps for running the manufacturing technique are:

1. *Making the lateral molds.*
   The casting of one stack of components is done using a series of simple molds, one per component, which serve as formwork for the flat lateral faces of the components. Since the components are stackable, their lateral molds are also stackable. Due to this, these molds can be manufactured together by cutting their stackable parts from flat sheets of material (Figure 2a). This reduces the material waste and the production time.

2. *Making the base.*
   The first casting component of a stack does not often have a bottom flat surface. Due to this, it is necessary first to manufacture a base. This can be cast like the rest of the components of the stack or built using another technique.

3. *Casting the first component.*
   For casting the first component (Figure 2b), first the lateral mold is placed over the base. By doing this, only the top side of the mold remains open. Second, if required, the steel reinforcement and other assembly devices are placed and fixed inside the mold. Then, the mold is filled with a concrete which has a sufficient yield stress to allow it to be shaped. Finally, the top surface is manually shaped by sliding a bar element along the edges of two opposite sides of the lateral mold or by using other simple tools. This process will be easier when the curvature of the top surface is not too complex such as when the top surface is a ruled surface, a translational surface or a freeform surface without sharp changes of curvature. For this reason, it will be important to control the geometric method in order to obtain an appropriate curvature on the top surface of the components. As we will see later, the curvature of the top surface of the components depends on the number of components used to define the global curvature of the shell.

Due to the manual production process, which must be carried out by skilled workers, the quality of the surface finish is that of handcrafted products. This finish can be smoothened and improved by

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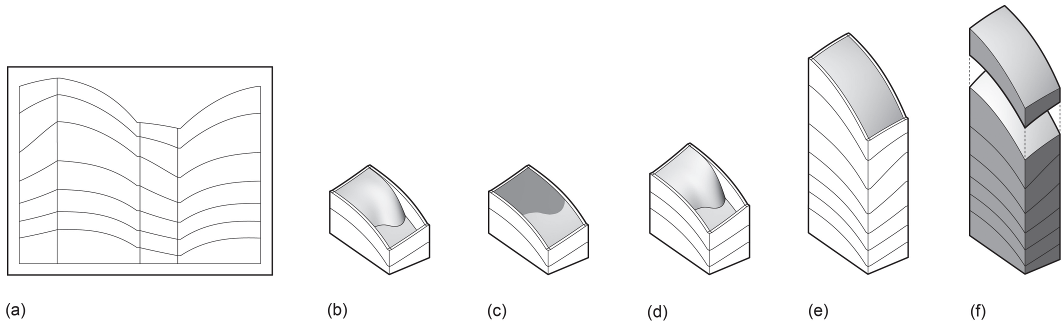

Figure 2. *Step-by-step functioning of the manufacturing technique.*

applying an optional surface polishing. Although the final quality of the surface finish may be rougher than when the components are cast using a mold, this way of manufacturing the components allows eliminating the need to produce complex non-reusable molds and therefore largely reduces the material waste.

In the case a smoother finish is desired or the top surface of the components is highly curved and therefore it is difficult to be shaped manually, it is also possible to use additional molds, such as 3d-cut foam molds or CNC foam milled molds. In the first case, since the components are stackable, the required foam molds are also stackable and therefore they can be cut from a large piece of foam. This reduces the material waste and the production time. In the second case, since the casting technique only requires one complex mold per component instead of two, the need of complex molds is reduced to half. In both cases, the casting process will be done sideways in order to avoid the appearance of undesired air bubbles in the top surface of the components.

4. *Placing the separating layer.*
   Once the material of the top surface is set, it is possible to cast the next component of the stack. To do this, it is necessary first to apply a separation layer such as a standard de-molding spray on the top surface of the previous component (Figure 2c). This prevents the casting material from sticking to the previous component ensuring that both components can easily be separated from each other once the casting process is completed.

5. *Casting the second and subsequent components.*
   Placing the next lateral mold on top of the previous component, the next component is cast (Figure 2d). The top surface is shaped following the same procedure chosen for the production of the previous component. Subsequent components of the stack are manufactured following the same procedure (Figure 2e).

For the production of multiple stacks, it is convenient to gradually produce each component belonging to the same level of the stacks rather

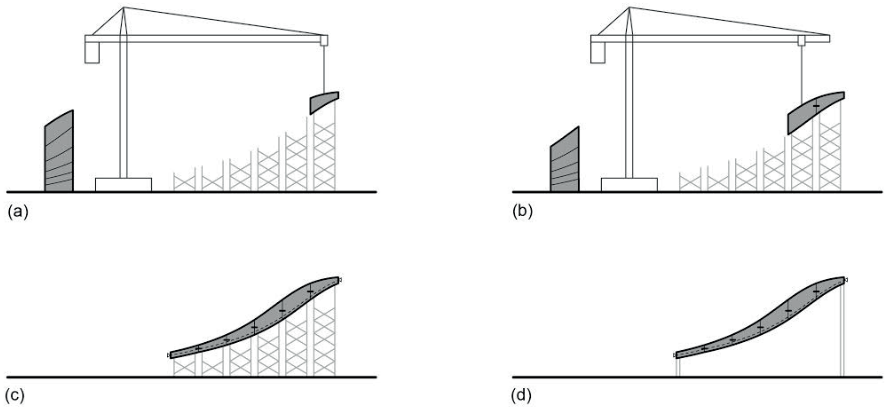

Figure 3. *Scheme of the construction process. (a-b) Placing the building components on the scaffolding. (c) Assembly. (d) Decentering.*

than one complete stack after the other. This prevents wasting time waiting for the material from the previous component to set.

6. *Transporting the components.*
   Once the casting process is finished, the components are efficiently transported to the site in stacks. This avoids the need to build a custom support device for each component, reducing the waste and cost involved in the manufacturing of such supporting structures. Furthermore, this feature also decreases the number of deliveries of the building elements to the construction site due to a more efficient use of the transportation volume of the vehicles. This, therefore, reduces the shipping costs and the CO_2 emissions.

7. *Separation of the components and assembly.*
   Once at the construction site, the components are separated from each other (Figure 2f) and assembled together to give shape to the designed architectural shell. The chosen assembly method will vary in relation to the function of the architectural shell. If this is a cladding system, the components can simply be supported by a substructure, generally built in steel. If the goal is to build a shell structure, the components can be assembled together by means of steel pin joints and/or by post-tensioning depending on the scale of the components and the internal forces.

The CASTonCAST system shows important advantages when applied in combination with Precast Segmental Construction for the construction of prestressed precast concrete shell structures.[16] As we will see later, the system can ensure that the global geometry of the shell gets embedded in the building elements, following the tradition of stone voussoirs. Thanks to this, the labor at the construction site is reduced to the placement of the components in their final location by using launching equipment and standard reusable scaffolding, and the assembly of the components by means of post-tension

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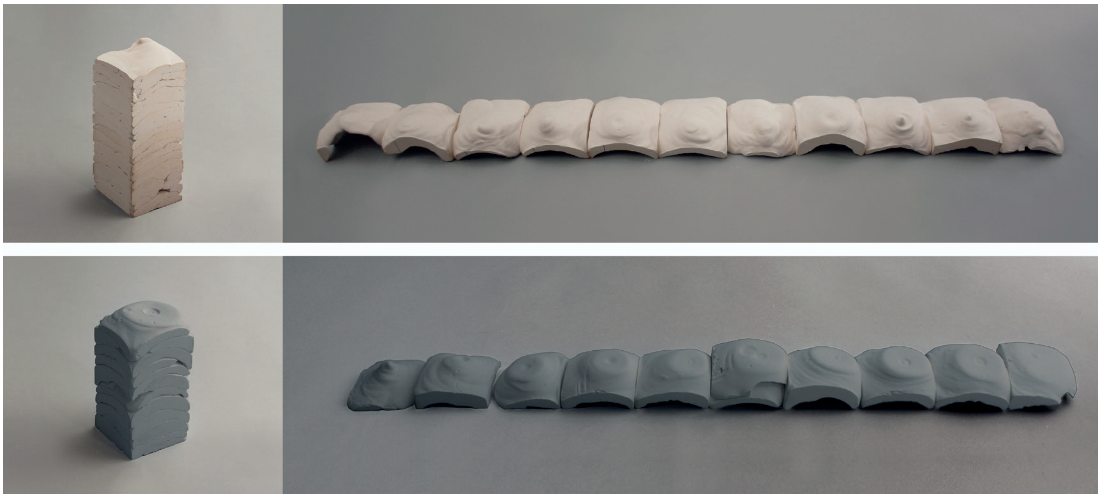

Figure 4. *Physical prototypes. Above: Material tests in plaster. Below: Material tests in cement.*

cables (Figure 3). Therefore, this construction technique, in comparison with construction techniques of concrete shell structures which rely on in-situ casting processes, increases considerably the speed of erection at the construction site and avoids the need of costly non-reusable formwork. The integration of this construction technique in the CASTonCAST system will be further investigated.

Material requirements

The first set of physical experiments (Figure 4) had the goal to find out the requirements the material must fulfil in order to identify appropriate materials which could successfully run the manufacturing process. These tests consisted of manufacturing a sequence of components one on top of another by simply pouring the material inside a vertical prismatic container of base 8×8 cm. Well-known chemical setting materials such as plaster and concrete succeeded in satisfying all the found relevant requirements. These are:

- *Molding and casting material.*
  During the manufacturing process the components have two functions: serving as final building elements and as molds. Due to this, the material must be versatile to serve both as molding and casting material.

- *Moldable and shapeable.*
  The material must adapt to the shape of the mold and, in the case of the open-cast, it must also be easily shapeable using simple tools. For this, in the case of concrete, it will be important to control its rheology.[17] More specifically, the composition needs a sufficient yield stress so that the workability measured with a slump test is in the range of the slump class S3 according to EN 206-1:2000.

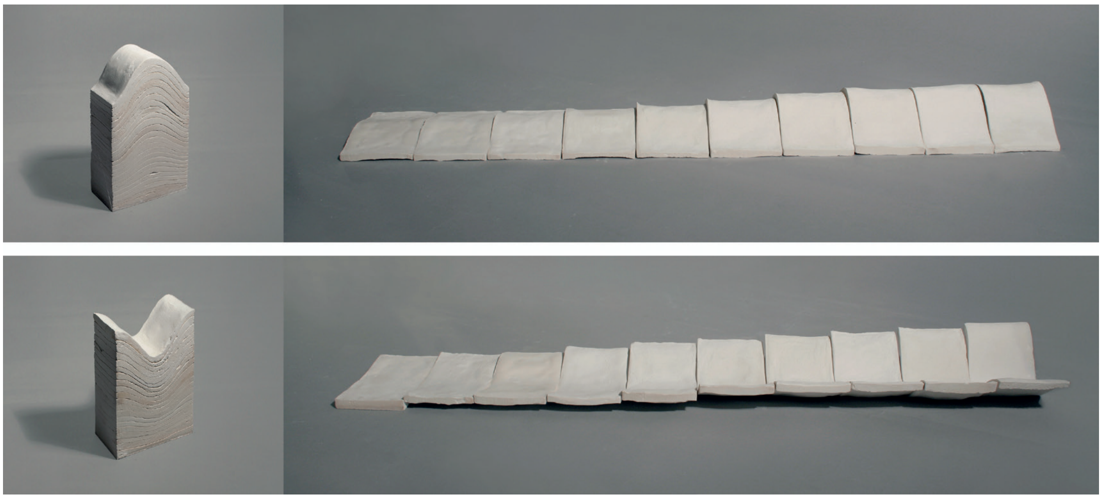

Figure 5. *Physical prototypes. Above: Larger accumulation of material in the central region. Below: Larger accumulation of material at the sides.*

- *Appropriate setting speed.*
  For the production of the components, the hardening speed should be slow enough that the material remains malleable until the manufacturing is completed. The concrete mixture specified above provides enough time for this purpose, remaining malleable for up to 90 minutes after mixing without changing its properties. Furthermore, the hardening speed should neither be too slow so that the next component can be manufactured without a loss of time. In this case, again, concrete has an appropriate behaviour since it is able to be used as a mold around 12 hours after mixing. This does not represent a time loss, since during this time, components from other stacks can be manufactured.

While concrete is an appropriate material for producing large scale building components, such as cladding elements or load-bearing components for shell structures, the physical tests presented in this article are mainly built using plaster since these are only at a prototype scale.

GEOMETRIC METHOD

Concept

The initial material tests served to prove that the manufacturing technique can be easily run using traditional casting materials. After these tests, further stacks were cast by manually shaping the top surface of the components following curvatures chosen arbitrarily. Although these tests showed that it is possible to produce easily components with a different curvature on the top and bottom surface, when placing them sequentially one next to the other they were not able to give shape to a meaningful larger ensemble. At this stage it was necessary to develop geometric rules in order to build curved shells by connecting sequentially multiple stackable components. The first steps on this direction came from a series of physical experiments (Figure 5) which consisted on casting a sequence of components inside of a prismatic container always accumulating a larger amount of material in a fixed

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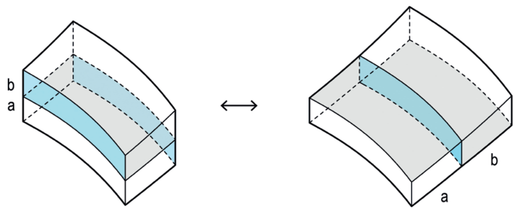

Figure 6. *Left: stack of two tiles. Right: strip. Stack congruence in grey and strip congruence in blue.*

linear region common to all components along the stack. By doing this, a progressive change of curvature in the tiles along the stack was obtained. When these components were later arranged one next to the other, connecting the lateral curved faces of the tiles in a face-to-face way, the progressive change of curvature of the components along the stack gave shape to a smooth curved strip. This set of physical experiments revealed the potential of a geometric method.

The geometric method studies the construction of freeform shapes by the connection of stackable tiles which represent building components manufactured one on top of another. For achieving this, the same group of tiles must be capable of being arranged in two clusters: stack and strip. We assign the term "stack" to the cluster in which the tiles are arranged in the same way in which the components are manufactured. The stack's envelope is often composed of planar lateral faces since this ensures that the lateral molds of the components can be constructed in a simple manner out of flat sheets of material. We assign the term "strip" to the cluster in which the tiles are arranged in the same way in which the components are finally assembled together giving shape to a shell.

The key of the geometric method relies on a simple requisite: for two tiles to be joined in two different clusters, both tiles must have two congruent surfaces between them. As a consequence of the manufacturing technique, two adjacent tiles of a stack have one congruent surface between them. This is the top surface of the bottom tile and the bottom surface of the top tile. We will refer to this congruence between adjacent tiles as the "stack congruence". To be able to arrange the tiles in a strip it is necessary that adjacent tiles of the stack have one more congruent surface or part of a surface between them. This congruence can be forced in between the lateral faces of the tiles as, for example, in between the back face of one tile and front face of the next tile (Figure 6). We will refer to this congruence between adjacent tiles as the "strip congruence".

The next point presents a modelling technique which follows a stack-to-strip approach. This consists on modelling a stack of solid tiles and later arranging them in order to construct the resulting strip.

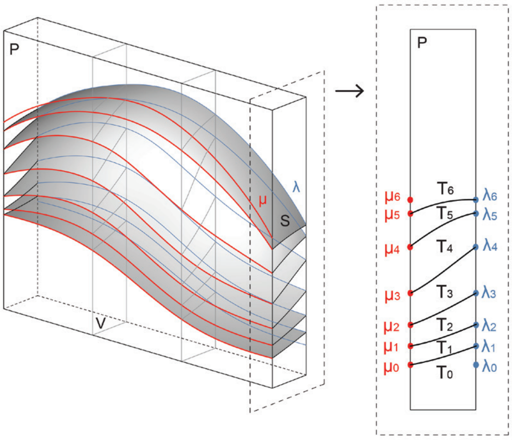

Figure 7. *Stack-to-strip modelling process.*

Stack-to-strip modelling

Due to the constraint explained in the previous point, in the stack, the lateral faces of the tiles which hold the strip congruence are grouped in two congruent sets, one placed on the front face of the stack and the other one on the back face of the stack. This shows that the front and back faces of the stack must lie on a pair of congruent surfaces. We will refer to these surfaces as the generating surfaces of the stack. This feature allows a simple stack-to-strip modelling process.

For modelling a strip composed of a series of stackable tiles, first a polyhedron P *with one front and one back congruent faces, the generating surfaces of the stack, is modelled (Figure 7). For the sake of simplicity in this explanation, let us assume that* P *is a rectangular prism. Second, a set of layered non-intersecting curves* μ_i*, the generating curves, are drawn on the front face of* P *and a congruent copy of this set of curves,* λ_i*, is placed on the back face. Then, the curves from* μi *are connected to those from* λ_i *by means of a series of non-intersecting surfaces* S_i *contained inside of* P *in a way* μ_i *gets connected to* λ_{i+1} *for* $i \in \{0,..., n-1\}$*. These surfaces are the top and bottom surfaces of the tiles which ensure the stack congruence. Next, the surfaces* S_i *split* P *into a series of solids* T_i*. Keeping* T_i *for* $i \in \{1,..., n-1\}$*, the tiles arranged in the stack cluster are obtained. The stack may be split by a series of transversal planes* V_i *into multiple stacks with smaller tiles (Figure 8). Finally, the strip cluster is modelled by gluing sequentially adjacent tiles of the stack from their surfaces which hold the strip congruence. Notice these pairs of faces are congruent due to the fact* μ_i *and* λ_i *are two congruent sets of curves.*

For manufacturing and construction reasons, it is important to control the main geometric parameters of the components during the modelling process. These are the thickness, the width, the length and the curvature of the top surface. In order to modify the thickness of the shell from Figure 8, we must

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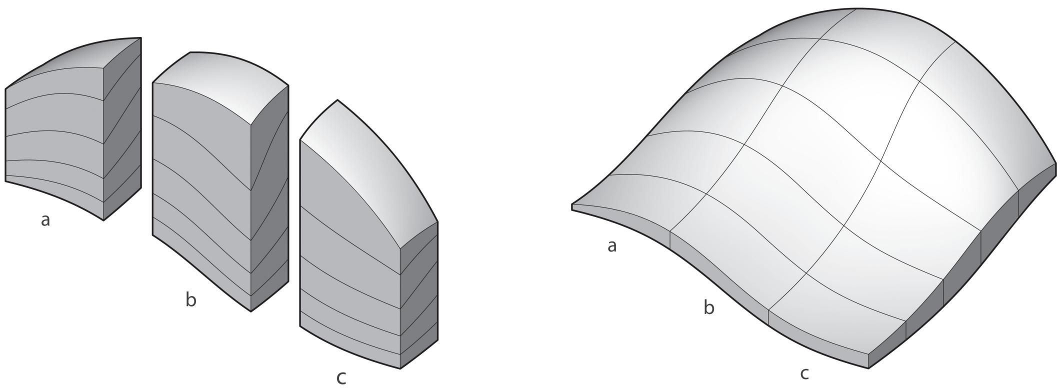

Figure 8. *Left: modelled stacks of tiles. Right: Assembled shell.*

first change the number of components in the stack by adding or removing generating curves and then adjust the width of the components by changing the distance in between the generating surfaces of the stack. The length and the curvature of the top surface of the components can be modified by splitting the tiles of the stack cluster by means of a series of transversal planes. The smaller the components are, the more components are needed to model a shell and, therefore, the less curved is the top surface of the panels. Controlling this parameter is important to ensure that the top surface of the components can be easily shaped during the manufacturing process.

Global curvature

In the stack-to-strip modelling technique, shaping the shell into a desired continuous freeform shape depends on the interactive manipulation of two main elements: the generating curves and the generating surfaces of the stack. Since a shell is composed of one or more linear strips, we can easily identify two main directions in the shell: across and along the strips. Across the strips, the global curvature of the shell depends entirely on the curvature of the generating curves. This is due to the fact the generating curves directly define a series of transversal sections of the shell and, therefore, they inform us about the material thickness of the tiles. By manipulating the curvature of the generating curves, we can easily notice that the greater the variation of curvature in between these curves, the greater the variations in material thickness and also the greater the variation of the global curvature across the strips of the shell (Figure 10a-b). This shows that there is a strong link in between the change of material thickness of the tiles and the shell global curvature. This relationship will be further investigated for integrating structural concerns in the geometric method.

More interesting is the creation of global curvature on the shell along the strips since this relies on both the generating curves and the generating surfaces of the stack (Figure 9). One possible way

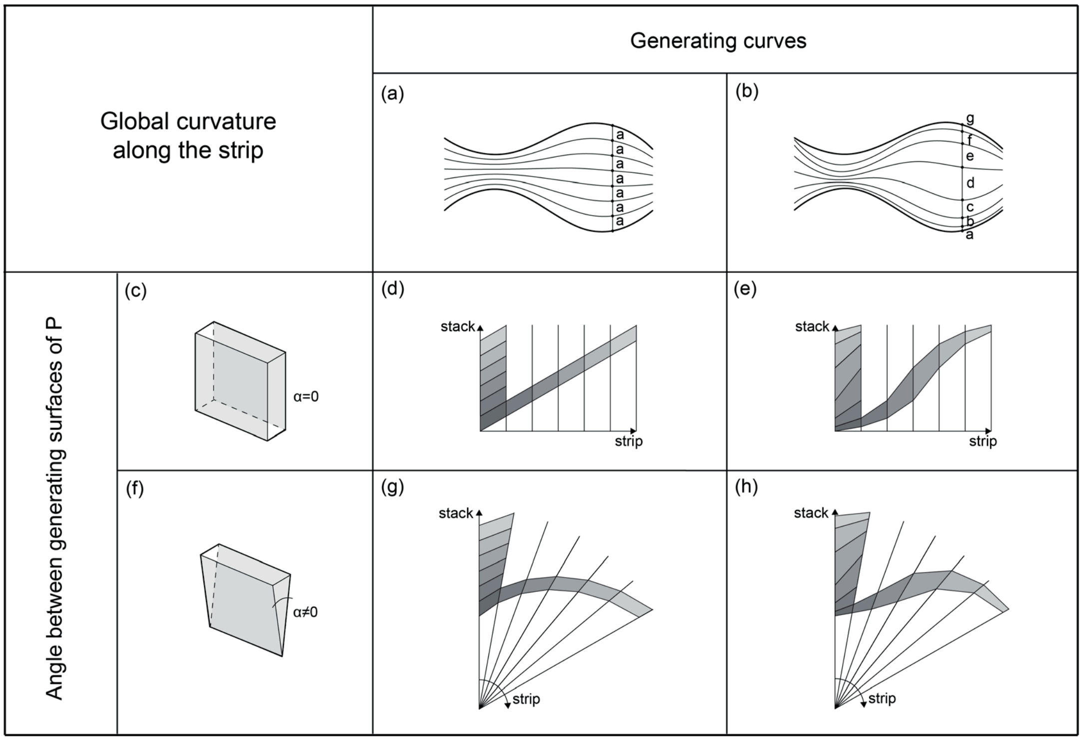

Figure 9. *Main parameters influencing the curvature along the strips.*

of drawing the generating curves is by first drawing the first and last curve and sub-divide the region they define in between them by means of the rest of generating curves. It is interesting to notice that if this subdivision is done in a uniform way (Figure 9a) and the generating surfaces are parallel (Figure 9c), the Gaussian curvature along the strip direction of the top and bottom surfaces of the resulting strip is zero (Figure 9d). In this case, the thickness of the strip is uniform. However, if this subdivision is done in a non-uniform way (Figure 9b), curvature along the strips is created (Figure 9e). In this case, the thickness of the strip is non-uniform. Again, here, we observe the link in between change of material thickness and curvature.

In addition, the generating surfaces of the stack can also influence the global curvature of the shell along the strip depending on whether they are parallel, α=0 (Figure 9c), or they define an angle among them, α≠0 (Figure 9f). If these are parallel, like in the case of a prismatic polyhedron P (Figure 7-8), the tiles are simply translated to their final position in the strip (Figure 9d-e). If one generating surface is the

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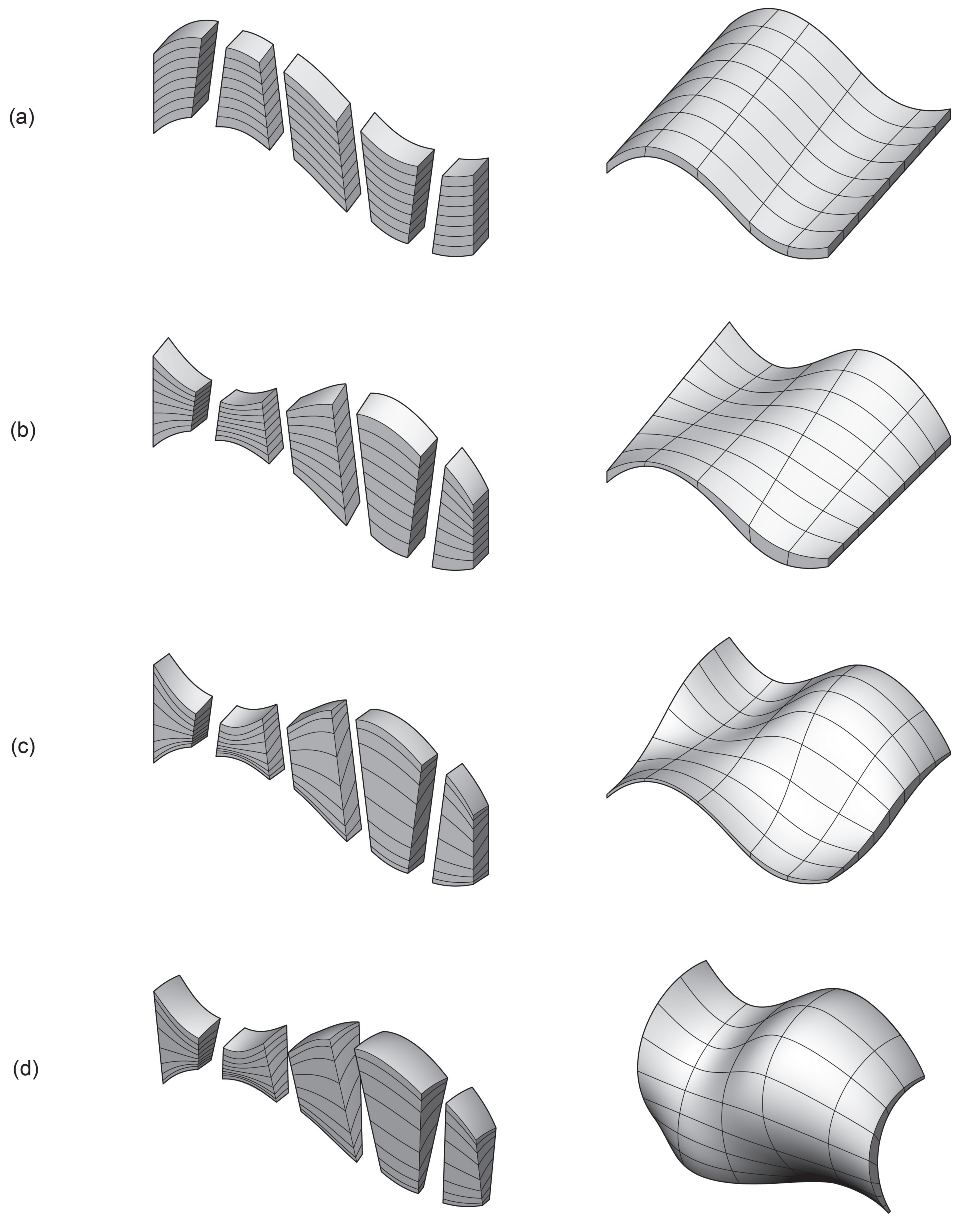

Figure 10. *Influence on the global curvature of the main parameters.*

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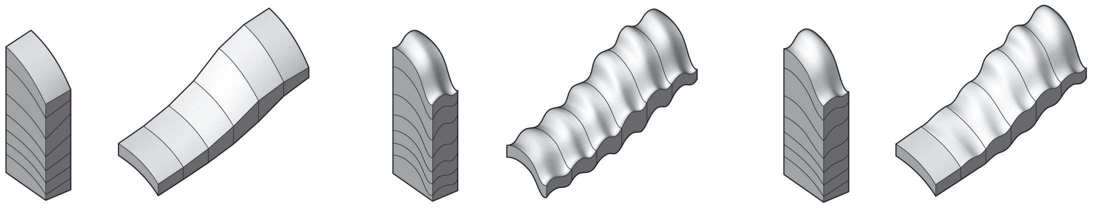

Figure 11. *Different local curvature of the tiles.*

rotation of the other one, like in the case of a wedge polyhedron P, *the tiles suffer a rotation along the strip (Figure 9g-h). Along the strip direction, therefore, both the generating curves and the generating surfaces, by means of the thickness parameter and the angle* α *respectively, have the ability to influence the global curvature. The combinations among these different states can create the following four hybrid cases:*

1. *Uniform thickness and* α*=0 (Figure 10a-b). In this case, both parameters are in their passive state. The shell has no curvature along strips.*

2. *Non-uniform thickness and* α*=0 (Figure 10c). Along the strips the global curvature of the shell depends on the variation of material thickness defined by the generating curves.*

3. *Uniform thickness and* α*≠0. Along the strips the global curvature of the shell depends only on* α.

4. *Non-uniform thickness and* α*≠0 (Figure 10d). In this case, both parameters are in their active state. The global curvature of the shell along the strips depends on both the variation of the material thickness and* α.

Local curvature

Independently from the global curvature of the shell, it is possible to define the local curvature of the top and bottom surfaces of the tiles. In this manner, the tiles can intentionally be single curved (Figure 11a), curved following the global curvature of the shell (Figure 8), highly double-curved (Figure 11b) or even express the transition from different curvatures (Figure 11c). This allows the local curvature to be adjusted to specific manufacturing requirements and/or aesthetic criteria.

PHYSICAL PROTOTYPES

Three main physical prototypes built in plaster were made to test and exhibit the potentials of both main parts of the CASTonCAST system together. In the first prototype (Figure 12 above), the shell is composed of eight strips each with eight components cast inside of prismatic containers of base 8×8 cm. In the second one (Figure 12 middle), the shell is composed of three strips of 15 components cast inside of wedge-shaped containers. Due to the shape of the container, the size of the tiles span from 8×8 cm

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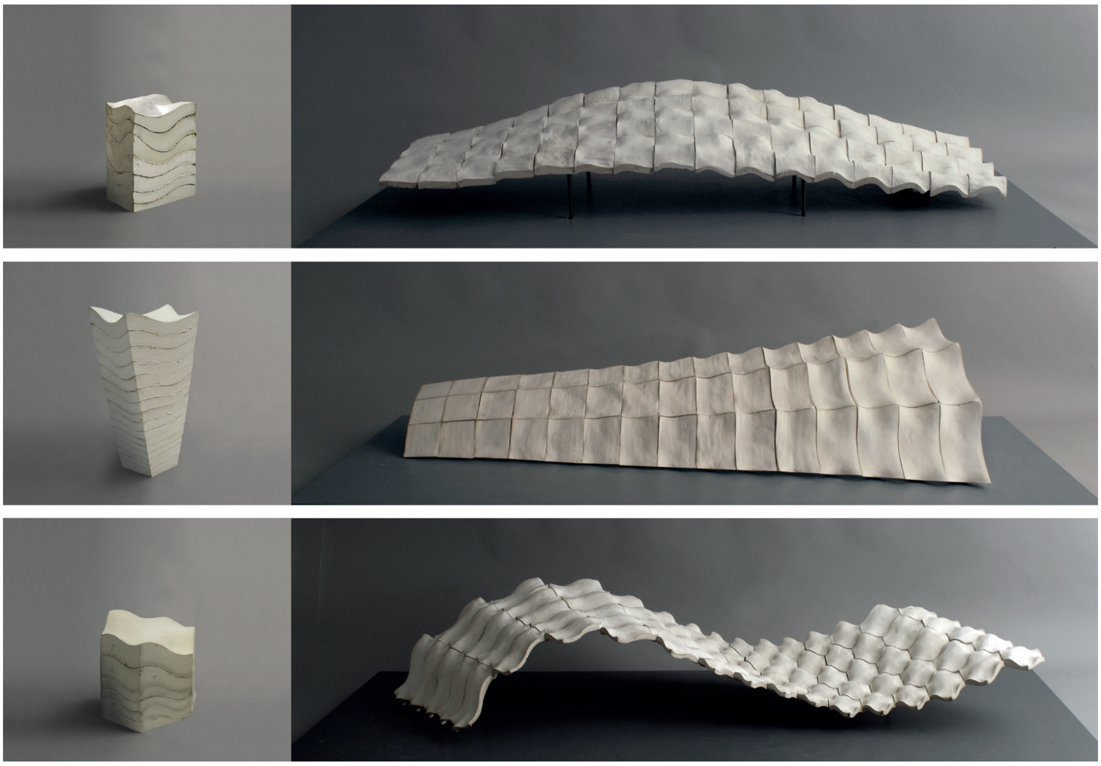

Figure 12. *Physical prototypes.*

to 8×25 cm. The last prototype (Figure 12 below), consists of fifteen strips each with five components cast inside of a container with a hexagonal base. In all three cases, the assembly method used consists in connecting the tiles with a series of pin joints and epoxy adhesive.

The final assembled shell in all these three prototypes intentionally shows two types of curvature. In the first place, the shells exhibit a global curvature which is modelled by using the stack-to-strip modelling technique described in this article. In the second place, a local curvature on the tiles was intentionally superimposed on the global curvature as a way to explore the limitations and expressive potentials of the manufacturing technique. This changing local curvature in these prototypes confers to the final shell a bumpy look which helps to visualize the capacity of the manufacturing technique to produce a series of differentiated building elements. During the design process, the designer can choose whether to add to the global curvature a local curvature on the tiles or not. Without it, the outcome shell is a smooth and continuous curved paneled shell, similar to those represented in Figure 8.

LIMITATIONS OF THE SYSTEM

During this research the following limitations on the system have been detected:

- *The fabrication technique, as other standard casting techniques, shows limitations in the production of components with acute angles. In this case, however, it constrains the range of possible solutions obtained by the geometric method.*

- *The geometric method can be used to model/ tessellate any curved solid shapes, provided that no limit of shell patches and stacks needed to construct such shape is fixed. However, certain shapes might require too many shell patches and therefore their production might not be so efficient. This topic requires further research.*

CONCLUSION AND FURTHER RESEARCH

This article introduces the CASTonCAST system for the design and production of architectural freeform shapes from precast stackable components. More specifically, it describes its two complementary main parts: a novel manufacturing technique for the production of precast curved building components in stacks, which can be run using low-technologies, and a new geometric method for the modelling and design of freeform shapes out of stackable tiles. The system shows economic and sustainable advantages in all its production phases: the manufacturing technique reduces the material losses and eliminates the need of complex and costly molds, the storage and transportation can be done efficiently in stacks and the assembly of the components on site can be done using reusable standard scaffolding. This underlines the importance of tackling the problem posed by the design and production of architectural freeform shapes by means of concurrent innovation in both manufacturing and geometry.

The aim of this research is to develop a usable system for the design and production of architectural freeform shapes for both cladding and structural purposes. To reach this goal both main parts of the system described in this article are currently being further developed. More specifically, the manufacturing technique is currently being tested for the production of larger scale components and the geometric technique is being extended to the strip-to-stack technique for the tessellation of freeform shapes into stackable tiles. In addition, research is currently being undertaken to integrate structural concerns in the system for the design of precast freeform shell structures.

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[14] *CASTonCAST fabrication system and method. Inventors: Lluis ENRIQUE, Povilas CEPAITIS, Diego ORDOÑEZ and Carlos PILES. UK patent application GB1101013.9 (patent pending).*

[15] *A similar casting technique of precast concrete structural elements, often used for the construction of precast segmental bridges is "counter-molding". This relies on casting building elements against the neighbor ones exactly in the same position as they are later assembled in the construction site for ensuring a perfect match during the assembly process. A thin-shell structure built using this technique is the thin-shell canopy over the Millau viaduct toll-gates. THIBAUX, T.,* et al. *Construction of an Ultra High Performance Fibre Reinforced Concrete thin shell structure over the Millau Viaduct toll-gates. 6th International RILEM Symposium on Fibre Reinforced Concretes. M. di Prisco, R. Felicetti and G.A. Plizzari (ed.). Varenna: RILEM Publications SARL, 2004, 1183-92.*

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