CASTonCAST Shell Structures

Realisation of a 1:10 Prototype of a Post-Tensioned Shell Structure from Precast Stackable Components

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Abstract

This paper presents an important step towards the integration of structural concerns in the CASTonCAST system for the design and production of shell structures built from precast stackable components. This step consists of studying the application of prestressing for assembling the components and providing stiffness to the shell. This was tested in the realisation of a 1:10 prototype of a post-tensioned shell structure built from precast stackable components. This prototype is also the first one to be built in concrete using the CASTonCAST system.

Keywords:
shell structures, precast concrete, prestressing, architectural freeform surfaces, strut-and-tie models

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1. Introduction

Between the 1920s and the 1970s, impressive reinforced concrete shell structures were built using the cast-in-place construction technique. After this period the construction of reinforced concrete shells declined due to the high costs associated to the intense labour required in the construction site and the high costs of formwork and scaffolding (Chilton 2000). During the last decades, the demand of freeform shapes in architecture has accentuated these problems, making the production of such curved structures in concrete more inefficient and unsustainable. For this reason, it is important to develop methods for the production of freeform shell structures which reduce the economic and environmental costs. Nowadays, new methods for producing efficient complex structures in concrete are being developed. It is worth mentioning the novel techniques for casting concrete building elements using flexible formwork (West 2001; Orr et al. 2011), flexible moulding systems (Schipper 2011; Pronk et al. 2009; Raun & Kirkegaard 2012), and additive manufacturing technologies (AM) such as D-shape (Dini 2006), Contour Crafting (Khoshnevis et al. 2004), Concrete Printing (Lim et al. 2009), and Smart Dynamic Casting (Lloret et al. 2015).

An alternative to these methods is the CASTonCAST system (Enrique et al. 2011; Enrique et al. 2016) (Fig. 1). This system deals with the design and production of architectural freeform shapes from precast stackable components. The system consists of two complementary parts:

(1) A novel manufacturing technique of complex building components which relies on producing a series of components in stacks by using the previous component as a mould 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 system presents the following advantages: First, it eliminates the need for costly complex moulds. Second, the method allows one to transport the components to the construction site in stacks. This avoids the need to manufacture supporting structures for each component. Finally, the labour at the construction site consists in placing the components on a reusable scaffolding and assembling them. This increases the speed of erection and reduces the construction costs.

This research has the aim of applying the CASTonCAST system for the design of freeform shell structures. The first step in this direction consists of studying the way the components are assembled together and the shell gets stiffness. Attracted by the efficiency in construction of precast segmental bridges and

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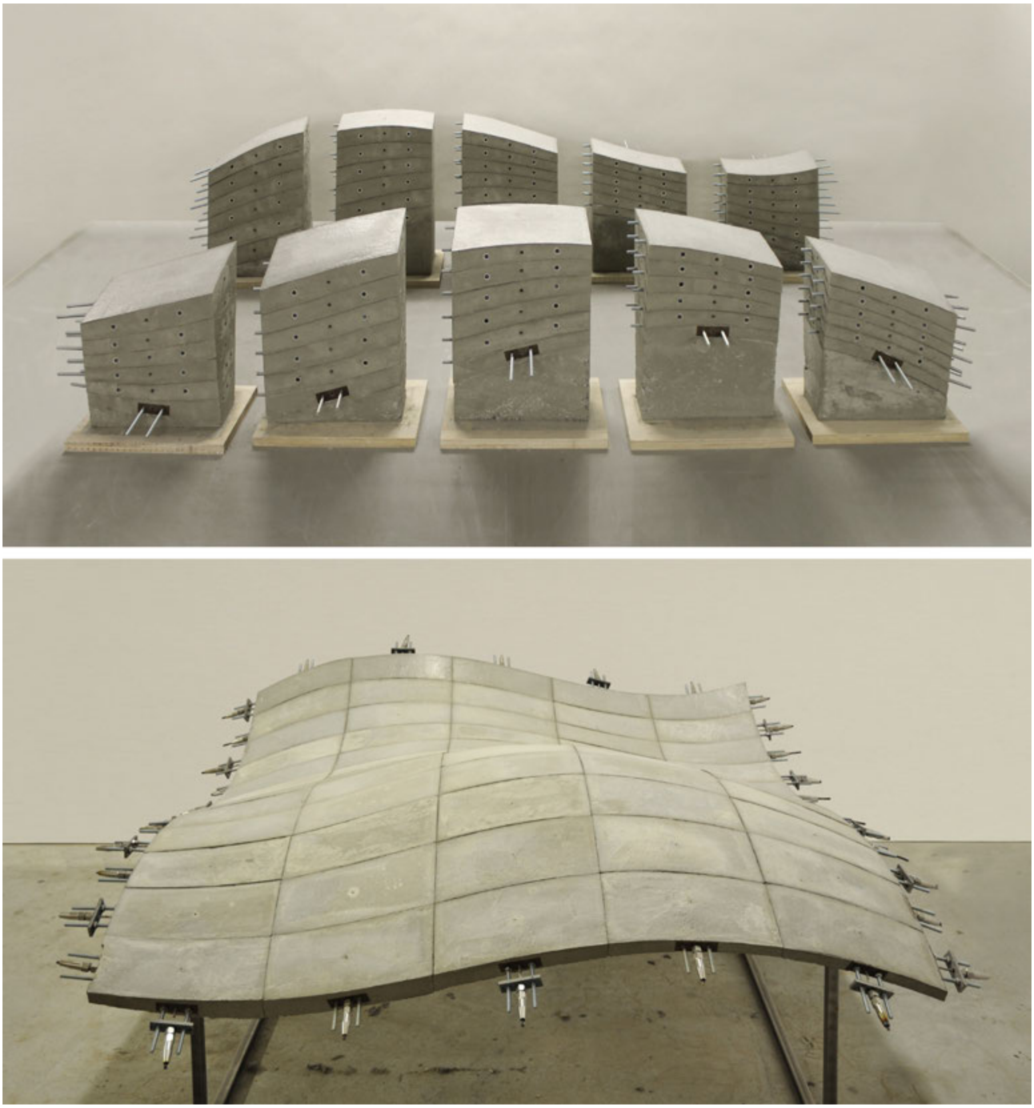

Figure 1. 1:10 Prototype of a post-tensioned shell structure built from precast stackable components: stacks of components (above) and post-tensioned shell (below).

inspired by built works such as the Jubilee Church designed by Richard Meier & Partners Architects, this research studies the application of prestressing in the CASTonCAST system for assembling the components and providing stiffness to the shell. In this paper this approach has been tested in the realisation of a 1:10 prototype of a post-tensioned shell structure built from precast stackable components (Fig. 1).

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2. Prototype

The prototype is composed of 60 stackable concrete components of size 25 x 8-12 x 2.5-6 cm, arranged in a matrix of 5 by 12. These are assembled by a network of 17 post-tensioning steel cables of 4 mm diameter. The total size of the prototype is 140 x 140 x 2.5-6 cm, and its weight is approximately 135 kg. Since the components at real scale are meant to be around 2.5 m length by 1.2 m wide, we can say that the prototype is constructed approximately at a 1:10 scale. However, at real scale the thickness of a shell structure should be between 5 and 25 cm.

2.1 Geometry

The shell was designed using the CASTonCAST geometric method (Enrique et al. 2016). This method allows the construction of freeform shapes by the connection of stackable tiles which represent building components manufactured one on top of another. To achieve this, the same group of tiles must be able to be arranged in two clusters: stack and strip. The key of the method relies on simple requisite: for two tiles to be joined in two different clusters, both tiles must have two congruent surfaces between them (Fig. 2).

The shape of the shell was designed with the intention that its main surfaces have regions with both positive and negative Gaussian curvatures. During the design process it was important to control two main aspects in order to ensure that the components could be easily produced: First, the thickness of the shell had to be between 2.5 and 6 cm. Second, the curvature of the top surface of the components should not be too complex. To control these two aspects, a stack-to-strip modelling process was followed. This consists on modelling a stack of solid tiles and later arranging them in order to construct the resulting strip.

For modelling the stack, first the generating curves were created (Fig. 3). These curves represent a series of transversal sections of the shell, and therefore they define both the thickness and the curvature of the shell. This shows that there is an interesting relationship between the change of thickness and the global curvature of the shell. In this process, it was necessary to respect the range of admissible thicknesses previously defined. Since at real scale the range of admissible thicknesses is larger than at the prototype scale, the design space is also wider.

Then, the angle between the generating surfaces of the stack was defined (Fig. 3). This affects the curvature of the shell along the strips. In order to get more variation of the curvature along the strip, the shell was constructed from two stacks with a different angle between their generating surfaces. As Figure 3 shows, both stacks are linked. For this, the back face of the last tile of the first stack and the front face of the first tile of the second stack must be congruent. This

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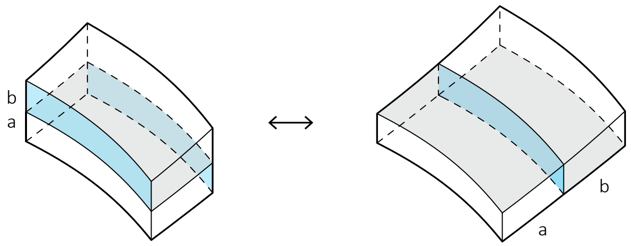

Figure 2. Stack and strip of two tiles

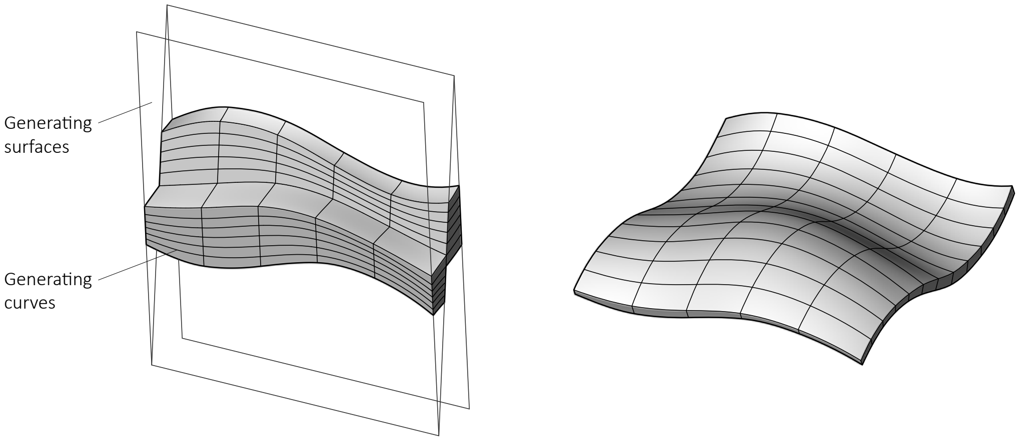

Figure 3. Geometric modelling of the shell.

allowed joining the two shell patches corresponding to each of the stacks giving shape to the shell. Both the generating curves and the generating surfaces were manipulated until the desired shape was obtained.

Finally, once the shape of the shell was defined, the tiles of the stack were subdivided by a series of transversal planes into smaller tiles. This step allowed controlling the appropriate size of the components and the curvature of the top surface of the components.

2.2 Structure

A study of the structural behavior was developed in order to check the internal forces in the prestressed shell. In this study, two conditions had to be fulfilled: First, the effect of prestressing had to ensure that no internal tensile forces appear in the mass of concrete of the shell; this was important for ensuring that

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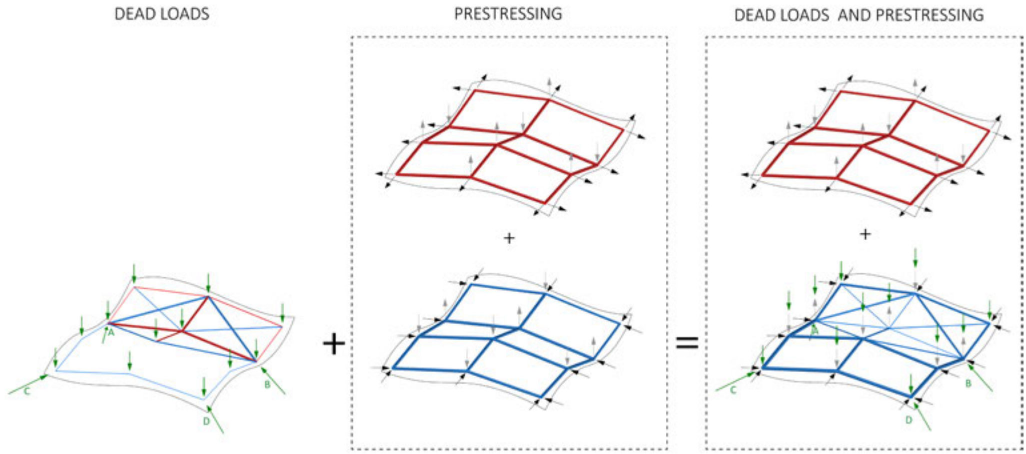

Figure 4. Study of the internal forces in the prototype using the Load Path Network Method. Compression in blue and tension in red.

the precast elements were appropriately compressed and also to prevent cracks from appearing. Second, the magnitude of the internal forces had to respect the yield conditions of the material. The available parameters to achieve this were: the shape of the shell, the thickness, the position of the supports and the amount of prestressing force.

The study was conducted using the Load Path Network Method (Enrique and Schwartz, 2016). LPNM is an equilibrium-based method for the generation of three-dimensional strut-and-tie models based on the lower-bound theorem of the theory of plasticity (Muttoni et al. 1997). This method allows one to construct and visualise possible paths of the internal forces in equilibrium in a given structure. Using this method, a scheme of a possible spatial configuration of the internal forces in equilibrium within the designed shape was modelled (Fig. 4). For this, first a possible load path of the self-weight was modelled. This path of internal forces shows that the shell takes advantage of its three-dimensional shape for distributing the internal forces by means of a network of compressive and tensile axial forces. In this step, the initial shape and the position of the supports had to be slightly modified in order to reduce the magnitude of the internal forces.

Then, a simplified network of prestressing cables was modelled. In order to fulfil the conditions defined before, the magnitude of the prestressing force in the cables needed to be larger than the largest tensile force of the first load path, and, at the same time, it had to respect the yield strength of the concrete mass and the steel cables. In this case, the required prestressing force in the cables was equivalent to 40% of the admissible tensile strength of a steel cable

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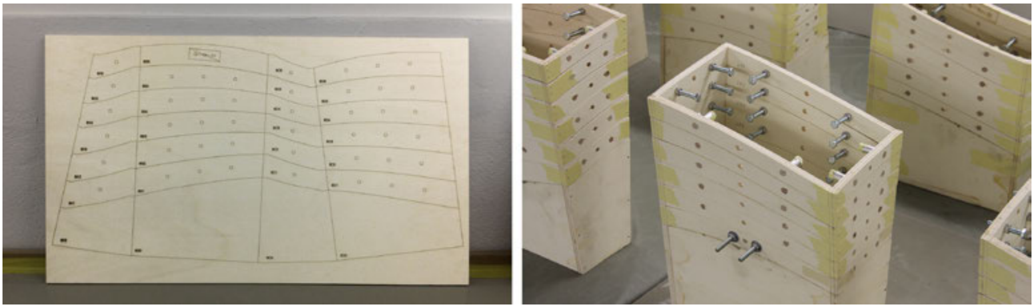

Figure 5. Production of the lateral moulds.

of 4 mm diameter. By superimposing the two systems of forces the mass of concrete of the shell remained only under compressive forces.

The equilibrium solution chosen might not be the one describing the real structural behavior of the shell; however, according to the lower-bound theorem of the theory of plasticity, the modelled solution of internal forces guarantees the structural safety (Muttoni et al. 1997).

2.3 Production

The CASTonCAST manufacturing technique (Enrique et al. 2016) consists of casting a series of components in stacks using the previous component as a bottom mould for the next component. The main steps for the production of this prototype were:

1. **Production of the lateral moulds**
For the production of a stack of components, moulds for the flat lateral faces of the components are required. Like the components, these lateral moulds are stackable. Thanks to this, they can be manufactured together by cutting their stackable parts from flat sheets of material (Fig. 5). This reduces the material waste and the production time. For the production of this prototype, a total of 10 flat sheets of timber of size 83 x 45 x 1 cm were required for producing lateral moulds of the 60 components.

   The assembly devices were fixed in the lateral moulds. These are female-male stainless steel pin joints and two plastic tubes connecting the opposite faces of the mould for inserting the post-tensioning cables.

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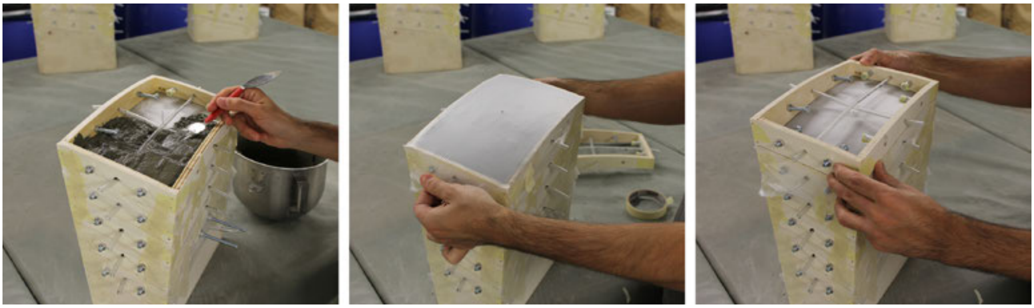

Figure 6. Production of the components: casting (left), placing the separation layer (centre) and placing the next lateral mould (right).

2. Production of the bases

The first component of the stacks did not have a bottom flat surface. Due to this, it was necessary first to manufacture bases. These were produced using lean concrete. For further prototypes, the bases will be produced from reusable materials in order to reduce the material waste.

3. Casting the components

For casting one component, first the mould was filled with concrete and later the top surface of the components was shaped manually using a bricklaying trowel (Fig. 6 left). To do this successfully, it was necessary to control during the design process that the curvature of the top surface of the components was not too complex. In addition, it was important to control the concrete rheology and workability.

The concrete mixture used contained a cement-sand ratio of 1:2 and a water-cement ratio of 0.6. Due to the small scale of the components, no gravel nor steel reinforcement was used. However, polypropylene fibres were added to the mixture in order to reduce the width of the cracks and improve the resistance to shrinkage during the curing.

Once the concrete had hardened, a thin plastic layer was applied on the top surface of the component in order to prevent that the material of the next component adheres to it. (Fig. 6 centre). This can also be achieved using a standard demoulding spray. Then, the next lateral mould was fixed in order to start the casting of the next component (Fig. 6 right). Each new component could be cast approximately 12 hours after casting the previous one. In order to reduce the production time, the stacks were cast by layers, starting by casting the first component for all the stacks, then, the second one for all the stacks, and so on.

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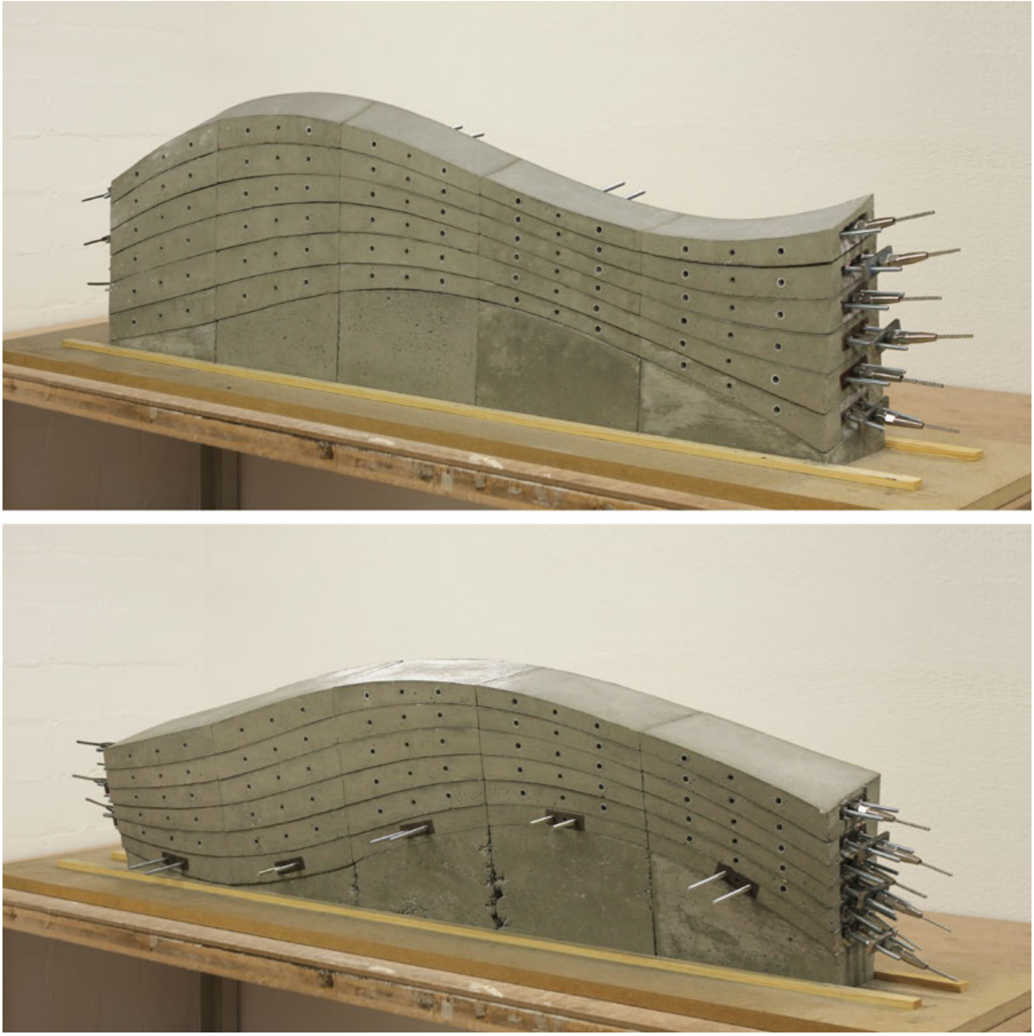

Figure 7. Longitudinal post-tensioning of the components.

Due to the manual production process, which at real scale must be carried out by skilled workers, the quality of the surface finish was that of handcrafted products. This finish could have been smoothed and improved by applying an optional surface polishing. Although the final quality of the surface finish may be rougher than when the components are cast using a mould, this method of manufacturing the components allows one to eliminate the need of producing complex non-reusable moulds and therefore reduces largely the material waste.

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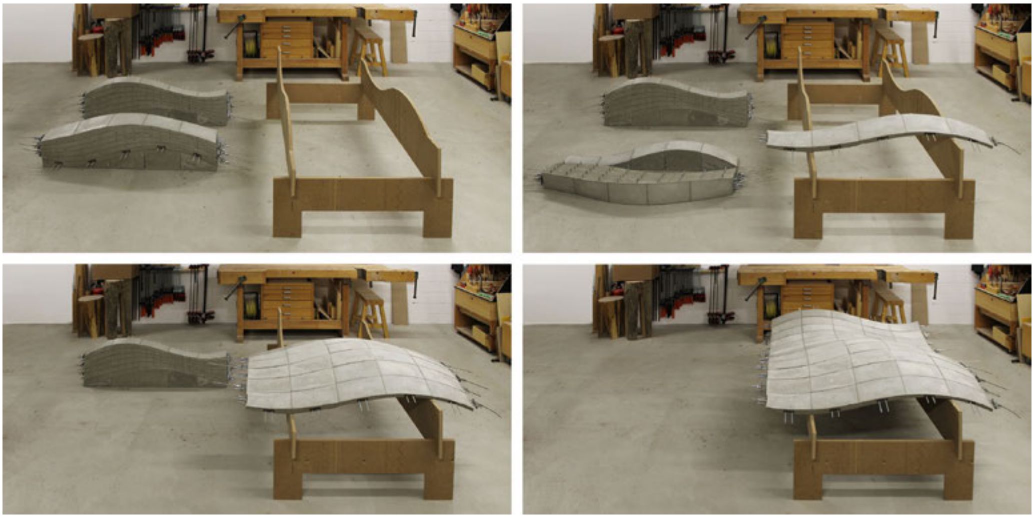

Figure 8. Assembly sequence.

2.4 Assembly

The assembly of the components was solved by means of two combined systems: female-male steel pin joints located in the lateral faces of the components and a bidirectional network of post-tensioning cables. The steel pin joints served to match the components precisely and make the shell stiff against shear forces. The bidirectional network of post-tensioning cables was in charge of joining the precast concrete components, providing stiffness to the shell structure and preventing cracks from appearing.

The post-tensioning process was done in two phases: longitudinal and transversal post-tensioning. The longitudinal post-tensioning consisted of assembling the components of adjacent stacks belonging to the same level. This process shaped two large stacks composed of six stackable post-tensioned curved beams each (Fig. 7). Since the components are stackable, the first curved beam could be post-tensioned directly on top of the bases and the subsequent curved beams could be post-tensioned on top of the previous ones. Thanks to this, there was no need of building custom support devices for the assembly process. This feature reduces the economic cost and the material waste involved in the manufacturing of such supporting structures.

After the longitudinal post-tensioning, the 12 curved beams were assembled together on top of a simple scaffolding (Fig. 8). This was composed of four MDF panels of 2 cm thickness which were produced using a CNC machine. Only two

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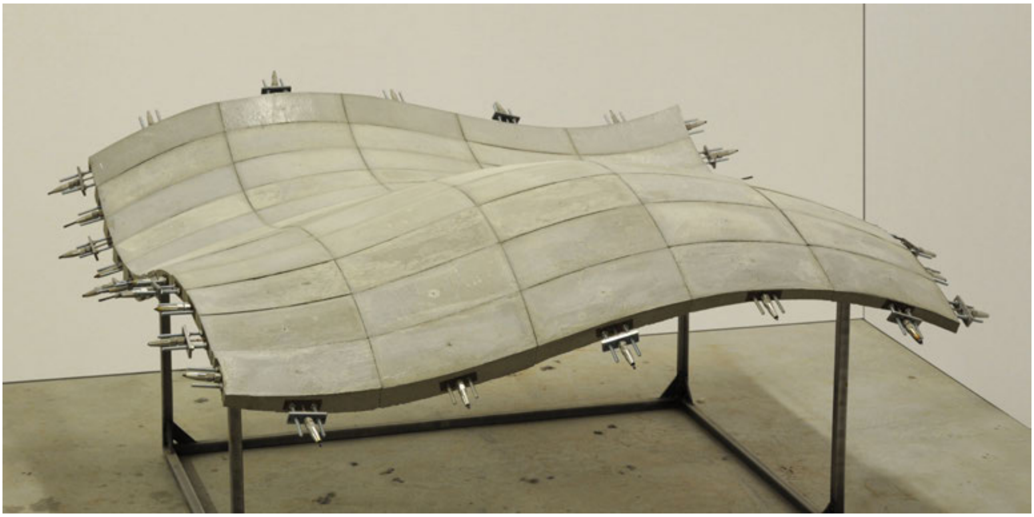

Figure 9. Post-tensioned shell built from precast stackable components.

of these panels had a curved edge following the curvature of the shell in order to help placing the beams in their exact position. The beams were assembled by joining the back face of each beam with the front face of the next one. Due to inaccuracies during the fabrication process, it was required to slightly sand the steel pin joints with an electric circular saw. This showed that the production process requires a high level of precision. After connecting all the beams, these were assembled by means of five transversal post-tensioning cables. Finally, the shell was decentred and supported by a steel frame (Fig. 9).

At real scale, the longitudinal post-tensioning would take place at the manufacturing plant in order to reduce to time of erection at the construction site. Then, the stacks of post-tensioned curved beams would be transported to the construction site where the shell would be assembled. One of the two stacks of post-tensioned curved beams of the prototype, without the bases, built at a real scale would weight around 20-30 tons and would be 12.5 m long. This means that a four-axis trailer 14-16 m long with a valid loading capacity of 30-50 tons could transport the full shell to the construction site in two trips, carrying in each trip one full stack composed of 30 components. Once at the construction site, the curved beams would be placed on a scaffolding built from standard reusable elements. In this way, the construction of costly non-reusable scaffolding would be avoided.

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3. Conclusions and Further Research

The results of this study show that bringing together the CASTonCAST system and prestressing has a great potential for the design and production of freeform precast prestressed shell structures. However, in order to apply the system at real scale, the next questions must be studied:

1. Geometry
The geometric method is currently being extended to the strip-to-stack approach in order to study how to efficiently tessellate a given freeform shape into stackable tiles.

2. Structure
At the moment, the structural analysis is used to check the structural behaviour of a modelled shape, but it does not actively participate in the design process. For this reason, the link between geometry and structure must be strengthened.

3. Fabrication
The production of the components at real scale is currently being investigated. This step involves solving important aspects such as controlling the rheology of the concrete mixture, shaping the top surface of the components, manufacturing the bases, adding steel reinforcement and testing the separation layer, among others.

4. Assembly
Further research needs to be done in order to study ways of assembling the shell on site only with the use of reusable standard scaffolding.

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