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Flexible Mould for Precast Concrete Elements

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Abstract

The present paper describes the development of a digitally controlled mould that forms a double curved and fair surface directly from the digital CAD model. The primary motivation for the development of the mould is to reduce the cost of constructing double curved, cast elements for architecture, both in-situ cast and modular. Today, such elements are usually cast in milled formwork that is expensive and produces a lot of waste. Architects are often limited in their freedom of design by the high costs of the existing methods and as a result, the possibilities for drawing and evaluating complex shapes in architecture today, are not reflected in the build architecture.

Keywords: Concrete mould, flexible mould, organic architecture, CNC milling.

1. Introduction

Complex freeform architecture is one of the most striking trends in contemporary architecture. Today, design and fabrication of such structures are based on digital technologies which have been developed for other industries (automotive, naval, aerospace industry). Architecture differs from these traditional target industries of CAD/CAM technology in many ways including aesthetics, statics, structural aspects, scale and manufacturing technologies. It can be easy to develop a digital design by computer tools, however the translation to a real piece of architecture can be very hard and expensive. The traditional production methods available for free-form architecture have a lack and architects and engineers are forced to simplify their designs. Production of architectural freeform structures requires the segmentation into panels, which may be either flat, single or double curved and produced in different building materials. Today, methods for manufacturing freeform concrete formwork are available, and more are being developed [1-4]. The most notable will be examined in this paper for verifying the quality of the developed solution. The common way of producing unique elements is to manufacture one mould for each unique element. This method has been made more available by the development of faster CNC milling in cheaper materials, but since the method is still labor intensive and produces a lot of waste, research is carried out in several projects to find a solution, where one mould simply rearranges itself into a variety of familiar shapes. Such a concept has natural limitations, but will fill a gap as a complimentary technology to the existing. The core of the concept presented here is to have a flexible surface manipulated into a given shape using a digital signal created directly from the CAD drawing of the design. This happens fast, automatic and without production of waste, and the manipulated surface is fair and robust, eliminating the need for additional, manual treatment. Limitations to the possibilities of the flexible form are limited curvature and limited level of detail, making it especially suited for larger, double curved surfaces like facades or walls, where the curvature of each element is relatively small in comparison to the overall shape. The present paper describes the development of the flexible mould for production of precast thin-shell fiber-reinforced concrete elements which can have a given form. The mould consists of pistons fixing points on a membrane which creates the interpolated surface and is fixed to the form sides in a way that allows it to move up and down.

2. Concrete casting techniques

Today, a number of technologies have emerged, that offers casting methods for a range of purposes. On a large scale, the market is dominated by well known techniques such as precast elements made from standard moulds and in-situ casting in standardized modular systems. On a small scale, new methods for casting and new types of moulds have emerged to meet the rising demand for customization and creation of curved concrete architecture. Some of the methods for double curved moulds which have been investigated related to the present project are mentioned below.

2.1 Milled foam moulds

The milled foam method represents the newest and the most economic version of custom manufactured moulds, historically made by hand and recently milled in different materials using CNC.

Fig. 1: Photo of a robot CNC-machine milling in a styropor material.

The advantage of foams in comparison to heavier materials is, that they are cheaper compared on volume, they allow fast milling, and they are easy to manually alter and fair after the milling process, that leaves a grooved surface texture. The main strength of the method is that it can be used for very advanced geometry as long as it is possible to de-mould the casted object. Further there is almost no curvature or detailing level limitations besides that of the milling tool. Another clear advantage for this method is that the entire surface is manufactured to tolerances. The weakness of the method is, that it requires manual fairing and coating to a large extend, if the surface has to be of a perfectly smooth, polished quality. For a large project, the formwork is extensive, and after use it has to be thrown out, creating even more waste than was produced during milling.

2.2 Textile formwork

Casting in membrane formwork or textile moulds have been around for a long time. A common feature for all objects that can be cast in this way is, that they must consist of convex surfaces exclusively, since the method relies on the principle that all textiles must be in tension caused by the viscous pressure. The final shape of the cast piece is a result of the membrane's adaption to the pressure, like the shape of an inflated balloon.
The formwork is inexpensive in comparison to the surface area and totally smooth surfaces can be achieved. Because of the limited use of material, little waste is produced. Being inaccurate, the formwork can be produced relatively fast without the use of advanced equipment. The inability to do anything else than convex forms is a distinct limitation. Also, the only precisely controlled parts of the cast geometry, is where the formwork have been fixed to its supports.

Fig. 2: Photo of a textile formwork.

2.3 Spray applied concrete

This method has been around for decades, but is still used for curved surfaces today. In short, the concrete paste is mixed with chopped fiberglass in a spraying nozzle, and applied to an underlying form with the reinforcement iron bars bend in place. After application, the concrete surface is manually faired or kept rough. The fibers' added to the concrete serve to add extra strength, but more importantly to keep the newly applied concrete in place. The method is mainly used for in-situ castings, and can form large spans and surfaces in one continuous, structural piece, as the reinforcement is a continuous structure as well.

The method is very labor intensive, as both the bending of reinforcement and the application of concrete is a manual process. It is also very difficult to create perfectly smooth surfaces, as the surface is finished off using hand tools.

Fig. 3: Photo showing spray applied concrete.

2.4 System based traditional formwork, PERI

PERI is a German producer of traditional scaffolding systems, but they have expanded their product portfolio to include both flexible single curvature formwork and custom double curved formwork. PERI specialty is that they use standard components for the production of all their form work and both the single curvature flexible form and their custom double curved forms are integrated into a complete and rationalized in-situ system. They have also developed software that can automatically determine what parts are needed based on a given geometry. It is a complete and reliable solution from software to hardware, design to construction. The main weakness is that there is still waste produced in the process of creating the double curved moulds, and that it is only possible to create double curved surfaces of very small curvature.

Fig. 4: Photo showing PERI's single curvature scaffolding.

The systems and methods shown above cover each their different aspects of freeform architecture. Whether building scale or curvature is taken into consideration, there seems to be a gap in scale from the textile and milled moulds to PERI's large scale buildings and the labor intensive, hard to fair spray applied concrete. PERI's boards or plywood sheets forced to create double curvature has a fairly small maximum curvature, and it seems futile to use a precision tool like a CNC milling machine, with its capability to produce very accurate and complex geometries, to create larger modules of relatively small curvature without further detailing. When looking at this curvature scale - smaller buildings created from a larger number of precast elements of familiar scale and curvature, it seems such elements could be generated from a common tool, the curvatures of which could be found between the maximum curvature of the force-bend scaffolding from PERI and the small, complex curvatures possible by milled moulds. A flexible tool could be competitive with foam milling in this area, if it were made, so that no additional, manual treatment of cast elements or surface were needed, no waste produced and production speed in comparison to equipment price were better. A tool for creating modular solutions should come with a software or system to rationalize production and communicate possibilities to architects. At the same time, the direct connection between drawing and machine, as with the CNC miller, should be established, to get an automated process. If a tool can be created to meet the criteria stated above, it could help promote the construction of the freeform architecture that is so commonly seen in digital architecture and competition drawings today, by offering cheaper and more efficient custom building parts. It could help bring the build architecture closer to the digital possibilities.

2.5 Flexible moulds

The most important aspect to consider when designing a flexible form is its limitations. The wider the desired range of possible shapes, the more difficult and advanced the construction will be. As discussed in the previous section, CNC milled foam moulds will at some point of complexity be the most attractive solution, as they are able to mill shapes that would be extremely hard to achieve by any other way of manipulating a surface. It is also clear, that no matter how a surface is manipulated in a flexible form, the very nature of the method results in a specialization in a common family of shapes. For instance, if a flexible mould were to create a perfect box, it may be designed to take different length, width and height, but because it needs specialized geometry like corners, it would be unable to create a sphere with no corners. A flexible mould aiming at the ability to do both, would possibly fail to achieve a perfect result in either case.

It all comes down to the fact, that every point on the surface of a flexible mould does not have the ability to change from continuity to discontinuity, because that would demand an infinitely high number of control points. Without an infinitely high number of control points, the flexible form, therefore, has to aim at creating smooth, continuous surfaces, the complexity of which must simply be governed by the number of control points. It is then left to decide, what the least number of control points is, relative to the properties of the membrane which will result in a mould design capable of achieving the curvatures needed for most freeform building surfaces. The initial motivation for the design of a flexible mould for double curved surfaces, was the encounter of other attempts to come up with a functional design for such a form, and the market potentials described in these projects. The technical difficulties and solutions defined in the projects presented here have been the inspiration for our present design.

2.6 Membrane Mould

[1] presents a prototype for casting fiber reinforced polyester panels. The mould concept is to have a flexible membrane manipulated by air filled balloons. The use of balloons solves the problem of creating smooth bulges on a membrane with no stiffness in bending, but it is hard to control the tolerances. The edge conditions are, however, defined relatively precise by linear, stiff interpolators connected to rods and angle control.

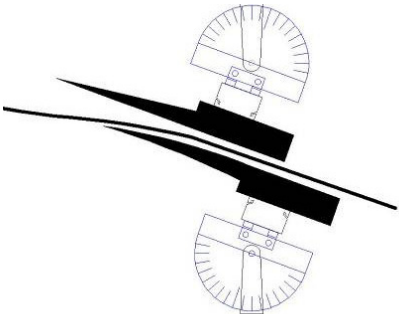

Fig. 5: Edge control by angle measurements [1].

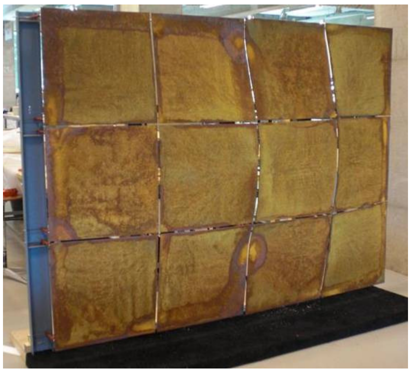

Fig. 6: This edge control means that the panels can be joined to create a relatively continuous surface [1].

2.7 North Sails

North Sails in North America produces custom cast sails in a digitally controlled, flexible form that uses a principle, where stiff elements created a smooth surface between points defined by digitally controlled actuators. They simply use what appears to be a thick rubber or silicone membrane which has an even surface, since it is supported by a large number of small, stiff rods placed close together underneath it. The small rods are placed on top of larger rods connected to the actuators. This simple system is possible because of the relatively small curvature in comparison to the mould size. The mould is highly specialized and appears to have been extremely expensive, but it is the best example of a flexible mould concept, that could easily be used to cast concrete panels, and it has been the main inspiration for the principles used in our mould.

Fig. 7: North Sails mould with numerous actuators.

3 Concept for a flexible mould

For a flexible mould, where only a set of points is defined, it is up to the membrane to interpolate the surface between those points. Inspiration can be found in old boat building techniques, where fair lines for a hull were drawn by bending a stiff member through a defined set of points. The principle is that the curvature depends on the distribution of internal forces. The internal forces will seek to be as low as possible, and therefore, the member will take the shape, where the least deformation is needed to get through the points. The principle of a stiff member interpolating a fair curve through points is relatively easy to imagine in 2D, and for a 2D solution, this would beyond doubt be the obvious choice for a "flexible curved ruler". When drawing free form NURBS curves in CAD programs, they are defined in much the same way, using mathematical expressions that resemble the behavior of a stiff member. The curve created by a physical member differs, depending on the stiffness. A stiffer member will have a more equally distributed curvature, while a softer member will tend to have higher peaks of curvature near the defined points, the softest possible being like a string with all curvature at points and straight sections between. This bond between the physical properties of a stiff member and the mathematical properties of a NURBS curve can be applied to surfaces as well. If a plate interpolator can be made, that has an equal stiffness for bending in all directions, but the freedom to expand freely in its own plane, it would constitute a perfect 3D interpolator parallel to the well known 2D solution, and the membrane presented by North Sails. Only, a membrane for a flexible mould for architecture should be able to achieve much larger curvatures between each actuator, then the solution of North Sails. To function as a surface suitable for casting concrete or other substances against without the need for further manual treatment, it should be durable and maintain a perfectly smooth and non-porous surface as well. A membrane with these properties has been developed for this project, and it is the core of the flexible mould invention.

Fig. 8: Pictures from testing the membrane principle. The membrane is fixed to the table around the edges, and supported by a single 6cm high rod in the center. The curvature can be seen to be evenly distributed around the support, and the membrane has a smooth curved cross section over the point support.

The number of actuators in a row defines the precision and possible complexity of the surface. A smaller number of actuators require a stiffer membrane and less control, a larger number means softer membrane and better control. In this way, the amount of actuators needed to depend on the complexity of the surface.

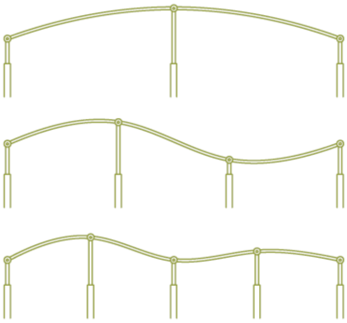

Fig. 9: Illustration of a surface deformed by 3, 4 and 5 actuators.

Five actuators in a section have been chosen not only because of the finer control, but also because the coherence between the NURBS surfaces in a CAD drawing and the physical shape of the membrane is better. The smaller leaps between the pistons mean less deflection caused by the viscous pressure, and most important, the edge conditions in a 5x5 configuration is less affected by the deflection elsewhere on the membrane, then they are with the 4x4, which is important to ensure similar edges on different panels, so that they can meet up nicely.

3.1 Fixation of pistons to membrane

Because the membrane is elastic and pistons are fixed in one position, the pistons cannot be fixed to a defined point underneath the membrane. Both membrane and pistons have to be fixed to a third system of sliding, bendable rods situated under the membrane, which allows the membrane to flex freely in its own plane, while still being fixed vertically as defined by the actuators. Since the upper limit for membrane stiffness is defined by the membrane itself, this underlying system is fixed to the membrane in many points to create additional stiffness to further reduce deflection from viscous pressure.

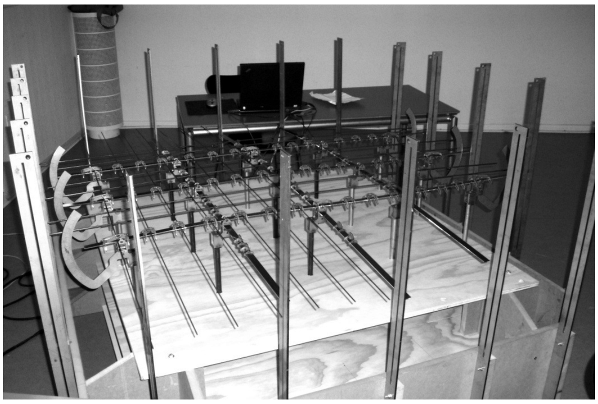

Fig. 10: The structure connecting the membrane to the actuators consists of spring steel members that are allowed to slide in both directions to obtain the movements of the flexible membrane. The system is designed to ensure, that the surface of the membrane has a constant offset from the surface defined by the actuator heads.

3.2 Edge control

Curvature in the membrane is created by moments caused by the deflection of it. Along the edges, no bending moment is applied in the direction perpendicular to the edge, and therefore one has to be applied to ensure double curvature at the edges. For that reason, handles has been applied to the underlying system. The handles are controlled manually, at least on the first prototype, and they are forced into position and fixed after the actuators have moved the membrane. These handles also serve the purpose of safeguarding, that the inclination along the edges of the membrane is comparable to that of the cast element next to it, to obtain an overall smooth surface.

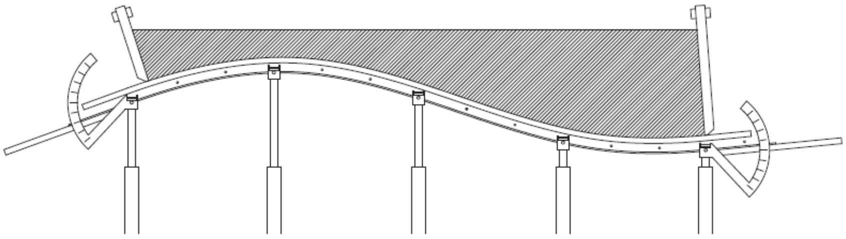

Fig. 11: Principle drawing showing the pistons connected to the underlying rod system, handles and scales for controlling the edge angle precisely and flexible side scaffolding allowing for custom outline and edge angles of the cast element.

3.3 Functionality and limitations

The mould can take any digitally defined shape within its limitations within one minute from the execution of a program reading 25 surfaces coordinates directly from the CAD design file. Once the actuator pistons have taken their positions, the handles must be adjusted manually, one by one, to a fixed angle calculated by the program and printed/shown. This will take a few minutes, as there are twenty handles around the circumference. The main limitation of the mould is its maximum curvature. It is defined by the construction of the membrane, and for the prototype, it is approximately a radius of 1.5m. The whole system can of cause be scaled to achieve smaller radii. The maximum curvature is for a double curved area with the given curvature in both directions. For single or almost single curvature, smaller radii are possible, but the performance has yet to be tested. Another limitation is that the surface designed has to fit within the 1.2m x 1.2m x 0.3 m which is the box defined by the pistons. This box is adequate to create a square piece of a sphere as big as the mould, with a radius of 1.44m. For most of the freeform architectural references, these limitations mean, that it is still conceivable to produce the larger part of the surface.

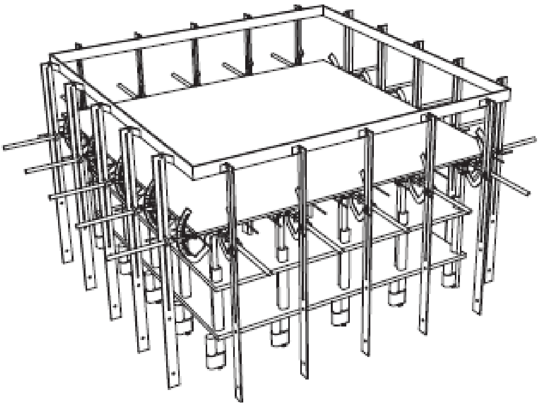

Fig. 12: Perspective, showing the mould design, the top frame is for mounting flexible side scaffolding, and it further supports the system for fixating the side handles.

The flowing illustrations explain how the flexible mould can be used from design to production of freeform architecture.

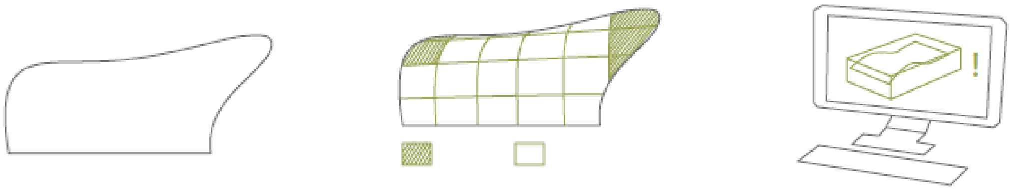

Fig. 13: Double curved surface , a subdivision of surface and validation of subdivision

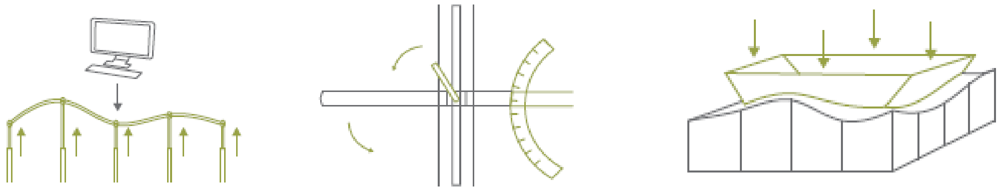

Fig. 14: Positioning of actuators, adjusting edge angles and mounting mould sides.

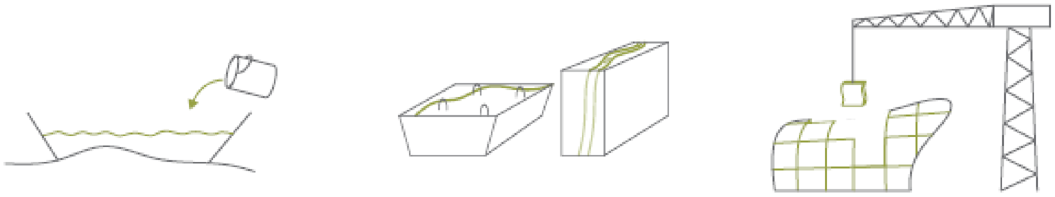

Fig. 15: Pouring filling, single or double sided moulds and of mounting elements

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Fig. 14: Computer rendering of a wall made up of elements produced with the double sided mould technique.

4 Conclusions

Complex freeform architecture is one of the most striking trends in contemporary architecture. Today, design and fabrication of such structures are based on digital technologies which have been developed for other industries (automotive, naval, aerospace industry). The present paper has presented traditional production methods available for free-form architecture which force architects and engineers to simplify their designs. Further the paper has described the development of a flexible mould for production of precast thin-shell fiber-reinforced concrete elements which can have a given form. The mould consists of pistons fixing points on a membrane which creates the interpolated surface and is fixed to the form sides in a way that allows it to move up and down. The main focus for the development has been on concrete facade elements, but a flexible, digitally controlled mould can be used in other areas as well. Throughout the project interest has been shown to use the mould for composites as well, and among other ideas are the idea of casting acoustic panels, double curved vacuum formed veneer and even flexible golf courses.

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