Adaptive mould - A cost-effective mould system linking design and manufacturing of double-curved GFRC panels

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Abstract

The paper presents a concept for an adaptive mould surface which is designed to fit the needs of contemporary architecture. The core of the concept is an adaptive surface manipulated into a given shape using information directly from the CAD drawing of the design. This is an automatic process 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 adaptive mould 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 paper describes a mould system and examples with double-curved Glass Fiber Reinforced Concrete (GFRC) panels produced by the mould.

Keywords: Adaptive mould, manufacturing, freeform, double curved, architecture

INTRODUCTION

Complex freeform architecture is one of the most striking trends in contemporary architecture. Architecture differs from traditional target industries of CAD/CAM technology in many ways, including aesthetics, statics, structural aspects, scale and manufacturing technologies. Designing a piece of freeform architecture in a CAD program is fairly easy, but the translation to a real piece of architecture can be difficult and expensive and as traditional production methods for free-form architecture prove costly, architects, and engineers are forced to simplify designs.

Today, methods for manufacturing freeform concrete form work are available, and more are being developed (Pronk et al. 1), (Helvoit et al. 2), (Boers et al. 3), (Guldentops et al. 4) and (Lloret et al. 5). The common way of producing moulds for unique elements today is to manufacture one mould for each unique element using 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 would become a complimentary technology to the existing.

The paper will present a reconfigurable mould surface, which is designed to fit the needs of contemporary architecture. The core of the concept presented is a dynamic surface manipulated into a given shape using a digital signal created directly from the CAD drawing of the design. This will happen 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 paper describes the mould system and examples with double-curved surface panels produced by the mould.

CONCEPT FOR A RECONFIGURABLE DOUBLE-CURVED MOULD

In the adaptive mould system, only a set of points is defined. A stiff membrane interpolates the surface between those points. Stresses in the deflected membrane will seek to be evenly distributed, and therefore, it will create a fair curve through the defined points. A stiffer membrane will have a more equally distributed curvature, while a softer membrane will tend to have higher peaks of curvature near the defined points. This relation 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, and the freedom to expand in its own plane it would constitute a 3D interpolator parallel to the well-known 2D solution (NURBS curve). To function as a surface suitable for casting concrete or other substances against without the need for further manual treatment, the membrane should furthermore be durable and maintain a perfectly smooth and non-porous surface. A membrane with these properties has been developed is the core of the adaptive surface mould invention. 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, see figure 1. A larger number means softer membrane and better control. In this way, the amount of actuators needed depends on the complexity of the surface.

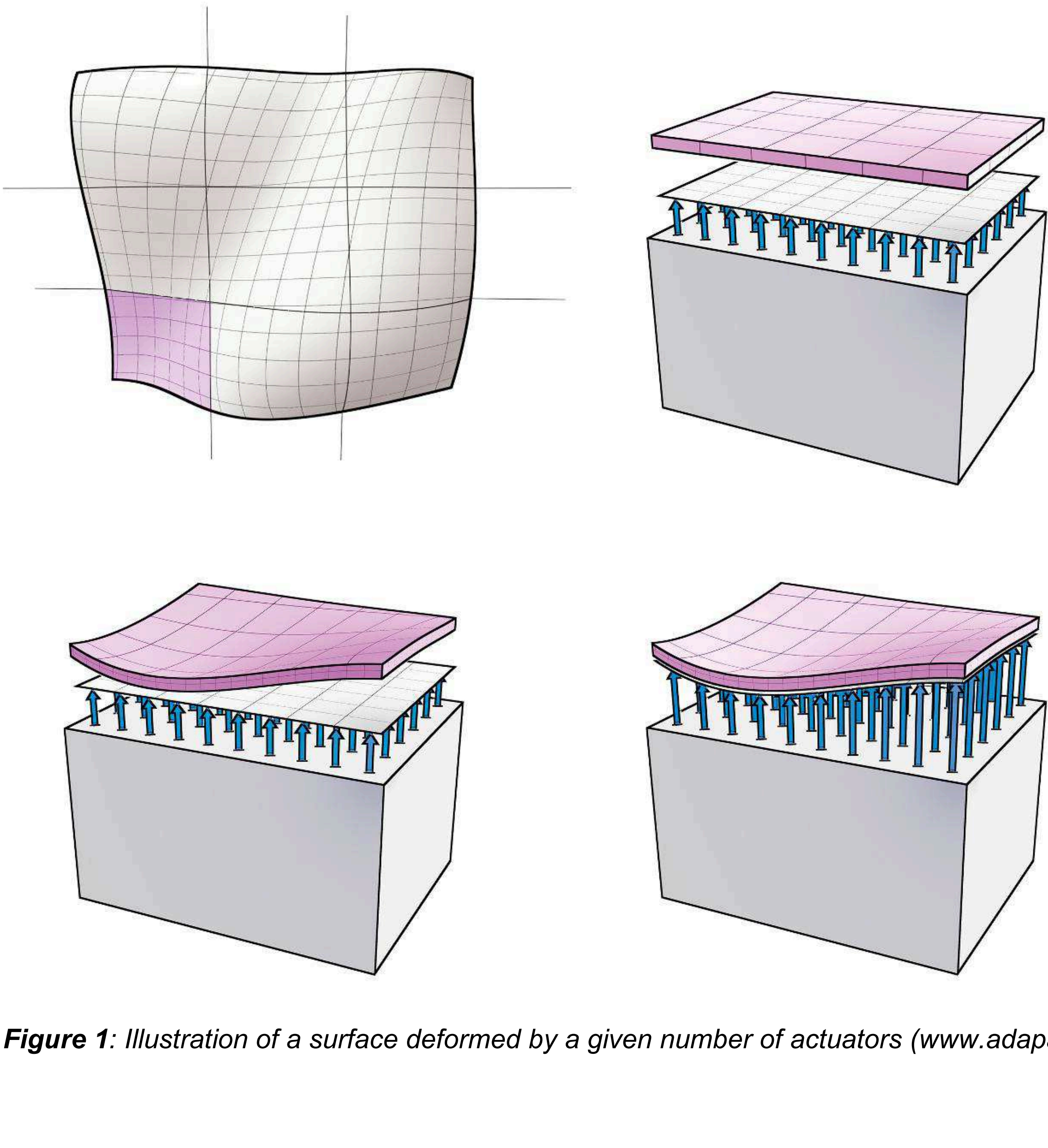

***Figure 1**: Illustration of a surface deformed by a given number of actuators (www.adapa.dk)*

Functionality and limitations
The mould can take any digitally defined shape within its limitations within one minute from the execution of a program reading surfaces coordinates directly from the CAD design file. The main limitation of the mould is its minimum curvature. It is defined by the construction of the membrane, and for the prototype, it is approximately a radius of 0.4 m. The system can be scaled to achieve smaller radii. Another limitation is that the surface designed has to fit within the region defined by the pistons. This region is adequate to create a square piece of a sphere as big as the mould, with a radius of 0.4 m. For most of the freeform architectural references, these limitations mean, that it is conceivable to produce the main parts of the facades. Control of the actuators via CAD software is programmed using the Arduino platform and Rhino supporting NURBS, which is ideal for generating surfaces applicable to the mould system.

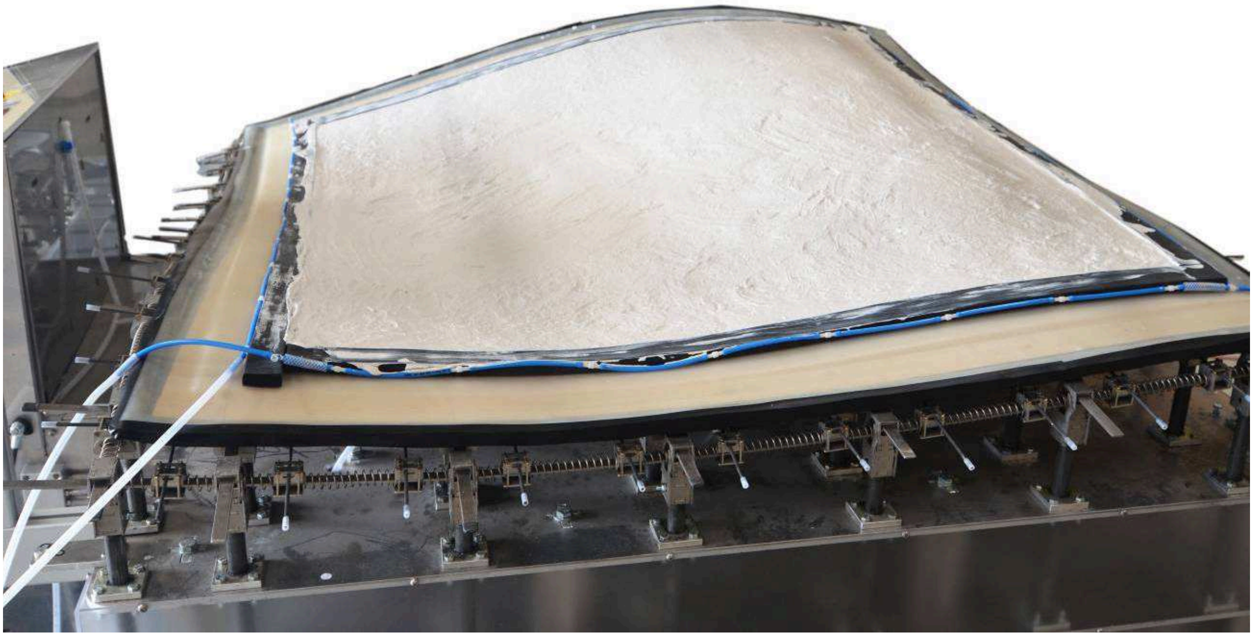

Figure 2*. Casting of a double curved fiber reinforced concrete panel (www.adapa.dk).*

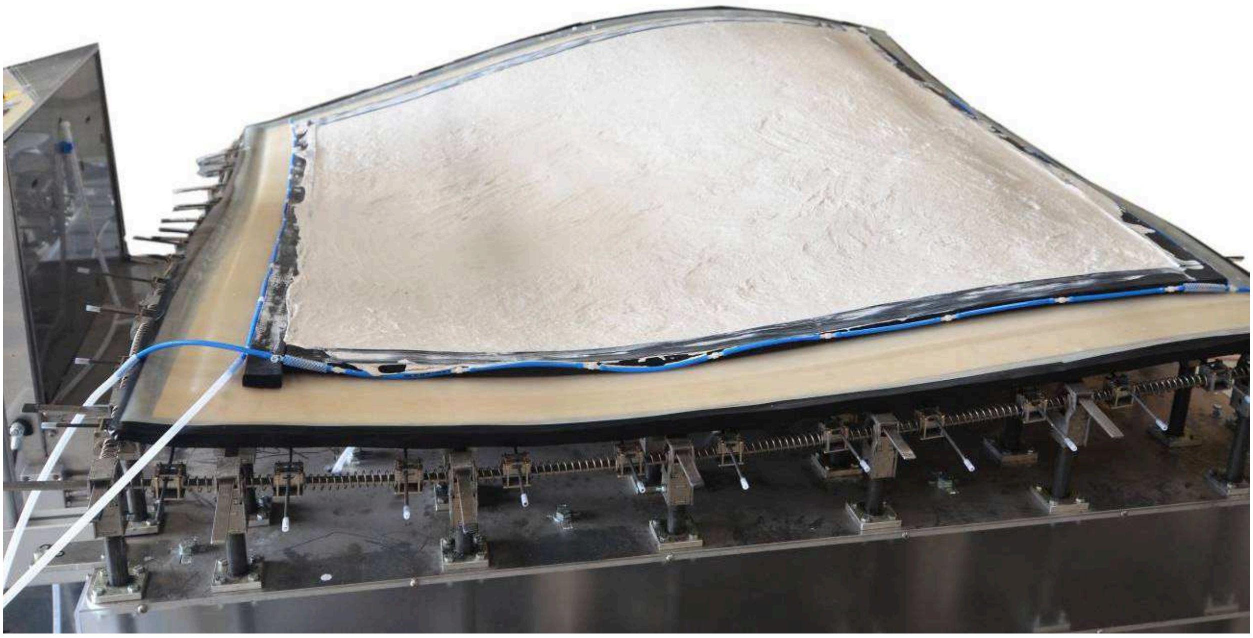

Figure 3. *Casting of a double curved fiber reinforced concrete panel (www.adapa.dk).*

The mould has from the early design stages been developed towards a specific physical solution space determined by the smallest possible radius and the maximum area and height of actuators, see figure 2. Therefore, it is a crucial decision when determining the exact solution space needed for a specific application i.e. facade construction.

Tolerances

Tolerances can be split in two categories. The first is the tolerances of the optimum created surface in comparison to that of the CAD drawing; the second is the accuracy of the system's structure.

The difference between the drawing and physical surface of the mould stems from the fact, that the membrane interpolates between the points in a different way to the drawing. Having said that, the 25 points and edge conditions precisely specified and the membrane technology certifies not only a fair surface but also a fair derived curvature. Furthermore, the inaccuracy in comparison to the drawing does not suggest that panels will not meet up properly, since they will differ from the drawing in the same way. An estimate on the maximum discrepancy between drawing and surface would be around 1-2mm, granted the digital surface is fair as well.

The tolerances within the system can vary in three ways. The normal tolerance is a result of the numerous moving parts, each contributing to minor inaccuracies. This is estimated to provide a difference of 0,1-0,2mm of difference between the piston end pushing and the piston end pulling the surface. Since the tolerances can be measured for push and pull, it can be taken into account.

The last kind of tolerance derives from the fact that the membrane is elastic. Because the membrane is one structural piece, an edge with pistons in exactly the same positions may change its shape slightly depending on the overall shape, as the edge is pulled in by various forces. This is the main reason why 25 and not 16 actuators are chosen, and the effect will only be known from testing the prototype. The stiffness of the underlying system also helps prevent the effect, since it consists of structurally independent parts. The effect is estimated to be 0-1mm for the worst cases.

Panel materials

Initially, the mould technology was developed towards concrete panels since these were in general usage within the architectural construction. However, other materials showed at an early stage promise as a material to be shaped on the mould, such as Glassfiber reinforced gypsum (GFRG), Thermoplastics, and Glassfiber reinforced plastic (GFRP).

The concrete panel industry regards the mould limited in one major aspect, hardening time. Typical hardening time for a GFRC panel would be around 18 hours before a demoulding can occur, and this sets a severe limitation to the optimization of panel production. Although the concrete panel industry has solutions for this available in their laboratories where the recipe for fast hardening concrete mixes have been tested, the implementation of these in production has been deemed too costly. However, seeing the potential in having a hardening time of three hours combined with the adaptive mould technology these advances may be pursued.

To produce double curved concrete panel or other materials with the adaptive mould it is necessary to use much effort in finding the optimal solution for dividing a surface both seen from a structural and aesthetical perspective

MANUFACTURING OF DOUBLE-CURVED PANELS

To produce double curved panels with the adaptive mould it is necessary to use much effort in finding the optimal solution for dividing a surface both seen from a structural and aesthetical perspective. Figures 4 - 6 outline how the adaptive mould can be used from design to production of freeform architecture.

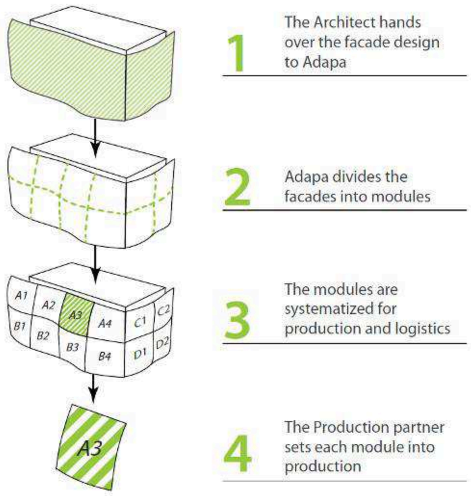

Figure 4. *Facade divided into panels and made ready for production on the mould.*

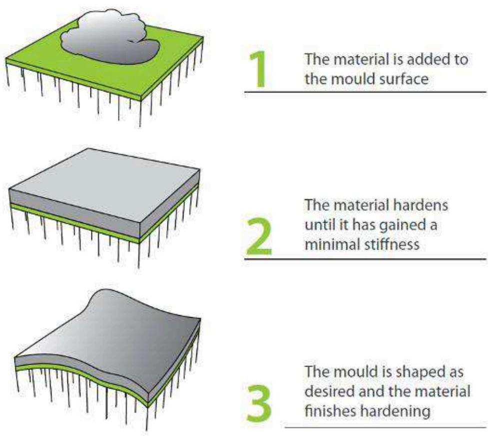

Figure 5. *Production technique for the adaptive mould.*

Panels produced using the adative mould offer a unique glossy or matt surface without extra fairing as seen in traditional manufacturing. This surface quality is enabled by selection of a high quality silicone surface able to withstand the chemical and temperature demands of the manufacturing tool. Hereby the surface quality is even for the entire production ensuring no visible differences from panel to panel. Figure 6 illustrates panels created in different materials with equal fairness due to the panels have been produced using the same surface although all are different geometries.

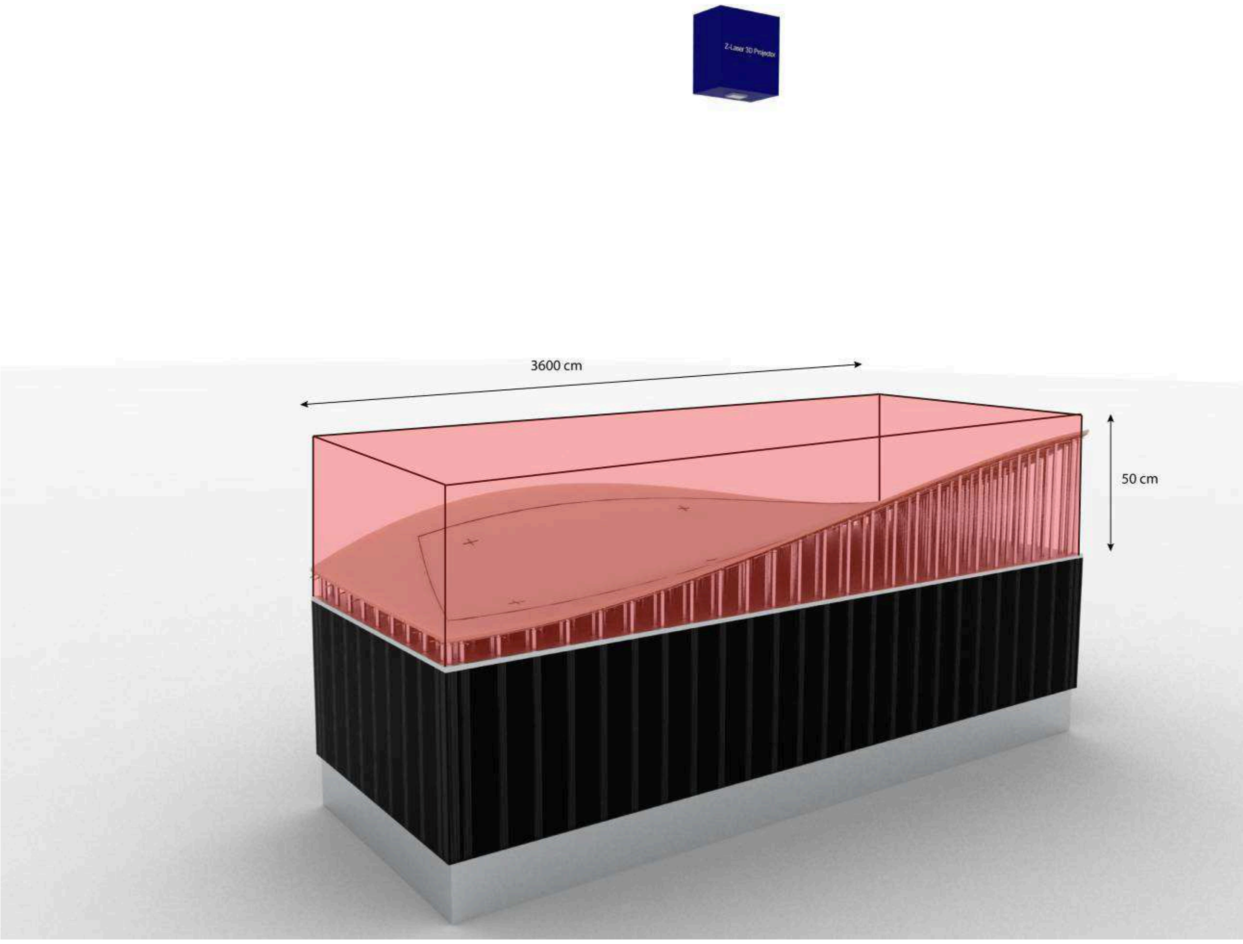

Figure 6. *Geometric constraints of the mould.*

Figure 7. *Exhibition panels at Foster+Partners made from GFRG, GFRC and Acrylic (1000x2200 mm).*

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 in other industries (automotive, naval, aerospace industry).

This paper has presented traditional production methods available for free-form architecture, which forces architects and engineers to simplify their designs. Further, the paper has described the development of a adaptive mould for production of precast elements, which can have a given double curved 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 GFRG, GFRC, but a adaptive, digitally controlled mould can be used in other areas as well. Throughout the project, interest has also been shown in using the mould for composites, and among other, ideas are the idea of casting acoustic panels, double curved vacuum and formed veneer. The adaptive mould concept can advance modern, free form architecture, as the concept offers cheaper and faster production of custom element. Today, double curved architecture is popular in digital architecture, and famous architects are building free-form buildings and pavilions. In the less-expensive part of the market, free form architecture is not as common, and often, like in the Blue Planet project by 3XN in Copenhagen, the double curvature is created by a steel frame work covered with tiling. This is currently the easy solution, as 2D digital technologies like laser cutting and water jet cutting is available as standard in the industry. Double curved concrete architecture seems to be a rarity, and it is hard to predict whether or not the introduction of the adaptive mould on the market will mean that more double curved concrete architecture will be designed, just because the technical opportunity is offered. However, in some cases, especially for facade elements, the method will offer a cheaper alternative for double curvature, that for economic reasons may be the only way to get a free-form expression. The facade element market is therefore identified as the key market for launching the adaptive mould.

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