Flexible mould by the use of spring steel mesh

Citation for published version (APA):
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Abstract
The present paper describes the development of a digitally controlled flexible mould that forms a double-curved smooth surface directly from a CAD model. The controlled surface consists of a plain woven spring steel mesh which adopts the desired smooth shape. The need for a flexible mould is to reduce the cost of double-curved and smooth architecture. Most elements are produced with a static mould or semi-flexible mould, which are time consuming and expensive. This technique is feasible, simple, cost efficient and can be used with different materials such as concrete, glass and composites.

Keywords: flexible mould, adjustable surface, free-form, double curved, fluid architecture.

1. Introduction
Today’s architecture is more demanding than before, especially concerning complex, free-form shapes. However the manufacturers lack the capability to actually produce the desired products designed by the architects. With the introduction of 3D software designing complex shapes became much easier; however the translation to a real object can be hard and expensive. The designers are forced to simplify their design because of the lack of available production methods. Producing fluid-form structures requires segmentation into panels, which are either flat, single- or double curved [1].
There is a need for a mould that can take almost any shape required. The key of the concept presented in this paper is to have a flexible surface formed into any given shape using a CAD model. It is much faster than milling and rapid prototyping, almost fully automatic and without waste of materials. The produced elements do not need any further treatments after production. 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 a flexible mould for production of glass and concrete, which can have almost any desired form. The mould consists of pistons fixed to a woven mesh which creates an interpolated surface. The pistons can move up and down the take on the desired shape created from a CAD model.

2. Mould techniques

Moulding techniques for this purpose can be divided into three different categories, as in Van Helvoirt, 2005 [2]:

1. The static mould. The most common mould of this kind is the EPS/PS (polystyrene) mould which has been 3D formed using a CNC cutter. This technique has a high accuracy but produces a lot of waste material;

2. The reusable mould, for example a mould made of clay or sand. There is no waste material and therefore the method is a lot more environmental friendly. It is labour intensive and cannot be used in all circumstances; and

3. The flexible mould. This type of mould can be used for a lot of differently shaped elements because the mould will form itself to the elements that will be produced. Examples of this kind of mould are the FlexiMould by Boers [3], and the adjustable mould by Rietbergen & Vollers [4]. The mould contains a field of height-adjustable pins. Each pin can be set into height individually using a computer-automated machine. The pins are covered with a polymer to smoothen the surface. It is important to avoid that the pins give a local distortion of the surface. The downside of these flexible moulds is the high investment. These expenses can only be gained back when a large amount of elements will be produced using this particular mould.

2.1. Flexible mould

Making use of flexible moulds can result in a significant cost reduction within the manufacturing process. Yet these flexible moulds are not feasible for commercial use because of the relatively high costs (Munro, 2007). These costs can be reduced by designing a simple and inexpensive flexible mould. The number of actuators required has a great impact on the costs as shown in figure 1. However, the amount of actuators has a direct influence on the form freedom of the flexible mould.

With a higher density of actuators, more extreme curvatures and more complex fluid forms can be produced. For architectural use, the curvature is limited. The radius of existing double curved constructions varies between 0.75m and 45m (Schipper, 2015), so a high density pin bed is not
necessary. The balance between costs and necessary curvature should determine the density of actuators.

The surface curvatures can be classified in four categories as shown in figure 2: zeroelastic, monoclastic, synclastic and anticlastic. When using a tensioned flexible layer only zeroelastic and anticlastic forms can be made which has a major limitation on the form freedom. With the use of a flexible top layer with a higher density of pistons, all different surface curvatures can be made. When considering the aspects of costs and its form freedom, the flexible top layer has the best balance between these aspects and is the most suitable method for the bending of curved panels.

3. 3Dflexmould

Avoiding high development costs that are involved with a pin bed mould and to avoid the problems with local distortion of the surface, the authors developed an adjustable mould without pins in the surface of the mould. Instead of pins a membrane is used with the capability to curve in two directions. The membrane is deformed by 25 pistons that move up and down and have a ball joint like connection to put no further stress in the membrane. With the combination of these two parts makes it possible to create any desired shape. In this way the benefits of a flexible mould (adjustable to a lot of
different elements) are combined with the benefits of a reusable mould (no waste materials and lower investment costs).

The developed flexible mould uses a spring steel mesh membrane that can take on any desired shape without losing its original shape. The shape will be set automatically in a form. Through the automation, a continuous production process of curved panels can be achieved. The Mould Design Tool\(^1\) developed for predicting the shape for the mould helps setting the mould in the correct shape. Figure 4 shows the mould in 3D and physical.

![Flexible Mould](image)

**Figure 3: Flexible Mould**

### 3.1. Spring steel mesh

The spring steel mesh is the key feature of the design. Spring steel has the characteristics to maintain its original shape even after deforming. The plain woven mesh is the most commonly used weave. Each weft wire passes alternately over and under each warp wire and vice versa. Warp and weft wire diameters are generally the same (see figure 4). Wires are crimped in the weaving operation. Two of the most important wire parameters are the wire diameter, \(d\), and the mesh number, \(H\). Mesh number is defined as number of openings in a linear inch measured from the centre of one wire to the centre of a parallel wire in the direction parallel to the centre of the other group of wires. The plain woven steel mesh has identical mechanical properties in both weft wire and warp wire directions.

\(^1\) The Mould Design Tool (MDT) is an own developed program that allows the user to set the mould in the right shape.
The mesh is woven from a 0.8 millimetre wire with an opening of 1.75 millimetre. Each side has 180 wires or the mesh number $M$.

The plain woven mesh consist of squares created by wraps and wefts by the steel wires. Shearing in a plain-weave steel occurs by the relative moment of two sets of steel wire, warp and weft, which are interlaced in a one-up and one-down. As the mesh is deformed the square starts to shear. The forces acting on the bar linkage can be resolved into shear and tensile force components acting perpendicular and parallel to the steel wire. At a small deformation the acting tensile force has a low magnitude which can be ignored.

Creating a computer simulation of the behaviour of the mesh requires a few adjustments and additions. To understand the behaviour the mesh is divided in $M \times M$ virtual masses (see figure 5). Each mass is linked to its neighbours by massless springs of natural length non equal to zero. The link between each neighbours is achieved in three different ways:

- Springs linking masses $[i, j]$ and $[i + 1, j]$, and masses $[i, j]$ and $[i, j + 1]$, will be referred to as “structural springs”;
- Springs linking masses $[i, j]$ and $[i + 1, j + 1]$, and masses $[i + 1, j]$ and $[i, j + 1]$ will be referred to as “shear springs”; and
- Springs linking masses $[i, j]$ and $[i + 2, j]$, and masses $[i, j]$ and $[i, j + 2]$, will be referred to as “flexion springs”.

Figure 4: Plain woven mesh
When there is pure shear stress inside the mesh only the “shear springs” are constrained; under pure flexion stresses only the “flexion springs” are constrained; whereas under pure compression or contraction stresses only the “structural springs” are constrained [5].

### 3.2. Control of the surface

The pistons controlling the meshes shape are made of three parts: an upper and lower tube and a bending spring. The joint of the piston has a different inflection point at each setting. The middle piston can only move in the z-direction. The mesh will deform and follow the constraint point in the middle. The pistons form after the desired shape. Figure 6 shows an operating piston.
The mesh mass point’s \( m \) must be seen as points in general. Recreating the surface after deformation is done by using NURBS splines and surfaces. NURBS are Non-Uniform Rational B-Splines. NURBS is a geometry that is easily manipulated by computer, allowing for great flexibility in modelling. NURBS can create smooth curves and surfaces with a small amount of points. The NURBS curves can be used to build a surface, define motion paths and control deformations.

The new generated surface is reconstructed by B-splines. The surface is then divided in a rectangular mesh. The intersections or knots are used as points to calculate the height of the pistons.
5. Results and Discussion

Validating the mould and the tool to control the desired shape a 3D measuring machine was used. The Prodim Proliner creates a point cloud that can be compared via software to verify the deviation. The precision of the machine is 0.8 millimetre.

The mould needs to be validated before any shape can be produced with the mould. By adjusting the pistons manually and measuring the surface a complete horizontal surface can be achieved. After running a simulation of the desired shape the surface is validated.

The result of a measurement can be seen in figure 9.1 and 9.2. The blue area shows a deviation of ± 1 millimetre, which is the most important area used in creating a curved surface. The edges of the mesh show a larger deviation due to insufficient support of pistons. The biggest fault error is the human error itself at this moment.
6. Conclusion
This paper discusses a study on the development of a flexible mould with the use of spring steel mesh membrane. The mould was used for bending glass, but can be used for different materials. Based on the study the following conclusions can be drawn:
- It was possible to create an accurate mould surface with a deviation of ± 1 millimetre with smooth curves and surfaces;
- The latest test results with bending float glass show a deviation of ± 3 millimetre, where insufficient slumping is the main error;
- Of course there is a limitation in the shapes that can be created, but most of them can be made with a high accuracy.

7. Future possibilities
The new production method has been put into the test and proves that it is possible to economically produce unique elements. It is possible to produce double-curved elements using a membrane mould. The unique elements show a deviation of +/- 3 millimetre in a small scale. The main advantages of the technique are the low costs and the simplicity of the mould. It is also possible to optimize the process by the introduction of computer-controlled positioning and the introduction of more pistons to control the surface better.

Acknowledgement
The authors would like to thank Brakel Atmos, Prodim, Solidrocks and VDNDP Bouwingenieurs for their support in this research.

References