EFFICIENT MATERIAL USE THROUGH SMART FLEXIBLE FORMWORK METHOD

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Abstract

Concrete is an excellent material for application in free-form architecture as a result of its initial fluid state. Double-curved building shapes have been realized in various fibre-reinforced mixtures, using advanced CNC-milled formwork systems. However, a substantial reduction of material use is still possible on two ends: by using a flexible formwork very thin and structurally efficient elements can be manufactured, reinforced with fibres or textiles. Moreover, the reusability of the flexible formwork considerably limits the waste material that was always remaining after the use of milled formwork systems. This paper discusses experiments with both formwork and mixtures in a PhD-study of the first author, demonstrating the ecological potential of this innovative production method.

1. INTRODUCTION

The formwork costs make up an important part of the total costs of architectural concrete structures, such as façade and roof elements. Especially when the shape of the formwork is non-orthogonal and double-curved, moulds are expensive. Although precasting can reduce these costs to some extent, repetition of elements then evidently becomes an essential boundary condition. Free-form architecture however is characterized by a geometry consisting of freely formed, irregular and often double-curved surfaces which greatly reduces the possibilities for repetitive formwork use. Due to both the complexity of the geometry that makes free-form shuttering difficult to manufacture manually, and the limited repetition that reduces reuse possibilities, nowadays robot-milled moulds of polystyrene foam (EPS) or fibre-board (MDF) are the most frequently used solution. In many cases a double mould is necessary to cover both faces of the cast element.

An illustration: for double-curved precast cladding elements in fibre-reinforced architectural concrete with a moderate curvature and a thickness of around 60 mm, an element price of € 500 to € 750 per square meter is a commercially accepted price range. The milled formwork costs make up 60 to 75% of this price. Apart from the direct economic costs, this material use inherently affects the sustainability of the total building: if the repetition factor is 1, the building is manufactured twice: once as formwork and once in concrete, thus reducing the ecological benefits of precasting. Ultimately, even if some of the formwork material can be recycled, this remains far from optimal. How can we increase the repetition factor of the formwork, while still maintaining freedom of form?

2. THE FLEXIBLE FORMWORK METHOD

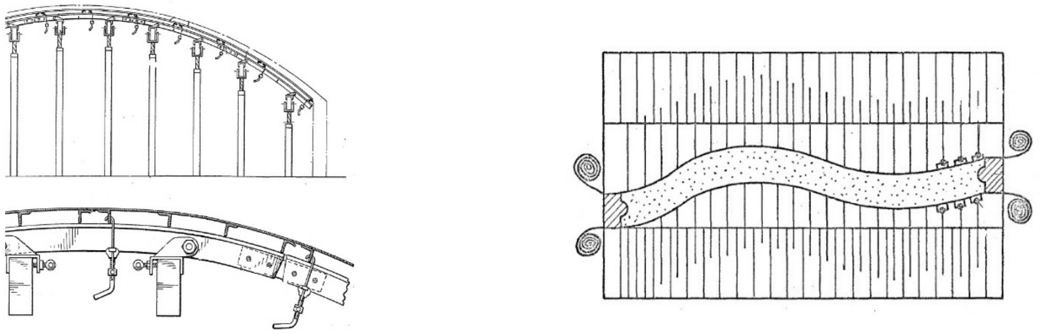
An answer to this question may be found in the use of flexible and reconfigurable formworks. The flexible formwork method is based on a principle that is already used in automotive and aerospace industries for purposes of rapid prototyping: a material is deformed from a flat piece into a desired curved shape by pressing it on rubber mat shaped by a bed of pins with variable heights. Examples of such pin-bed controlled mould systems are shown in Figure 1:

(a) Patent for metal parts by Mingzhe Li [1]

(b) Mould for plastics by Renzo Piano [2]

Figure 1: Pin-bed based flexible moulds

Munro and Walczyk [3] gave an excellent taxonomy of the use of flexible moulds in other industries than building industry. A patent research of the authors, interestingly enough, also revealed many patents describing flexible mould systems for the material concrete. Some of the patents were filed already decades ago; two examples are shown in Figure 2:



(a) Patent from Hawes, showing an open mould [4]

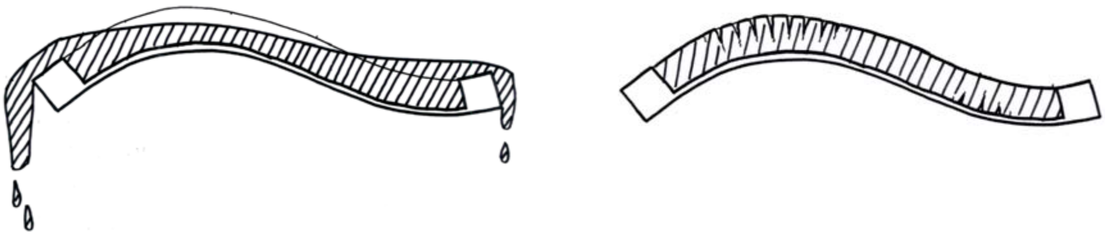
(b) Patent from Eisel, showing a double-sided mould [5]

Figure 2: Pin-bed based flexible moulds for concrete

In the PhD thesis of the first author an elaborate study of patents and earlier research on the flexible mould will be published shortly. Due to the understandable tendency of many concrete product manufacturers to keep crucial production information confidential, it was not possible to obtain reliable data on the penetration of this mould technology in current commercially operated production lines. The impression however is that both practical and fundamental unsolved issues have limited practical application so far. Below, these issues are discussed in more detail.

First, the background of flexible mould systems of other researchers worldwide will be discussed. In recent years, research work on the flexible mould was done by various academic groups around the world, including, but not limited to [6-11]. Each group has a different approach towards the formwork material and inherently also towards the control mechanisms to determine the accurate shape. For example, the use of fabric formwork brings along the study of form-finding methods and suitable textiles, whereas the use of CNC-milled reusable mould materials such as meltable waxes leads to research of wax properties and robotic milling equipment. The research groups that concentrate on pin-bed based methods basically have to deal with two important questions: 1) how to control the shape of an elastic mould surface and 2) how to find a concrete that is suitable and sufficiently reinforced for this method. This paper will concentrate on the last question.

Most of the groups looking into pin-bed controlled moulds start with a one-sided and open flat mould, that is filled with concrete in a horizontally levelled position. The concrete after a waiting period is deformed into its final shape by adjusting the heights of the pins in the pin-bed. Figure 3 illustrates the dilemma that has to be solved: using a too fluid concrete or deforming it too early will lead to redistribution of the fluid concrete over the mould, possibly resulting in spilling or unequal element thickness. If, on the other hand, the deformation of the mould is postponed for a too long period after casting, cracking will occur and structural damage is introduced. The authors have studied the time intervals to be considered during this process, and have also initiated a model approach that describes this specific workflow.



(a) Concrete still too fluid → spill of concrete or unequal element thickness

(b) Concrete too far hardened → cracking

Figure 3: Deformation after casting should take place *after* the stage that the concrete is still too fluid (a) but *before* it is too far hardened (b)

3. FROM FLUID TO HARDENED: PROPOSAL FOR A MODEL

Experimental work at Delft University, reported in a.o. [12], demonstrated that the flexible mould method is viable and can be used to manufacture accurately shaped double-curved concrete elements. An initial model was proposed that described the process. This model distinguishes two geometrical parameters of importance: 1) the maximum slope angle $\theta_{element}$ of the mould in the deformed situation, which potentially causes flow of concrete from a higher point to a lower point, and 2) the necessary strain $\varepsilon_{element}$ to deform from a flat to a double-curved shape. Both parameters can be derived from the intended geometry of the architectural element, and can be linked to the properties of the fresh concrete. The fresh mixture develops of green strength during the first hours (Figure 4, left graph) that on one hand lead to an increasing shear yield strength τ_0, coupled to an increase in $\theta_{allowable}$, but on the other hand to a decrease in strain capacity $\varepsilon_{allowable}$ (Figure 4, middle graph). This delimits the timespan that successful deformation is possible, as is illustrated in the right graph in Figure 4:

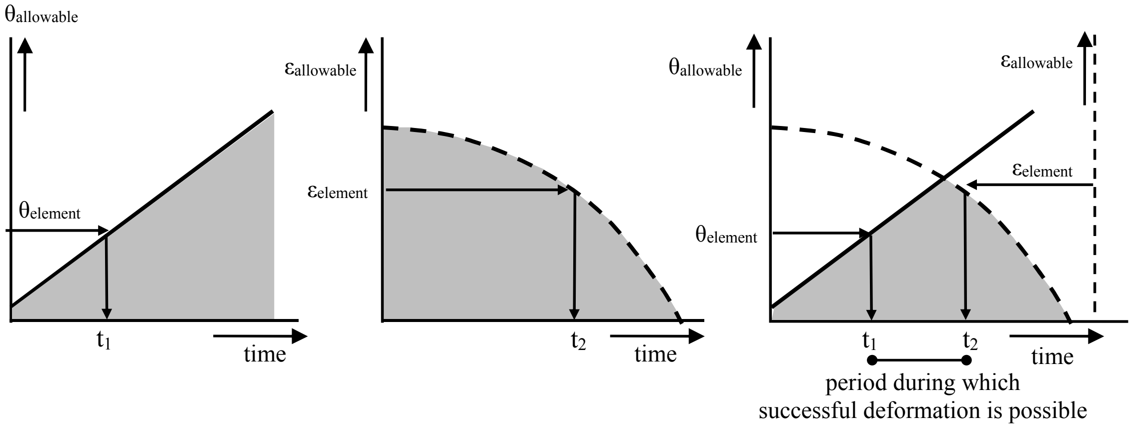


Figure 4: Model to determine the period during which deformation is possible

In the left graph the thixotropic strength development is depicted, that can be deliberately fastened or slowed down by choosing a more or less fine-grained mixture with increasing or decreasing proportion of fine particles such as fly ash, fine cement or limestone powder. In the present research the authors used a linear thixotropy model proposed by Roussel [13], as was reported in [14]. From the measured development of the rheological properties in time, which can be described with the Bingham fluid model (see [15], [16]) the allowable angle of the mould can be calculated, as depicted by the increasing height of the grey area under the diagonal line. A specific maximum slope $\theta_{element}$ of the mould cannot be installed earlier than time t_1 for a given concrete mixture.

The middle graph depicts the decreasing strain capacity in time as a result of the same thixotropic strength development. For reliable data on strain capacity and its development over time in the first hours it was more difficult to find data in literature. Dao et al. [17] carried out measurements on tensile strength and strain capacity in the context of cracking due to plastic shrinkage, which shows many similarities to the present research, since shrinkage is an imposed deformation similar to forced deformation after casting. The curved line in the middle graph is an assumed limit, as will be discussed later. It is used as an illustration of the concept. After time t_2, the strain capacity is reduced too much to allow deformation beyond $\varepsilon_{element}$. If deformation occurs after t_2, visible cracks or damage on the micro-scale will be the result. The dashed curve and the grey area depict the area of allowable deformation.

The right graph in Figure 4 demonstrates the intended practical application of the model: the grey, more or less triangular area is the result of combining the two earlier graphs, showing on the horizontal axis the interval $t_1 \rightarrow t_2$ that is the period within which successful deformation is possible. This interval will need to be determined for each mixture, or, if a specific interval is aimed for, the mixture could be designed to show the desired thixotropic and strain properties.

4. DETERMINING STRENGTH DEVELOPMENT

Two methods were applied to determine the thixotropic strength increase in time: 1) the BML Viscometer and 2) repeated slump (flow) tests with Abrams' cone or the Haegermann cone (see Figure 5). Especially for self-compacting concrete mixtures, the slump (flow) tests proved a practical method to quickly determine the yield strength. By using multiple cones, the development over time could be followed up to the point that the yield strength became so high that the slump value approximates zero. Reliable empirical formulas for the relation between slump (flow) values are available from literature, but the results diverge for low slump values.

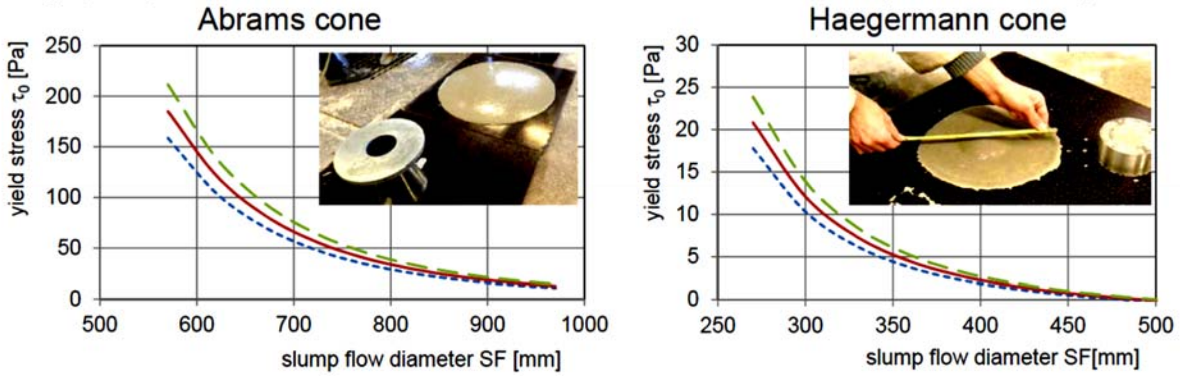


Figure 5 : Quick determiniation of the yield stress using slump tests for a specific concrete mixture weight of 1800 kg/m3 (lowest curve), 2100 kg/m3 (middle curve) and 2400 kg/m3 (top curve)

For repeating tests on the same batch of concrete, slump (flow) tests are the most suited method for determining the yield stress, since repeated tests on the same mixture in a viscometer are difficult due to disturbance of the thixotropic strength build-up by the measurement itself. The BML viscometer, on the other hand, appeared more suited for exact numerical calibration of these slump (flow) tests; results were reported in [14].

5. DETERMINING STRAIN CAPACITY

Determination of the strain capacity was carried out in two ways: careful observation of the appearance of cracks in the deformed elements and the execution of mini-deformation tests followed by microscopic research. The tests mentioned last are currently being carried out at Delft University of Technology. Some of his preliminary results are discussed here.

For these tests, small moulds were prepared (L x W = 150 x 90 mm) and curved after casting over various radii and deformed at various moments in time. The thickness of the elements was varied between 25 and 50 mm. The deformation time was chosen in the range from 0:30 h:mm to 2:30 h:mm after casting. In the elements that were deformed after more than two hours, clear cracks were visible.

Figure 6: (left) Visual inspection; (right) mini-deformation tests and microscopic investigation

However, the category without visible cracks might be the most interesting, since the closer inspection of these samples will allow us to draw conclusions on possible microscopic damage.

After the specimens were fully prepared, they were analysed using a stereo microscope. This allowed to inspect visually the concrete samples and to investigate micro-cracking on the top surface of the concrete element. The images collected from the microscope were taken in two different magnifications - 6.3x and 12.5x, this helped to measure more accurately cracks of different sizes. Using the stereo microscope with a UV light filter helped in increasing the precision of the measurements collected, since under UV light the epoxy impregnated spots become fluorescent and clearly visible. At this moment, this work is ongoing, but preliminary outcomes of a pilot-test show that the thickness of the concrete element and the time of deformation are indeed parameters that determine occurrence of cracks, the crack width and crack depth. Promising is that under the proper conditions damage is non-existing or limited, and also that self-healing mechanisms in the still young concrete seem to be able to span possible micro-cracks that are the result of the deformation of the mould. Further results of this work are expected to be published in the fall of 2014 [18].

6. PRODUCTION LINE

An envisioned production line showing the flexible mould method on an industrial scale is subdivided in steps in Figure 7 on the following page: the advantages of casting in a flat mould are the easy edge positioning and concrete thickness control. The deformation takes place in Step 5, after which some time for strength development is needed. After demoulding in Step 7, the empty moulds can be reused for a completely different element shape, thus resulting in both economic and environmental benefits. Recently, a valorisation grant was requested for further development of both the mechanical engineering of the mould mechanism and further research related to concrete technology aspects.

7. CONCLUSIONS

The flexible mould method is a viable method to produce double-curved elements with a single and open mould, which can significantly reduce formwork costs. The following conclusions can be drawn:

- For the determination of the proper moment of deformation, a model is proposed considering the yield strength development of the fresh mixture on the one hand, and the reduced strain capacity over time on the other hand;

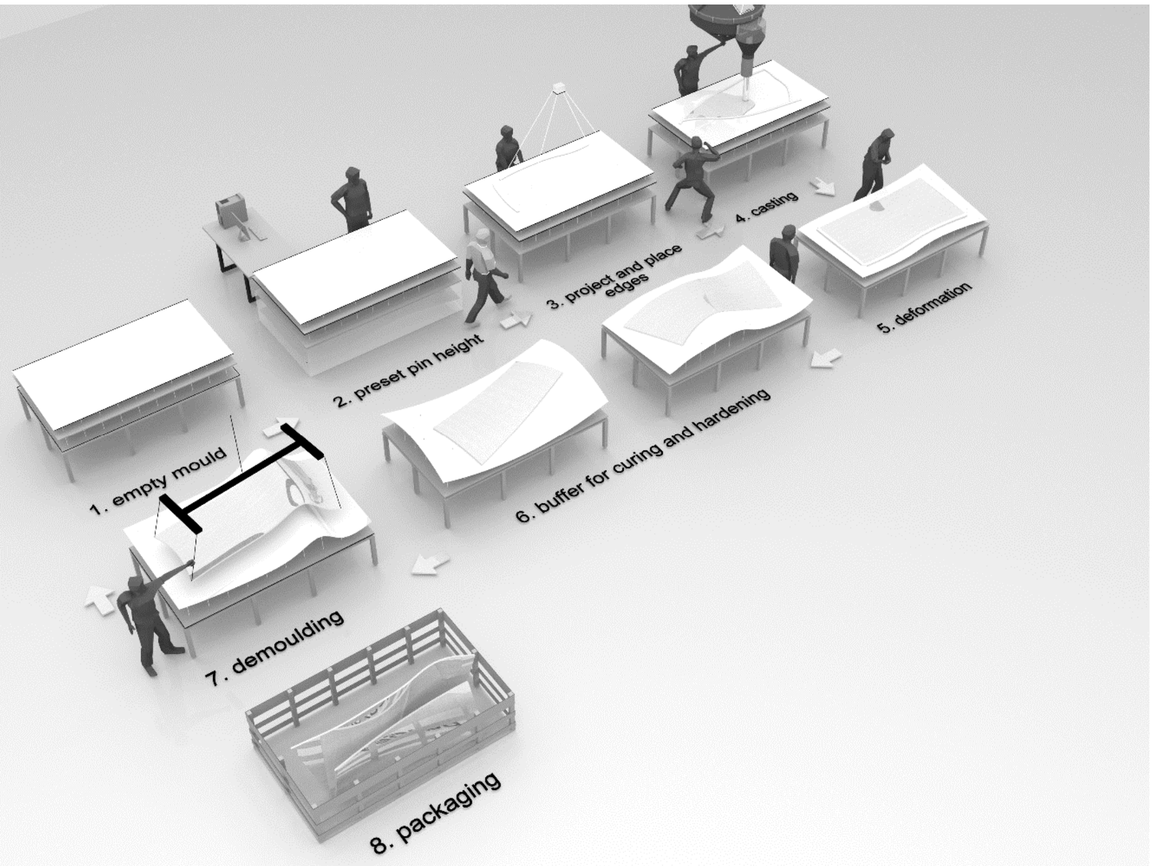


Figure 7: A virtual production line of double-curved concrete panels using the flexible mould technology

- Determination of strain capacity is more difficult than measurement of the yield strengths, and requires microscopic research; this work is still ongoing, but shows promising results.
- It is expected that in the near future and with proper investments, a production line can be realized using the flexible mould method and it will be possible to produce concrete elements in an environmentally more effective manner than using current CNC-milled foam techniques.
- Furthermore it is expected that the formwork costs can be significantly reduced, thus also providing a proper economic motive for endorsing this method.

Further work will involve a.o. microscopic research, reinforcement methods and improvement of the subsystem of the mould that allows to accurately deform. It is our ambition to provide a practically applicable method that limits the amount of waste material that is now still the result of using milled moulds for free-form architecture.

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