12 Deliberate deformation of concrete after casting

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This paper discusses the effect of intentional deformation of a flexible formwork after casting of the concrete and the influence of the characteristics of concrete in the fresh state on the quality of a concrete element. This deformation is intended to bring the concrete element in its desired final shape; the deformation typically takes place in the first hour after casting. In this research thin double-curved precast shell or cladding elements are considered. The paper introduces the method used to support the flexible formwork and focuses on the concrete technology necessary to control the process of deformation after casting. Relevant parameters are discussed that influence the concrete's behaviour shortly after casting. Rheological characteristics of the fresh concrete appear to be particularly important for the design of a suitable mixture. Since from traditional concrete research little experimental data on deformation after casting appeared to be available, experiments were carried out to test a number of prepositions. Results of these experiments are shown as well.

1 Introduction

The new generation of architects is educated in creating almost any possible free-form shape by making use of 3D-CAD software. This leads to building components with complex geometry. The manufacturing of these often uniquely shaped elements still does not follow this development in an equal pace. Double-curved surfaces need a double-curved formwork, of which the construction process is time-consuming. The construction of free-form surfaces made with concrete is relatively expensive due to the high labour costs of a formwork and the erection of the load-bearing structure in the production stage. As a consequence, double-curved surfaces are only applied in projects with a high profile and above average budget. An example of a building with a double-curved load-bearing façade is 'Der Neue Zollhof' (Düsseldorf, Germany) of architect Frank Owen Gehry; construction finished in 1999 (Figure 1). Prefabricated elements for this type of application might be produced with a custom-made wooden mould or with an EPS foam CNC milled formwork; the prefabricated elements for 'Der Neue Zollhof' were milled from PS-foam. Due to the variety of dimensions and shapes of the prefabricated elements, the re-usability of a formwork is limited. Because of high costs, some free-form buildings could only be built after modification and rationalization of the shape, in order to be able to construct it in an economically affordable way.

Figure 1: Double-curved load-bearing elements: Der Neue Zollhof' (Düsseldorf, Germany)

A more recent building, using double-curved cladding, to be finished in 2012, is 'Heydar Aliyev Cultural Centre' (Baku, Azerbaijan) of Zaha Hadid Architects (Figure 2).

Figure 2: Double-curved cladding elements: Heydar Aliyev Cultural Centre (Baku, Azerbaijan)

In contrast to the 'statical' method (as far as formwork is considered), a method with a flexible formwork is discussed in this paper. Instead of many different uniquely shaped formworks, one formwork could be reused many times, making a project with a double-curved surface feasible. A flexible formwork can be adjusted to cast concrete in the desired shape. In the sixties, Renzo Piano designed a flexible formwork; it consisted of a flexible layer that can be deformed into the desired curved surface by adjusting, for example, pistons, actuators or pins. The concept of a flexible formwork was further discussed and tested over the years; adjustable supports were also studied. Jansen (2004) studied the idea of placing strips to construct the mould. The mould consisted of pins which are adjustable in height and were covered with strips in two directions. A rubber mat was placed on top of the strips, which gave the element a smooth surface. A problem with this mould layout is to determine the best distance between the pistons and to choose the right stiffness of the strip layers. Another option is to place a pin-bed to provide support (Quack, 2001; Van Roosbroeck, 2006). It was difficult to obtain elements with a smooth surface; it was also difficult to produce elements having a constant thickness.

The choice of the formwork (thickness and material) also determines the shape of the element. Influenced by the weight of the concrete, the chosen curvature and the span between the supports, the stiffness and the deformability of the formwork and the concrete characteristics are critical design parameters. In case the stiffness of the bottom layer is too high it does not have contact with all pistons; with a stiffness too low the formwork deforms between the supports with surface irregularities and an inaccurate shape as a consequence. The contact between pistons and mould was -in some experiments- forced by creating hinges or other connecting points, but this can lead to rather high tensile forces as a result of the bending action in the mould.

2 A flexible formwork for double-curved elements

An economical solution for producing elements which all have unique shapes is a flexible formwork; a formwork that can be adjusted to obtain the desired shape. Rietbergen and Vollers (2007) developed a prototype of a flexible surface on an adjustable pin-bed (i.e. a grid of actuators). The pin-bed originally was designed for producing double-curved glass panels. The actuators are simultaneously adjusted in height by a computer (Figure 3).

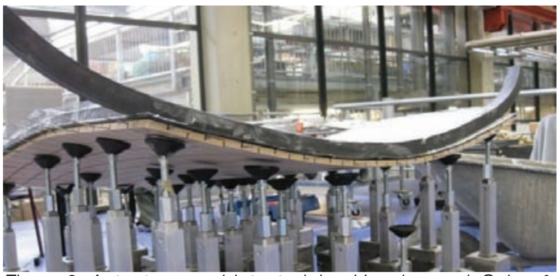

Figure 3: Actuator mould tested by Huyghe and Schoofs (Huyghe & Schoofs, 2009)

On top of the actuators a flexible layer was placed which was the formwork for the concrete. In order to assure a constant thickness of an element, concrete was poured with the mould in horizontal position. Advantages of starting with a horizontal mould are that no contra mould is needed, the thickness of the element can be controlled easily and the pouring is relatively easy and quick. Casting concrete in the deformed situation of the formwork increases the range of element thickness with less accurate dimensions as a consequence. The patent of Vollers & Rietbergen for the production with a flexible formwork describes the deforming process of a flat glass plate into a double-curved one (Vollers & Rietbergen, 2009); a second patent describes the process for viscous liquid material (Vollers & Rietbergen, 2010). The three patented steps for producing concrete elements are:

- Installing the formwork layer above a row of CNC-cut support strips
- Casting concrete on the formwork, positioned horizontally
- Lowering the formwork onto the row of support strips

In both patents a 'material' is placed in an initially horizontal position (Figure 4a); a glass plate is heated to reduce the stiffness. Afterwards the plate can be deformed by lowering it on the curved supports (Figure 4b).

Figure 4: Two production steps for single-curved test specimens: a) casting in horizontal position, b) mould after deforming

The strength of the viscous material is sufficient to make sure that it does not flow, and then it is lowered to the curved supports. The material hardens or cools down in the final, deformed position. The second patent (Vollers & Rietbergen, 2010) describes ways to build the elastic mould surface for viscous liquids. In the first patent (Vollers & Rietbergen, 2009) a glass plate is placed directly on rods, so an additional mould surface is not needed. The patents also describe ways to construct the curved supports: panels in one direction that provide support lines and steel rods in the other direction, or by positioning pistons/actuators as supports. Huyghe and Schoofs (2009) executed a series of experiments with the flexible formwork developed earlier by Vollers and Rietbergen. Several production parameters were considered in this study like the thickness and the type of vertical mould strip. Janssen (2011) developed and tested a calculation model that predicts the deformation of the horizontal formwork layer and forces at the supports, which allows selecting a formwork material with adequate stiffness and deformability. In the experiments of Huyghe and Schoofs, this appeared to be a difficult problem to solve.

Recently, a pin-bed was developed by co-author Vollers and Free-D Geometries (Figure 5). Each pin can lift/pull 1 KN. A flexible surface appropriate to the to be transformed material, is to be positioned on the pin-bed.

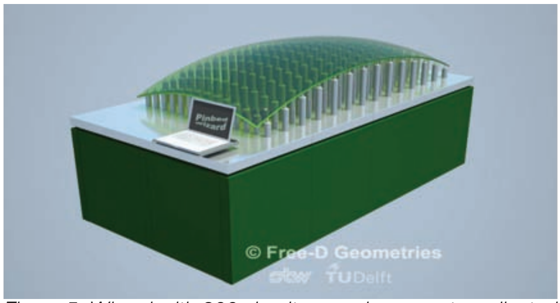

Figure 5: Wizard with 200 simultaneously computer adjusted actuators

According to the production principle described above, a flexible mould can be deformed before the concrete is poured, or with the fresh concrete already on top of it. Deforming the mould with the fresh concrete on top of it means that the weight of the concrete pushes the mould into the desired shape. Deforming the mould without concrete means that additional forces at the supports are required to bring the mould into its final shape. Janssen's calculation models takes into account this elastic behaviour accurately.

3 Concrete characteristics

In the hardened state, concrete has to have specified characteristics; with very slender elements, often demoulding, storage, transport and/or mounting are most important for the design. Applying self-compacting concrete is the best option for casting in a horizontal position. It eliminates the need for compaction. However, at the moment of deformation the criteria concerning concrete characteristics in the fresh state differ from the moment of casting The rheological behaviour of concrete is a governing parameter in the production process with the described production method. Concrete has to have a minimum yield value, which is adequate to obtain the required curvature of the element; a criterion on the yield value (minimum yield stress) can be formulated as follows:

$$\tau_0 \geq \tau_{0,crit} \quad (1)$$

With Equation 2 (De Larrard, 1999):

$$\tau_{0,crit} = \rho g h \sin(\theta) \quad (2)$$

where: ρ = density of concrete; g = standard acceleration of gravity; h = depth of the slab / concrete layer; θ = slope angle

The yield value can be estimated from the slump test (NEN-EN 12350-2, 2009) with Equation 3 (Ferraris & De Larrard, 1998):

$$\tau_0 = \frac{\rho}{347}(300 - s) \quad (3)$$

where: ρ = density of concrete; s = slump value

Concrete and cement paste in particular are thixotropic materials, which means that a time-depended structural build-up of fine particles takes place when the concrete is at rest. This characteristic allows casting concrete at a lower yield value (a higher flowability) than the critical yield stress and utilising the structural build-up to deform the mould within a shorter period after casting. With the progress of cement hydration the yield value also increases but it also decreases the deformability of the concrete. The cohesion of concrete can be enhanced with measures like the addition of plastic fibres, producing a concrete with a smaller maximum aggregate size or the addition of a thixotropy-enhancing admixture. Vibrating the concrete before deforming the mould (in horizontal position) allows applying a concrete with a relative higher yield value compared to a flowable concrete, which shortens the period between casting and deforming of the mould. The maximum curvature, defined by R or its reciprocal $\kappa = 1/R$, and the thickness t of the element determine the required deformation capacity of the concrete. Since concrete is subjected to an elongation ε (in $\varepsilon = \kappa \cdot z$; with $z = \pm\, t/2$) which is due to deforming the mould it should be controlled whether an element has accurate dimensions in relation to the concrete mixture used and vice versa.

4 Experimental set-up

4.1 Mixture composition and performance in the fresh state

In order to study the concrete characteristics in the fresh state and the effect of the production process, two mixtures were tested (Janssen, 2011). The first mixture (M1) was a fine mortar with a maximum aggregate size of 0.25 mm, the second (M2) was a mortar with a maximum aggregate size of 4 mm. The paste content of the first mixture was also higher. Both mixtures had an average compressive strength (cubes of 100 mm) of about 80MPa 28 day after casting (M1: 78MPa; M2: 82MPa). Both mixtures were self-compacting after mixing. Mixture M1 contained a significant higher dosage of superplasticiser (fly ash and fine quartz sand were added as fillers), which caused a retardation of the strength development. Based on the initial testing with Mixture M1 several adjustments were made for the second mixture. Figure 6 shows mixture M2 45 minutes after casting; a ring was used as a mould (the diameter of the applied PVC-ring was 112 mm).

Figure 6: Consistency testing 45 minutes after casting (Mixture M2)

The yield value increases in time; a plastic consistency of the concrete (Figure 6) allowed deforming concrete with sufficient internal cohesion to prevent the formation of cracks. Whether or not a crack appears also depends on the required strain capacity that is determined by the curvature and the thickness of the element. Due to the larger maximum aggregate size Mixture M2 is less homogenous; the shortened processing time and consequently better controllability of the production process outweighed this disadvantage. Tests were executed with Mixture M2 on small deforming test samples, single- and double-curved test specimens.

4.2 Small deforming test samples

Preliminary tests with small samples (d=50 mm) were executed in order to determine the characteristics of concrete in the mould; the deformability was investigated at different times after mixing. On a flexible Vivak-plate a flexible strip of polyester foam (cross-section: 50 mm*50 mm) was glued. After lifting the middle part, the mould was deformed and the effect of a curvature of the mould could be simulated. Lifting the plate only a few millimetres already gives a good estimation of the maximum curvature of double-curved elements. With this test set-up and at any moment after casting the following can be determined: 1) whether the yield stress is sufficiently high and 2) whether concrete deforms or a single crack appears at the location with the highest curvature. Figure 7 shows a small test specimen in the deformed stage; the yield value was not high enough and as a consequence, the slope of the concrete is too small.

Figure 7: Small-scale test for curved elements; the yield value of the mixture is too low as can be seen from the concrete level

Executing deforming tests with a small test specimen provides a good indication of how concrete characteristics affect the production process. Compared to a large double-curved element the wall-effect of the vertical strip is more pronounced. It was decided to perform further testing on a larger scale with single-and double-curved test specimens.

4.3 Single-curved test specimens

Five single-curved specimens (horizontal length = 2000 mm) were produced in order to determine the effect of the flexible mould layer, the maximum curvature and the type of vertical formwork strip. Table 1 summarizes the test parameters of the five single-curved test specimens.

Table 1: Test parameters of single-curved test specimens.

Nr	Wait period [min]	Mould bottom	Layer thickness [mm]	Radius element [m] (support number)	Vertical formwork strip
1	50	Wood	3.8	5 (11)	Polyether SG 40 extra firm
2	50	Steel	1.0	5 (11)	Cold foam HR SG 55
3	50	Wood	3.8	2.5 (6)	Polyether SG 40 extra firm
4	50	Wood	3.8	1.5 (6)	Polyether SG 40 extra firm
5	30	Wood	3.8	1.5 (6)	Polyether SG 40 extra firm

A Polyether foam-strip (cross-section: 50 mm*50 mm) was clued on the mould plate of Elements 1 and 3-5; cold foam was used for Element 2 (cold foam is stiffer compared to polyether foam). A foil was placed in the mould to prevent leaking of liquids. The number of supports were 6 or 11; with more supports a thinner plate is required to obtain compressive forces at all supports. Wood with a thickness of less than 3.8 millimetres was not available for order.

The height of the supports was calculated from the curvature of the test elements. In total, eleven supports for Elements 1-2 and six supports for Elements 3-5, respectively, were placed; the width of the mould (including vertical strips) was 400 mm. The thickness of the mould layer was predicted and optimised according to the calculation model described by Janssen (2011). Large-scale tests were also carried out to validate his model.

4.4 Double-curved test specimens with strip moulds

Initial testing indicated that an accurate shape of a double-curved element could not be obtained with a plate as a mould surface. Local instabilities were caused by relative high normal stresses in the plate material, due to membrane action.

Therefore, two tests were executed with a mould supported by strips arranged in two perpendicular directions. All wooden strips had a width of 50 millimetres and a thickness of 3.8 millimetres. The lower strip layer was directed in the shortest direction of the mould. These strips were connected with the supporting tubes and the upper strips in the middle of the mould by a nail. The fixed point assures that the strips stay on the tubes and the nail counteracts horizontal movements. The strips are supported by studs on bolts; the height of the supports was determined to obtain the accurate shape of the element. The studs were screwed in vertical direction on a wooden plate. In total 66 of these support points were placed - in a set up of six times eleven. With a distance of 200 millimetres between the supports (in both directions) the total dimension of the mould was 2 meters by 1 meter. With a plate thickness of 3.8 millimetres tensile forces were predicted for most of the supports at the border. By drilling holes in the strips at the supports these tensile forces could be carried by ropes, which were fixed before casting. Vertical polyether foam strips (cross-section: 50 mm*50 mm) were glued on the formwork layer.

Concrete cannot be poured directly on the strips since it flows through the strips. The same material that is used for the vertical strips was used as bottom layer (Polyether foam, d=10 mm); at joints it was sealed to prevent leakage. Tensile forces were predicted by the calculation model at some points; holes were made for ties in the mould in order to be able to take up the tension forces.

5 Results

Two types of scaled elements were produced: five single-curved test specimens and two double-curved test specimens with strip moulds. In the following, the results of both types of elements are summarized.

5.1 Single-curved test specimens

Table 2 summarises conclusions concerning the production and characteristics of the elements in the hardened state.

Table 2: Production of five single-curved test specimens

Nr	Production of element	Crack	Characteristics in hardened state
1	Mould touches all supports	No	Desired shape is obtained
2	Mould touches all supports	No	Desired shape is obtained, steel and cold foam are more expensive
3	Mould touches all supports	No	Desired shape is obtained, foil is stretched which is visible at the sides of the element
4	As predicted, the plate did not touch the supports at both ends, a rope was used to carry the tensile force	Yes	Desired shape is obtained, after demoulding a crack was visible at the surface in the middle of the element
5	Mould touches all supports with help of ropes to carry the tensile force	No	Desired shape is obtained, no crack appeared because the mould was deformed already after 30 minutes

All elements were demoulded one day after casting; until this time a plastic foil was placed on the surface to counteract drying. The edges at the corners of the element were sharp. The glued vertical polyether and cold foam strips were able to follow the deformation of the mould plate and they were also able to withstand the horizontal pressure of the concrete. Acceptable elements were obtained with Tests 1-3 and Test 5; a crack was observed after demoulding for Element 4. The thickness of Element 5 was measured at 21 points along the longer side of the element. The design thickness was 50 mm; the average thickness was 47.1 mm (minimum: 45.5 mm; maximum: 51.0 mm). Due to the geometry of the element and the weight of the concrete, higher values were obtained at the end of the element. At the highest slope, the thickness was the lowest. Figure 8 shows Element Nr. 5 after demoulding.

Figure 8: Single-curved Element 5 after demoulding

The results can be schematically summarized in a graph (Figure 9) relating the curvature and time after mixing.

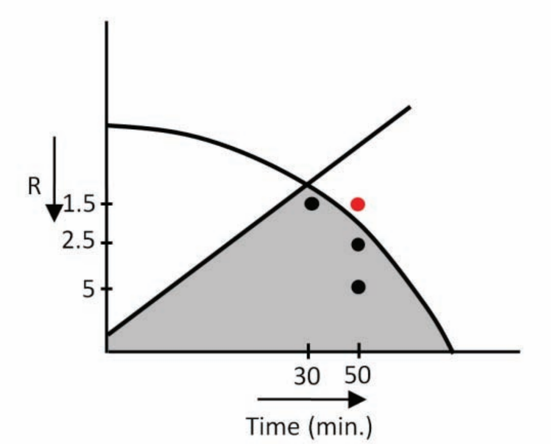

Figure 9: Applicability area for deforming of Mixture M2

The yield stress increases with time passing after mixing, which allows producing an element with a higher curvature (Figure 9: a straight line is assumed). However, the deformability of the concrete decreases in time, which is indicated by a curve. With an adequate yield stress and sufficient deformability an area of applicability of the concrete was determined (grey area). The dot outside the grey area represents Element 4; by shortening the waiting period (from 45 to 30 minutes) to deform the element an acceptable performance was obtained.

5.2 Double-curved test specimens with strip moulds

One element with positive Gaussian curvature and one with negative Gaussian curvature were cast.

5.2.1 Element 1

The lowest point of the element had a relative height of 35 mm (in one of the edges); the highest point was on 221 mm (in the middle of the element), which is a height difference of 186 mm. 45 minutes after casting the mould was lowered on its supports and the concrete deformed in the desired shape without cracks appearing on the surface. As was predicted with the calculation model, the mould did not touch all supports; the ropes were tightened at these points in order to obtain the desired shape of the element. After demoulding the surface of Element 1 was inspected. Since all supports were connected to the mould, the focus was on the curvature between the supports. The surface was smooth and the slope increased gradually between the supporting points. The strip layers performed well as a supporting structure.

5.2.2 Element 2

In order to produce a double-curved element with realistic dimensions a segment from a free-form building was selected from Evolute (2011), which is a company that also produces software for the segmentation of surfaces. The element was scaled to enlarge the radius and to make use of the full length of the supports. The lowest point of the element had a relative height of 35 mm (in the middle of the longest site); the highest point was on 225 mm (in the middle of the shorter span at one end of the element), which is a height difference of 190 mm. This element had a sharpest curvature of about R = 2 meters. The same conclusions considering the deforming and a lack of contact with supports can be drawn. However, after the deformation process small cracks appeared at the surface. Because the concrete still was in the plastic stage and the stiffness was low, the cracks could be closed by finishing the surface. By deforming after

30 instead 45 minutes after casting, the crack width was limited. Figure 10 shows Element 2; no additional cracks were observed at the surface after demoulding.

Figure 10: Produced double-curved element (Element 2)

6 Conclusions

This paper discusses a study on the applicability of a flexible formwork method to produce double-curved elements with concrete. Parameters of the study were the concrete type, the mould layer and the vertical strip; tests were executed on different scales. Based on the study the following conclusions can be drawn:

- The concrete characteristics in the fresh state are important to be considered for the described production process; in the 'area of applicability' the applied mixture performed well.
- Depending on the boundary conditions, supports might not be in contact with the flexible mould. The elastic behaviour of the mould plane and the location of the supports can be predicted by simulation and precautions can be taken to transmit the required tensile load.
- It was possible to produce double-curved concrete elements with accurate dimensions combining horizontal casting with applying a flexible support-system in a strip configuration.

7 Future work

A number of issues will be addressed in future research:

- The testing was carried out with rectangular panels. The majority of double-curved panels, however, will not be orthogonal, and have curved contours as well. This imposes special measure control demands on the position of edge profiles before and after deformation.
- In order to achieve weight reduction, panels will be designed with thin surfaces that on the backside have ribs and thicker edges. In addition, connecting devices, probably on the backside too will be needed. The exact measuring and production of such requires additional development.
- In situations where the elements are used as cladding panels, the concrete texture and "edge return" (visual quality of the edge of the panels) are of great importance for architects. Although the quality of the discussed concrete elements was promising, further attention will be paid to this aspect in future experiments.

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