Production of Curved Precast Concrete Elements for Shell Structures and Free-form Architecture using the Flexible Mould Method

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Abstract

Free-form buildings tend to be expensive. By optimizing the production process, economical and well-performing precast concrete structures can be manufactured. In this paper, a method is presented that allows producing highly accurate double curved-elements without the need for milling two expensive mould surfaces per single element. The flexible mould is fully reusable and the benefits of applying self-compacting concrete are utilised. The flexible mould process work as follows: Thin concrete panels are cast in a horizontally positioned flexible mould, using a self-levelling concrete. After a certain initial hardening, the mould is deformed and the concrete is allowed to harden further. The knowledge about rheological characteristics is essential during casting and to find the suitable moment for the mould to be deformed. The behaviour of the concrete in the plastic stage is important: A) to allow the concrete to follow the deformation of the flexible mould, B) to counteract its movement under a slope and C) to prevent cracking in an early phase. After the flexible mould has reached its final position, the concrete develops its strength and can be demoulded in a short production-cycle; aesthetically attractive elements of different and complex geometries can be produced with the same reusable mould.

Key-words: precast concrete, flexible mould, double-curved, complex geometry, SCC, rheology

Introduction

This paper discusses a very recent innovative technology that is in the focus of architects, inspiring and enabling them to realize new and complex shapes: the *flexible mould system*. Although architecture with curved geometry, found for example in domes, vaults and shell structures, has been appreciated throughout the centuries because of their inspiring and appealing shapes and structural benefits, in the last decades of the previous century they have become more and more rare. It seems that double-curved structures in concrete, as for example seen in the famous shells built by Torroja, Isler and Nervi, slowly became economically unfeasible (ref. 1), partly as a result of the increased labour and formwork costs, related to the complex shape, and partly because of the upcoming trend to precast concrete structures. Interestingly enough, three parallel developments have recently refreshed the interest for complex and double-curved geometry again: 1) recent CAD paradigms offer powerful modelling tools for parametric and complex-shaped 3D-modelling, 2) rapidly improving computational power of engineering tools enable the structural analysis of such structures, 3) these technological boosts enable and inspire architects and structural designers to apply these shapes in real buildings and structures, to realize shapes that are beautiful and functional at the same time (ref. 2). One problem, however, is not solved for buildings and structures in concrete: how to reduce the formwork costs, that have remained extremely high as a result of the complex shapes with limited repetition?

Concrete has always been a material that was very suitable for this type of architecture, but in the last decade it has even become 'cool' again. Two recent examples of (formwork for) buildings and bridges in concrete can be found in Figure 1. The shown structures use the state of the art regarding present formwork technology: Timber, steel, or

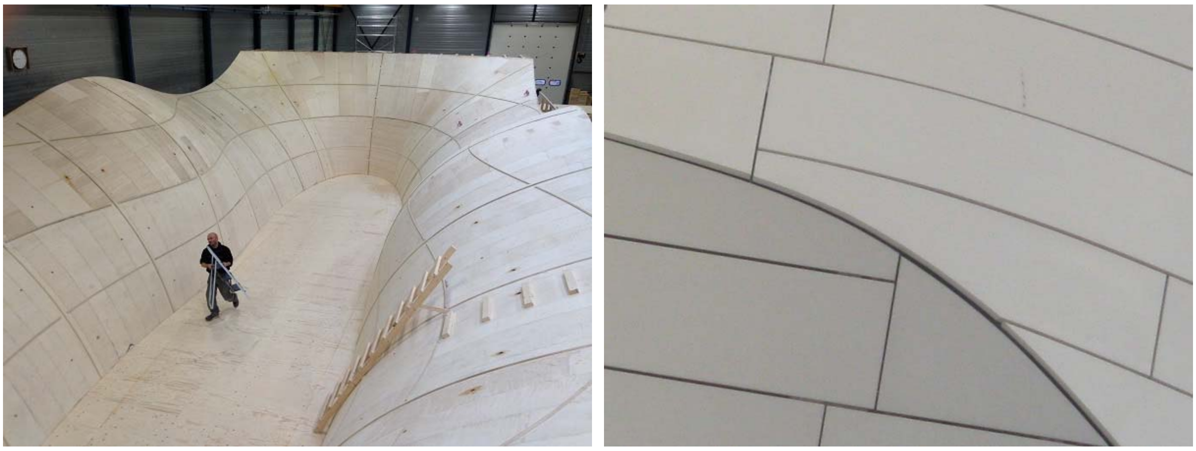

Figure 1 — Left: an example of timber formwork for double-curved bridge parts for the Verlengde Waalbrug Nijmegen, The Netherlands (Architectenbureau Zwarts & Jansma, formwork by Verhoeven Timmerfabriek), Right: concrete cladding detail of Louis Vuitton Fondation pour la Création, Paris (Frank Gehry Architects)

plastics to construct the formwork are applied, in many cases CNC-milled. For many free-form structures, the available budget is above average: it is accepted that for the more complex and appealing shape, a certain price needs to be paid. Free-form design simply results in complex shapes with very limited repetitive elements, as can be easily observed analysing Figure 1. Although modern technology such as CNC-milling and perhaps in the near future also 3D-printing may offer accurate solutions with limited labour costs, these technologies are relatively slow for large projects, are material- and time-consuming and thus expensive as well. The potential market is growing: free-form architecture is without doubt upcoming. Present formwork technology however, unfortunately, is not yet equipped for this large variation in forms. In this paper an innovative new formwork method will be presented: the *flexible mould*. It was developed from idea to feasible and operating method during the PhD research of the first author at Delft University of Technology, supported by both practical and theoretical work of the other authors.

The Innovative Flexible Mould Principle

The idea to reduce formwork costs is both simple and innovative: reuse the formwork many times by modifying the shape of the formwork after each casting. A mechanism that supports such a formwork can be controlled manually or CNC-steered, in order to produce elements with a wide range of curvatures. The mould edges can also be arranged to variable positions on the mould surface. The concrete is cast, though, when the mould is still in a *horizontally levelled* position. After casting, the concrete first is given rest some time for initial binding and stiffening, in order to counteract the flow of concrete out of the mould. The principle is explained in Figure 2 on the next page. Although in other industries, such as for example automotive and aerospace, the idea of a reconfigurable mould has already been adopted and realized in practice, mainly for rapid-prototyping applications (ref. 3), until now it was not applied in full-scale projects in the building industry, at least not to the authors' knowledge. Different research groups around the world are currently investigating the possibility to realize such a formwork system (refs. 4-7), which illustrates the research need for this technology and that the necessity for this development is felt and shared widely. Each research group, though, is choosing a different approach, some focussing on a high-tech CNC-controlled mould surface (refs. 4, 5), others try to apply other materials than only concrete (refs. 5, 6), and again others using a mix of foam-milling technology and vacuum techniques (ref. 7). In the next sections the authors of the present article will discuss their work on 1) a simple but robust and reliable technology that can be readily applied in a 'rough' mass-production concrete factory environment , 2) the concrete rheology and technology necessary for controlling the process and 3) the possibilities to reinforce panels that are deformed after casting.

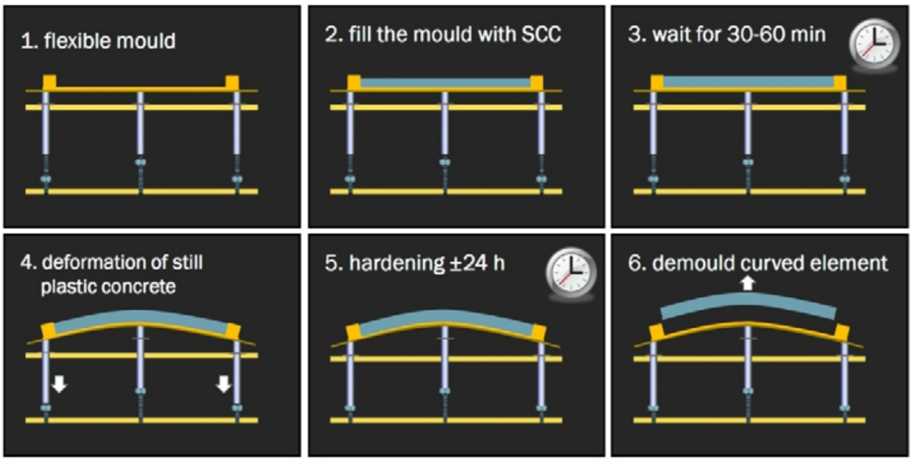

Figure 2 — The flexible mould process explained: Flexible materials are used for the mould, that is supported by a subsystem controlling the desired final shape (step 1). The mould is filled with self-compacting concrete (SCC) (step 2); fibres or textiles can be used as reinforcement. During a short period of structural build-up, the yield strength of concrete increases (step 3). Then the mould is carefully deformed into its final shape (step 4). Concrete hardens in the deformed mould (step 5) and finally the curved element is demoulded (step 6).

Formwork Mechanism

Deforming a flat surface into a double-curved surface is fundamentally impossible, unless large strains in the plane of the mould are allowed through the use of a very elastic mould and support layer (refs. 8-10). The use of such an elastic layer, however, inherently results in the contradiction that the discrete grid of vertically adjustable actuators, becomes visible in the resulting produced concrete panel. So on the one hand flexibility is required, on the other hand the mould has to be sufficiently stiff. In reference 9 and 10, the authors Janssen and Schipper did describe various experiments with both plates and strips as supporting layer, concluding that a mould system of perpendicular strips in combination with a flexible silicone foam and mould would be suitable for thin concrete panels. Still, various parameters remained difficult to control, among which the abovementioned contradiction of flexibility and stiffness. In recent research, Eigenraam (ref. 10) improved the concept mould system with a number of findings that allowed more flexibility, but yet offer a better control and accuracy.

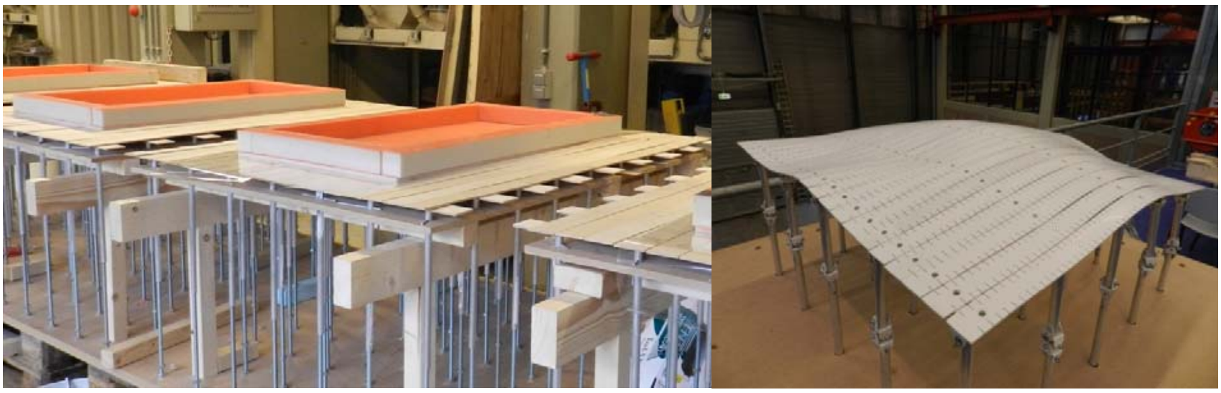

Figure 3 — left: Original test setup; right: improved prototype developed by Eigenraam

Figure 3 (left half) shows a prototype (600x600 mm^2) of this formwork surface, that offers a large degree of freedom in curvature. A patent is currently pending that describes the findings that made this control and accuracy possible. Deformation of the surface causes displacements in three-dimensional space. Not taking these displacements into account would result in deviation from the intended shape. The height of the support can be compensated for these effects. In-plane shear deformation of the mould surface plays an essential role in deforming a surface by which the Gaussian curvature changes (ref. 21). Therefore the prototype

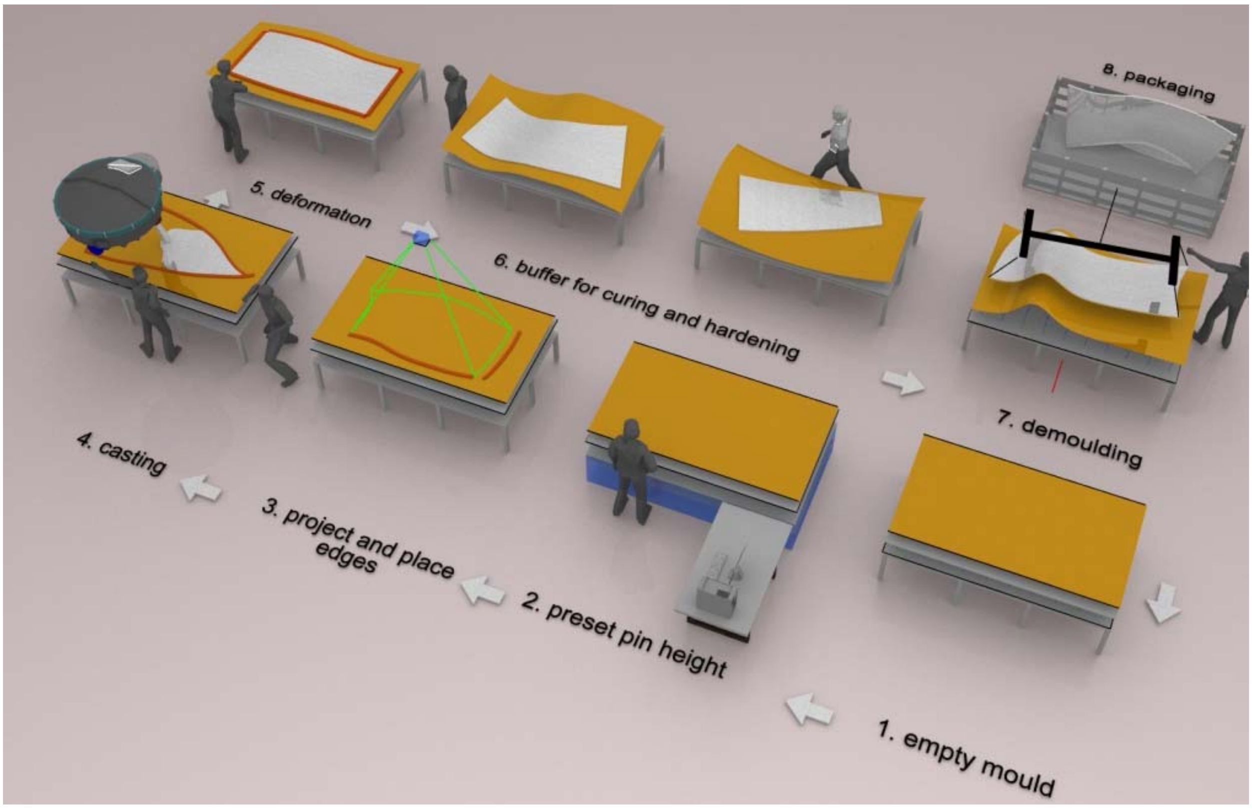

Figure 4 — A conceptual production-line (patent pending) for double-curved precast concrete panels: (1) each empty flexible mould is cleaned and oiled (2) controlled digitally, the pins supporting the flexible formwork are set to the proper height for each panel (3) the mould edges are fixed (4) the panel is cast (5) the panel is deformed into the shape prepared in step 2 and 3 (6) each panel needs hardening time (7) after which the panels are demoulded and (8) packaged (patent pending)

in Figure 3 has implemented several findings to facilitate the required shear deformation and thereby creates a flexible and more accurate mould surface. Although others researchers (refs. 5-7) as said have also developed formwork systems with similar capabilities, the system shown in Figure 3 (left), to the belief of the authors, is simpler, more affordable in a production line for large quantities of panels and more robust in the environment of a concrete plant (see Figure 4). Although the basics are relatively simple, the system could as well be combined with a high-tech CNC apparatus for height control, the Pinbed Wizard, recently completed as a working prototype by Vollers (ref. 11). In Figure 4 this is illustrated in the station at step 2, where the automated pin height preset is executed by a CNC-device. The advantage of the combination of the high-tech Pinbed Wizard with a number of low-tech flexible moulds is the increased production capacity: each panel will typically need a hardening period of 12 to 24 hours, depending on the cycle-time of the factory and the concrete mixture design. Since for the realization of any building of serious scale generally hundreds or thousands (!) of panels need to be produced, it will be necessary to use like 5 to 10 separate moulds for the production time to remain within a reasonable limit.

From Self-Compacting Fluid to Plastic Solid

In this section the criteria for the concrete mixture characteristics and the control during deformation will be discussed. The initial fluidity of concrete initially facilitates its transportation to the mould and its casting into the finally desired shape. During the succeeding process of stabilisation and hardening, the fluid gradually transforms into a solid in a number of minutes, hours or days. The speed at which this transformation process develops can be controlled by many factors: cement dosage and type, temperature, aggregate types and sieve distribution, additives such as plasticizers or retarders.

During the 'dormant period', that is in the first one or two hours after adding water to the cement, the hardening process has yet started, at least not significantly (ref. 12). Roussel (ref. 13) initially also considered it reasonable that there exists a period for a "couple of thousands seconds" in which irreversible effects of hydration are not yet dominating, a period in which colloidal or thixotropic behaviour is dominant. However, in a recent publication on the thixotropic behaviour of cement pastes (ref. 14), Roussel *et al.* showed that in thixotropic mixtures early hydration (CSH-nucleation) starting directly after mixing certainly *is* responsible for a far larger part of the thixotropic behaviour than colloidal effects. These CSH-bridges can still be broken relatively easy, and will rebuild at rest as long as sufficient reactive material is available, which explains the thixotropic behaviour that is observed at macro scale. Exactly this material behaviour is utilized during the deformation of the flexible mould.

The flexible mould method is characterized by the deformation of the mould at a specified moment (see Figure 2). Deformation will take place early in the transition stage from fluid to solid phase, since otherwise cracking might occur, a non-desirable effect. Janssen (ref. 9) depicted this transition in

Figure 5:

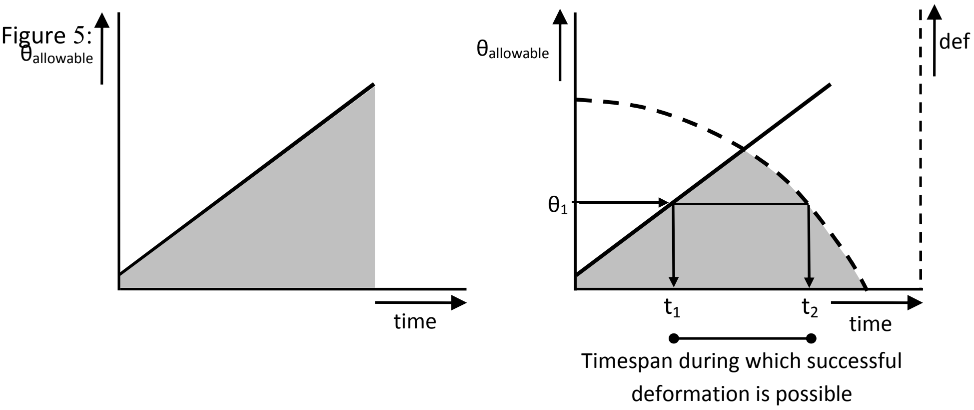

Figure 5 — First model by Janssen (ref. 9)

The thixotropic strength is assumed to develop linearly in the first hours, as illustrated in the left graph in

Figure 5, and in agreement with (ref. 14). The manufacturing process with the flexible mould method can, from a mechanical point of view, be seen as an imposed deformation. As a result of the deformation, parts of the concrete are bent and others rotated compared to their initially horizontal position. The displacements are in the same order as or even larger than the thickness of the concrete layer, and rotations may get as high as 45º to the horizontal direction. In order for the concrete not to flow out of the mould, a minimum shear yield strength is necessary to allow a specific angle θ of the mould surface. In

Figure 5 this is depicted on the left vertical axis with $\theta_{allowable}$. The graph illustrates that, for an angle θ_1, the mould cannot be deformed earlier than t_l. This t_l is considered as the *lower boundary* for the moment of deformation. Deformation is possible as a result of the limited strength of the CSH-bonds. However, these bonds will, at a certain moment, have grown so strong that plastic deformation of the concrete is no longer possible. This is depicted by the curved dash-line in the right graph and the moment t_2 in

Figure 5. The right axis expresses the 'deformability' of the concrete, which reduces gradually during hardening. Waiting too long with the deformation, would cause cracking of the concrete. This is defined as the *upper boundary*. The time between lower and upper boundary is the time available for deformation period. In order to understand and control this transition from fluid to solid and determine the upper and lower boundary t_1 and t_2, a series of deformation tests were carried out.

Deformation Tests

In order to simultaneously vary parameters, a set of four identical moulds was prepared (see Figure 3, right). Four elements were cast simultaneously with concrete from the same batch and deformed consequently at different moments in time and/or with different curvatures. The time required to fill four moulds after mixing was about 20 minutes, followed by a resting period until deformation of 10-40 minutes (moment of deformation 30-60 min after casting). After initial testing, good results concerning workability during casting, obtained yield strength and plastic behaviour at the moment of deformation were obtained with the following two mixtures (see Table 1).

Table 1 — two mixtures were tested with the flexible mould: a course and fine mixture

ingredients [kg / m^3]	**mixture 1 (coarse)**	**mixture 2 (fine)**
Cement CEM I 52,5 R	400	570
Fly ash	160	100
Betoflow D, Omya	-	100
Superplasticizer Premia 196, Chryso	3.92	4.56
Water	172	225
Sand 0.125 - 1 mm	-	1294
Sand 0.125 - 4 mm	1046	-
Gravel 4 – 8 mm	563	-
Characteristics in the hardened state	**[MPa]**	**[MPa]**
Compressive strength (cube; 1/7/28 days)	45.2/64.8/79.7	48.4/58.3/90.4
Splitting tensile strength (cube; 1/7/28 days)	3.5/4.0/5.5	3.5/4.0/5.2
Flexural strength (prism; 1/7/28 days)	6.0/9.5/10.5	7.1/7.3/10.6
	(batch #15)	(batch #18)
Slump (flow) development at t =	0:03/0:29/0:43/1:03 h:min	0:06/0:24/0:42/1:05 h:min
Slump flow / slump	715/190/160/20 mm	865/650/620/50 mm

Cubes (150·150·150 mm^3) and prisms were tested (40·40·160 mm^3) to determine the strength. More than 50 elements (d=25 or 50 mm) were cast with single or double curvatures (double-curved in two directions, i.e. a dome shape). The radii were in the range of 1.5-2.5 m. The concrete elements had a rectangular projection area of 400·800 mm^2. Many elements were successfully cast, deformed and demoulded. In some cases the mould was deformed too early (with concrete still being too fluid). Several tests (slump flow, flow time T50 and/or slump) were carried out to determine the workability at different moments after mixing. In order to determine the right moment of deformation in relation to the workability of the mixture, slump tests were executed on the same batch at different moments.

In various articles, the relation between slump flow and yield strength is described. Roussel & Coussot (ref. 15) compared experimental results obtained with slump cones and viscometers on the one hand and numerical simulations and analytical models on the other hand. Under specified circumstances the following relation between yield stress τ_0 and slump flow spread R for slump cones with volume V proved reliable for self-compacting mixtures:

$$\tau_0 = \frac{225 \cdot \rho \cdot g \cdot V^2}{128 \cdot \pi \cdot R^5} \quad (1)$$

Similar empirical formulas can be found for stiffer concretes, now for relations between slump S and yield stress τ_0 , although a larger divergence is found between both linear formulas, depending, among others, on the aggregate volume and the viscometers used for calibration (refs. 16, 17):

$$\tau_0 = \frac{\rho}{0.176}(0.255 - S) \quad (2)$$

$$\tau_0 = \frac{\rho}{0.347}(0.300 - S) + 212 \quad (3)$$

The elements produced with batches 1 to- 18 in the research all had a length of L=0.80 m, a height h $\leq$ 0.05 m and a radius of R $\geq$ 1.50 m. In an earlier publication (ref. 18) it was concluded for this geometry that the critical yield strength, necessary for the concrete in order to stay in the mould, was in the range of 94 Pa $\leq \tau_0 \leq$ 314 Pa. It is interesting to see now from the test results the time the mixtures needed to reach this yield strength, in order to determine the lower boundary t_1 defined earlier. The yield strengths were calculated with the slump test results for the Batches 14 to 17, that were all prepared with the same mixture m_1, the same amount of superplasticizer (0.70%) and the same mixing order, resulting in a rather consistent behaviour. Figure 6 shows the calculated yield stresses for these four batches in the first hour, using the empirical relations discussed above. Mixtures of all batches 14-17 were self-compacting and self-levelling, starting off at a very low yield strength $\tau_0 < 3$ Pa if calculated from the slump spread according to Equation 1.

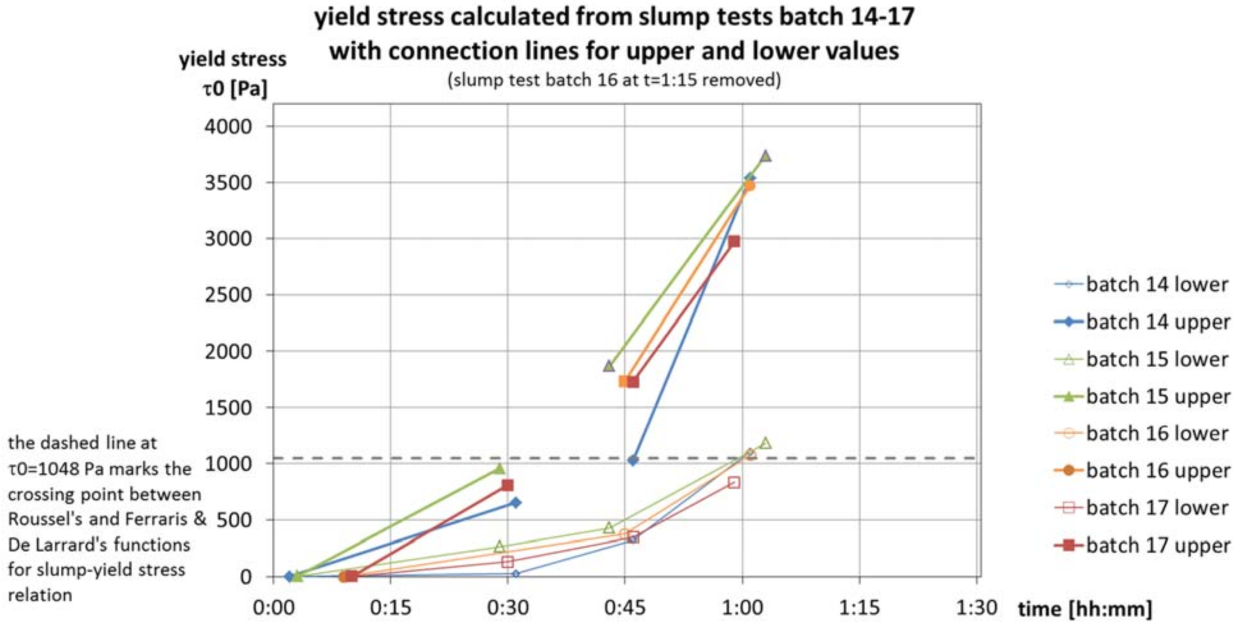

Figure 6 — Development of the yield strength in the first 1,5 hours - the low and high values represent different models found in literature according to Equations (2) and (3)

From Figure 6 it can be seen that in the first hour already a clear increase in yield strength can was measured, independent of the empirical formula that is used. It can be concluded that the necessary yield strength in the range of 94 Pa $\leq \tau_0 \leq$ 314 Pa is reached within roughly the first half hour after mixing, if the average of the lines is taken as an estimation of the yield stress. This is in agreement with the deformation test results: the concrete did not flow out of the mould. It can also be concluded that this mixture shows a clear change of workability in the first hour from self-compacting to a practically no-slump state, which was in agreement with what was experienced during the laboratory work. For this mixture it can therefore be safely concluded that the lower boundary for the moment of deformation is t_1 = 0:30 h:mm.

Although the above formulas and workability tests with slump flow spread *R* and slump *S* give a rough idea of the development of the yield strength over time, they have the disadvantage of being only empirically linked to the strength in S.I. units, and, as can be seen from Figure 6, the formulas are rather diverging. The slump tests can also be slightly inaccurate due to the human factor and instability of the concrete after lifting the cone. For these reasons, it was decided to also perform tests with the BML-Viscometer and to measure the mini-slump as a secondary test. The results of these measurements are reported in (ref. 18) and are out of the scope of this paper.

The upper boundary was defined earlier as the moment that the concrete becomes too stiff to deform, resulting in cracks. In a number of tests, this was indeed observed. With Batch 5, for example, Element 5.3 was deformed at t=1:00 h:mm. Figure 7 at the next page shows the resulting cracks, with an order of magnitude of 0.05-0.2 mm in width and at interval distances of 30 to 40 mm. The visual appearance of the cracks was comparable to the cracks sometimes caused by plastic shrinkage. This can be explained from the forced strain that is brought in the panels due to deformation, which has a comparable effect as shrinkage at

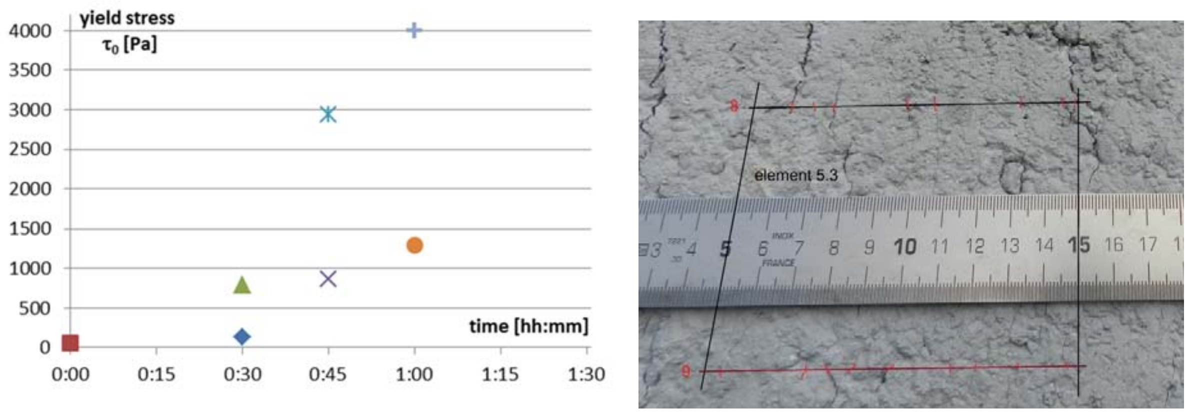

Figure 7 — Result of Element 5.3, deformed too late, at 1:00 h:mm. Left: the yield strength has increased quickly. Right: cracks are visible, comparable to the cracks generally caused by plastic shrinkage

the surface. In our situation, the concrete is stretched as a result of change in curvature; with plastic shrinkage the concrete shortens with constant length close to the surface. Although the graph in Figure 7 shows a yield strength of 1290 resp. 4000 Pa, the real value was probably larger, since the mixture after 1:00 h was so stiff that the slump value had reduced to 0 (no slump at all). The empirical formulas then obviously no longer relate slump to yield strength.

The 12 curved elements from Batches 14-17 though, were successfully deformed without cracks. The moment of deformation was between 0:32 h:mm and 1:17 h:mm. Detailed images of the resulting elements can be found on the project website (ref. 19). It is concluded that the upper boundary for the moment of deformation $t_2 \approx$ 1:00 h:mm for the mixture applied in Batches 14-17. For other mixture compositions, the lower and upper boundary would have to be determined experimentally as well. Figure 8 shows some examples of successfully cast elements:

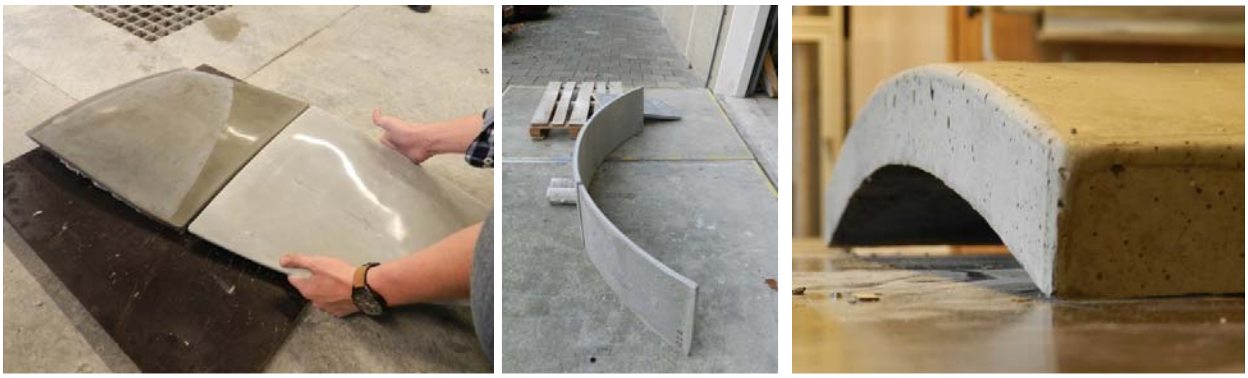

Figure 8 — Configurations of successfully deformed double-curved (left) and single-curved (middle) panels to be used as cladding elements (thickness 25 mm), and a single-curved element (right, h=50 mm)

Textile Reinforcement

Finally, experiments were also carried out with flexible reinforcement in the form an alkali-resistant glass fibre textile during the Master's thesis research of Kok (ref. 20). For this purpose, uncoated glass fibre yarns were used, with cross sectional areas of 0.916 mm^2 per yarn that were stitched on a mesh of 8.3 mm ×8.3 mm. The yarns had a tensile strength of 1700 MPa. The fine-grained concrete mixture m_2 was applied, the textiles were added using a wet-in-wet 'lasagna' manual layup method. Three types of tests were carried out:

1) In deformation tests, it was observed that layers of textile would accurately follow the deformation of the panels after casting. Since small deviations between the intended and realized position were measured, the effect on the strength was ±20% of the optimal situation, depending on the loading of the specimen.
2) Tensile tests showed the effect on the strength using different percentages of fibres. It was found that through internal slip between the filaments within the yarns, only 20 to 25% of the 1700 MPa could be effectively be utilized, but that this percentage was independent of the fibre percentage.

Figure 9 — Left: Production of the textile-reinforced elements according to the manual lay-up 'lasagna' method; right: 4-point bending test on 50 mm thick textile-reinforced concrete element.

3) Four-point bending showed similar results as the tensile tests: after a long strain hardening trajectory in which the full cracking pattern was completed, generally one crack opened further until failure (as can be seen in Figure 9). As a result of the different way of loading the textiles, the effectiveness of the fibres was higher than what was found in the uni-axial tensile tests, circa 35%. Apart from tests, also numerical models in Ansys and Maple were developed to estimate the effectiveness on stress distributing over the panels. The use of textiles as reinforcement proved to be a practical way to locally or generally increase the tensile and bending strengths of the panels, thus allowing for applications where brittle behaviour needs to be prevented.

Conclusions

Surveying the results of the various parts of the research on the flexible mould method, the following conclusions can be drawn:

- The innovative method offers a rational and accurate alternative for expensive mould techniques such as CNC-milling; the fact that a single and open mould is used simplifies the process; the process can be embedded in a manufacturing line to scale it up to industrial size;
- By choosing and measuring the right rheological properties of the concrete, the process of deformation after casting can be controlled. A lower boundary needs to be observed for the right yield strength to prevent concrete from flowing, the upper boundary guarantees sufficient plastic behaviour to allow deformation without cracking;
- The accuracy of the flexible subsystem is important and needs considerable attention. The system developed by Eigenraam showed good results and is filed for being patented;
- The use of textiles as studied by Kok offers a valuable addition to the ductile behaviour of the elements. This behaviour can be correctly predicted and was tested for various amounts of textiles.

As a finalizing remark, it must be said that, surprisingly, the first attention from industry is coming from the upcoming economy India, a country where shell structures are still built regularly. In countries such as India, China etc. where the building industry has a great market today, engineers are faced with problems with respect to quality control, precision and speed of execution. There are numerous projects which involve the requirement of double-curved facades and shell roof structures. Precast concrete is most often ignored as a façade option for complex geometries, only because architects are not confident of the quality which they anticipate, and they resort to alternative claddings materials. The flexible mould system would offer great benefits in obtaining high quality facades, roofs and precast shuttering for buildings and infrastructure with complex geometry. The process, being relative low-tech, could be transferred easily even across various regions of these countries where generally very high tech systems are not considered as viable solutions.

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