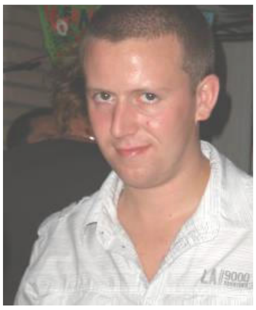
MANUFACTURING DOUBLE-CURVED ELEMENTS IN PRECAST CONCRETE USING A FLEXIBLE MOULD - FIRST EXPERIMENTAL RESULTS



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Abstract

The manufacturing of double-curved precast concrete elements is still expensive, due to the high costs and limited possibilities for repetitive use of the moulds or formwork. The goal of the research described in this paper is to develop a production method that overcomes these difficulties by enabling the mould to be reused many times and by making the shape of the mould adjustable in a flexible way.

First the paper gives an introduction of free-form architecture and the issues related to realizing complex geometry in concrete. Sequentially, the paper reports on the structural mechanics models that have been developed to accurately describe the behaviour of a flexible mould material. Finally laboratory experiments are reported, that are based on the concept of deforming an initially flat concrete element into a curved shape after a short initial hardening period. After this deformation process further hardening will take place in the final curved shape. The advantages of starting with an initial flat layer are that no contra-mould is needed, the element thickness can be controlled accurately and the casting process is relatively quick and simple.

Keywords: Precast, Shells, Panels, Formwork, Free-form, Curved

1 Curved elements in architecture

1.1 Free-form architecture

Fig. 1 Residential building "Het Funen" Amsterdam (architect: NLArchitects) with curved cast in site roof

Curvature adds possibilities to architecture that would not exist if only straight lines and flat surfaces make up the architect's toolbox. The use of curvature results in **richer and more expressive designs** [1, 2]. Some illustrations of the effect of curvature in buildings and structures are given in **Fig. 1** on the former and **Fig. 2** and 3 on this page. Although the use of curvature is not new, until now it has mainly stayed restricted to high profile projects or iconic architecture, and mostly to buildings with above average budgets. This is caused by the **higher costs of curved buildings** as a result of a.o. the extra effort needed for correct measuring in drawings and on the building site, the need for unconventional construction methods on the building site, or, in case of pre-manufacturing, the extra costs of manufacturing complex shapes in the factory.

The upcoming free-form or digital architecture, which expresses a lot of curved forms, is still received with some hesitation and reservation. The realized free-form buildings will have to convince people yet of their longer lasting value [3]. However, the social appreciation of free-form architecture is growing. Submissions for international design contests and conferences show an increasing use of and interest in **complex geometry**. The new generation of architects that completed there study have already learned how to use the **software** that allows these complex shapes to be dealt with in the design stage. Driven by the developments in the design possibilities and the assumption that **technology will follow architecture**, more experience will be gained in realizing curved shapes in buildings.

This research fits in this development. Author Bas Janssen worked on an Msc-thesis research on the topic of precast double-curved concrete elements. The work done for the MSc-thesis contributes to the PhD research of Roel Schipper,

1.2 Potential application of precast free-form elements

Concrete, due to its initially fluid nature, is a **suitable material** for building free-form architecture. Modern concrete mixtures guarantee the architect high performance in terms of durability, smooth finishing, texture, colour, slenderness and strength, which characteristics are important for architects. Recent workshops with architecture students all around the world show interesting applications of the relatively new materials UHPC and SCC, but also of the effect of coloured or unusual aggregates. The aspect **freedom of shape** is especially important in architecture that makes use of the shape language of curvature mentioned earlier, a shape language that is digitally enabled by the CAD programmes in use by architects.

Fig. 1 Jubilee Church, Rome (architect: Richard Meier), double-curved elements in precast concrete

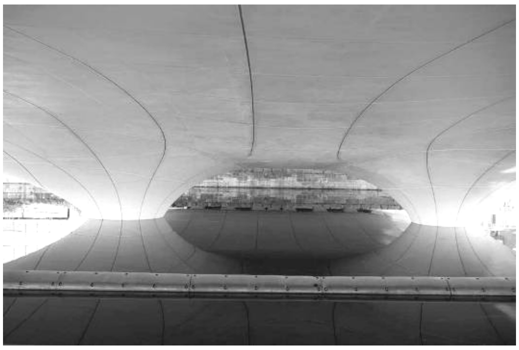


Fig. 2 Spencer Dock Bridge, Dublin (architect: Future Systems), cast in site concrete using double-curved formwork

The TU Delft research concentrates on manufacturing methods for curved **cladding** panels in precast concrete, curved **structural façade** elements and curved **plank floors**, so that both the external envelope of a building and its possible load bearing structure are addressed.

1.3 Complex geometry

A large number of primitives are available in CAD software to draw curved lines and surfaces in 2D and 3D space. Apart from mathematically relatively simple primitives, such as circles or ellipses in 2D and cones, spheres or tori in 3D, also **complex primitives** are commonly used nowadays: **splines** and **NURBS** are curved lines that are all defined by higher order interpolations between control points in a plane or in 3D space. Especially higher-order **NURBS-surfaces** allow the drawing of almost any curved surface or volume in 3D space [4]. It is especially this type of surfaces that is used more and more as a result of the advances in CAD software and the interest of architects in application of this type of freely formable shapes. **Fig. 4** gives an example of such **complex geometry**[1].

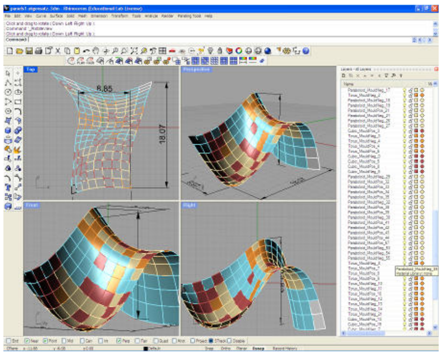


Fig. 3 Example of a NURBS-surface of a virtual building drawn in Rhinoceros®

1.4 Repetition and optimization issues

Different new technologies are necessary to **construct** these shapes in the factory or on the building site. A translation from '**file to factory**' not only requires knowledge of complex geometry and the underlying maths, but also creates the need for **novel manufacturing processes** that are able to transform these CAD models into 1:1 scale building elements. It is in the first step that the aid of mathematicians and computer scientists is necessary. Usually the free-form surfaces are first **translated** into **discrete panels or elements** of a size that can be manufactured and transported. After this **optimization** algorithms will assist in rationalizing the innumerable amount of different elements, each with its own complex shape. The **rationalization** leads to sets of similar or related elements and reduce shape complexity as far as possible within the boundaries of the architectural border conditions. E.g. slightly curved cladding panels can be replaced by real flat panels if the difference is not visible for the eye. Such optimization processes lead to a reduction of total building costs [5]. In the end, thus a CAD file containing a set of panels of reduced geometrical complexity is delivered, that, as next step, has to be manufactured.

2 Techniques for manufacturing curved elements

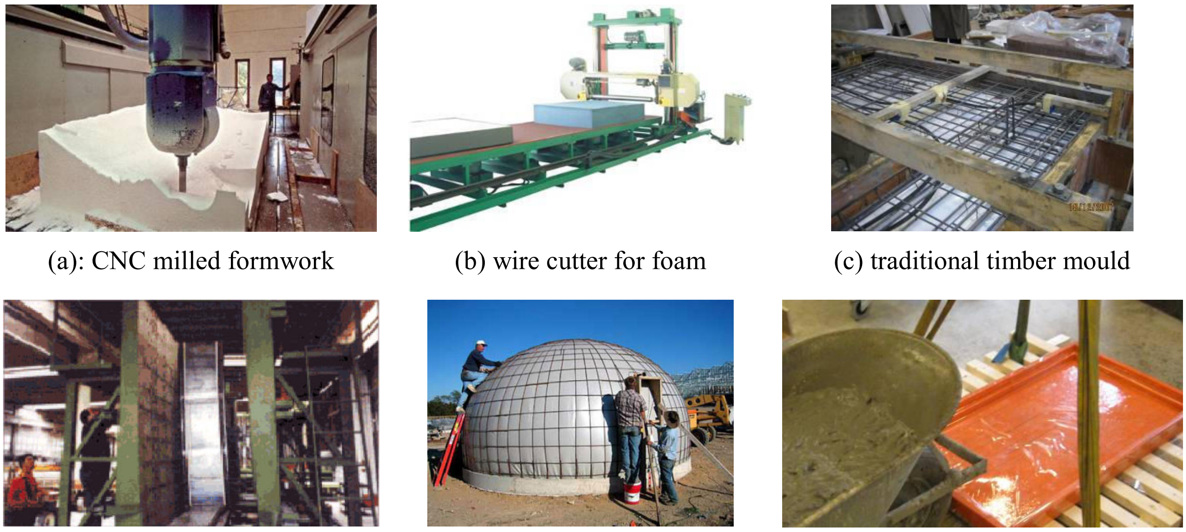
2.1 Existing techniques

For the production of curved elements, a number of techniques are available:

- **CNC foam milling**: from a block of foam, mostly expanded or extruded polystyrene (EPS/XPS), a shape is milled by a CNC controlled cutter. Usually the foam afterwards is covered with a harder polymer, such as polyurea or an other synthetic resin. This top layer is polished after hardening. The thus resulting shape can be used as contra-mould. The mould can be reused several times, but the cost will be relatively high in situations were lots of unique elements have to be manufactured. In situations of no repetition actually the building itself is milled scale 1:1.

[1] kindly made available by Evolute®, a software firm in Austria specialized in optimization processes for complex architectural geometry

- **Wire cutting**: from a block of foam, a shape is cut by a hot wire, optionally CNC controlled. After this, a mould can be made in the same manner as described above. The wire cutting method offers less freedom of form than milling, although it is geometrically possible to cut so called 'ruled surfaces' (curved surfaces described by a rotating and translating line). No examples of double-curved moulds made with this method have been found by the authors.



(a): CNC milled formwork (b) wire cutter for foam (c) traditional timber mould

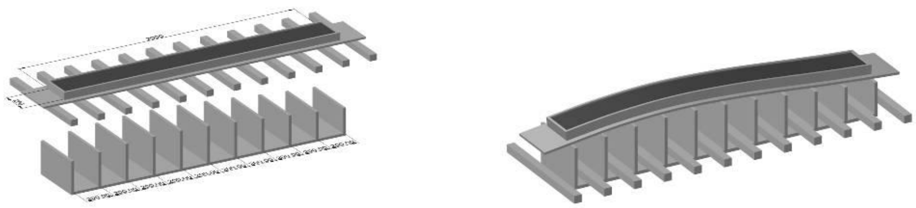
(d) steel mould (e) inflatable mould (f) rubber mould

Fig. 4 Existing techniques for manufacturing curved elements

- **Timber or fibreboard moulds**: in situations were some repetition is found, moulds can be made in timber (plywood) or fibreboard. For the production of curved surfaces, CNC milling and cutting of timber and board is possible, although this makes the moulds more expensive, and an additional finishing layer sometimes is necessary to obtain a smooth surface. By bending of board, single curved surfaces can be built relatively easy. Many precast projects nowadays make use of timber moulds, especially for those moulds that are not economically feasible with steel due to low repetition or due to complex shape.
- **Steel mould**: a steel mould can be deployed economically if sufficient repetition is found in a project. Many precast projects use steel moulds for the highly repetitive elements, often in combination with configurable edges or inserts for customized modifications per element.
- **Vacuum, textile or air pressure forming**: it is possible to use inflated or vacuumized foils or textiles as formwork for concrete [6, 7]. Whether these techniques are suitable for a specific project depends on the desired geometry. For vacuumized foils the danger of damaging the airtight skin is an important issue, especially in situations were steel rebar is in use. For textiles, the costs of cutting and sewing the textile and the control of the shape under the weight of the concrete limit somewhat the geometrical possibilities. Until now, application has mainly stayed restricted to academic environments.
- **Rubber mould**: concrete is cast in a flexible rubber formwork, which can be deformed in advance or afterwards. A counter-mould or lid is needed to prevent the concrete from flowing out of the mould, and an exemplar control shape is needed to guide the rubber formwork into its final shape. This method is a.o. used for the prefabrication of thin cladding panels.

2.2 The concept of a flexible mould

Mass-customized production of double-curved concrete elements has often been often regarded only possible after the realisation of a flexible mould: an adjustable formwork consisting of an elastic material that can be formed into the desired curved surface by the use of pistons, actuators, gravity, pin beds or other means. On this formwork the concrete is cast, either before or after deformation of the formwork, so that after the concrete has hardened, the curved element is ready.



(a) first concrete is cast (b) then deformation takes place

Fig. 5 First simple test setup: a single-curved formwork, in which first the concrete is cast in situation (a), and after some tens of minutes the flexible formwork and the still unhardened concrete are deformed into the desired shape (b)

Depending on the slump value of the concrete, a contra-mould is necessary to prevent the concrete from running out of the mould. In all tests described in this paper, the concrete is **first cast**, than given some time to stiffen/harden, and **after that** the formwork is deformed into its final shape. No contra-mould is necessary. After deformation of the formwork the final hardening of the concrete takes place. **Fig. 5** shows an illustration of the principle of first casting and then deforming.

2.3 Earlier research on flexible moulds

Several concepts for a flexible mould have been designed over the years, starting with a sketch of Renzo Piano already in the 1960's (shown in the top of **Fig. 6**). Some others have further discussed the usefulness of the concept. Most researchers draw an **elastic material** as intermediate layer between actuators and concrete, so that the casting of concrete is possible with a smooth surface, whilst protecting the mechanism of vulnerable moving parts.

One of the first prototypes, built by Rietbergen, Schoofs and Huyghe [8] demonstrated that the proper choice of the **elasticity** of the **intermediate layer** is one of the **key factors** to success: using a too stiff material led to difficulties in adjusting the formwork into the desired curvature, using a too flexible material led to a “flubbering” surface which was not acceptable from an aesthetic point of view, see **Fig. 7** on the next page. A theoretical study of the **behaviour** of the **elastic material under forced displacement** in the specific situation of a flexible mould was not found in literature by the authors. It is, however, necessary to understand and predict what is happening in the intermediate formwork layer in terms of elasticity, to be able to successfully choose the right material specifications and adjustment method.

In the next section **three structural mechanics models** used by the authors are discussed, that describe the mechanical behaviour of a linear and of a rectangular material under forced deformation.

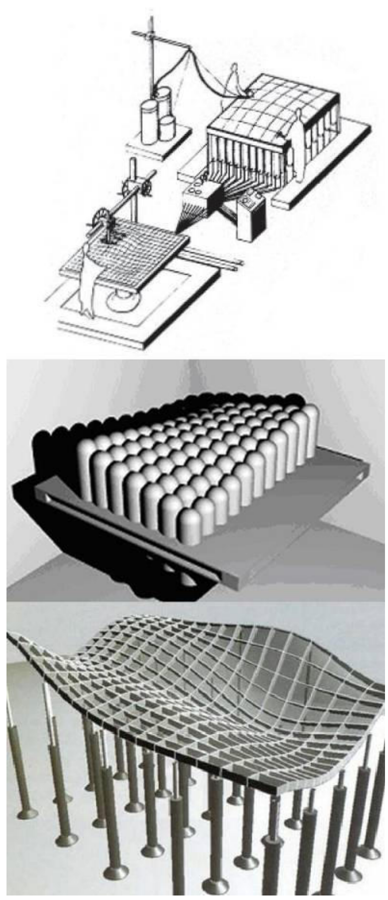


Fig. 6 Concepts for a flexible mould for concrete by Renzo Piano (top), Hansen (middle), Lars Spuybroek (bottom)

3 Structural mechanics modelling

3.1 Beam model – single-curved elements

In the first structural mechanics model a thin and flexible strip

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is bent along one axis in the desired shape, to serve as formwork for a single-curved element. The shape is defined by *i* support points that can be vertically adjusted with a displace- ment $w_i(x)$ according to the architectural model. The structural mechanics of a beam under bending are described by the fourth-order differential equation of Euler-Bernoulli. This equation relates the external load *q* (necessary in our situation to bend the formwork), the fourth derivative of the vertical displacements *w(x)* and the bending stiffness of the formwork *EI*.

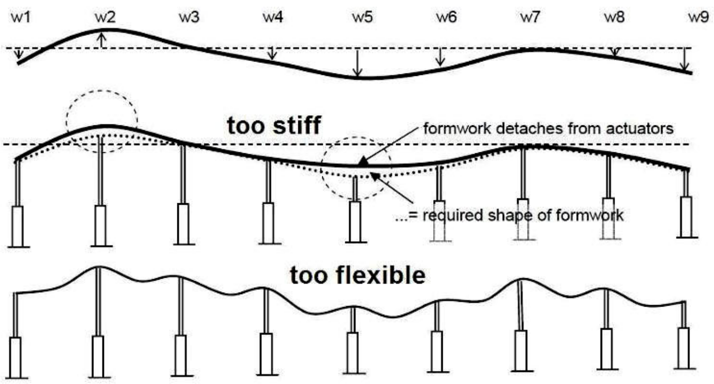

Fig. 7 Required bending stiffness of the mould depends on desired shape (here illustrated linearly; the same applies for a 3D surface as shown in Fig. 8 on the right)

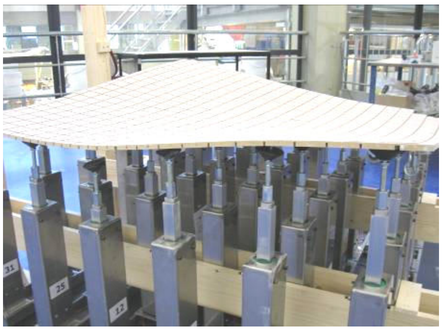

Fig. 8 Flexible mould prototype built by Rietbergen, Schoofs and Huyghe

Since in the test setup the formwork was supported at *i =11* points, the model is 9-foldly statically undetermined (see the model in **Fig. 9**). It is, however, possible to define enough equations to solve the system: the vertical displacements $w_i(x)$, the weight of the formwork and concrete *q* and the bending stiffness *EI* are all known, and enough connecting and border conditions are available between the parts, so the support reactions can be expressed as a function of all these input parameters. For the tests, the system was solved using Maple. In **Fig. 10** on the next page an example is shown of a specific shape and the resulting bending moments in the formwork and forces in the support points.

The Maple model enables to ‘play’ with the choice of *EI*:

- high EI: using a **stiffer formwork** leads to larger bending moments and larger reaction forces, which complicate the test setup;
- low EI: using a **less stiff formwork** leads to a shape in which the deflection between the support points as a result of the concrete weight q becomes visible in the final concrete element, which is undesirable from an architectural point of view (see lower image in **Fig. 7**).

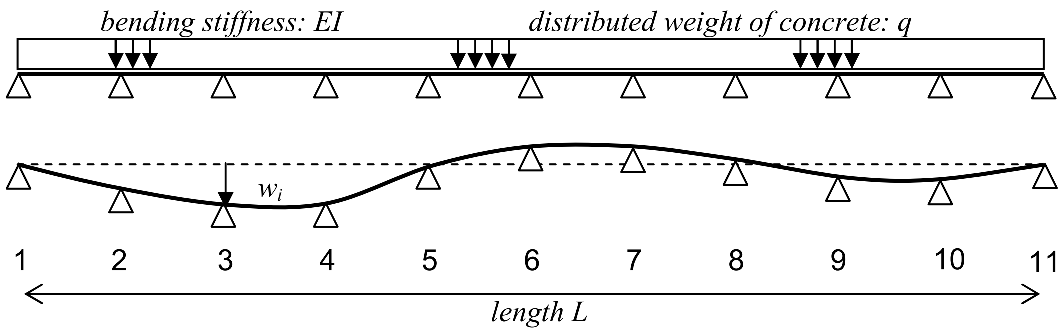

Fig. 9 Mechanics model of the formwork for a single-curved element: each control point *i* is seen as a support point of an elastic beam with length *L* bending stiffness *EI* with a forced displacement w_i. The weight of the concrete and the mould are equal to distributed load *q*

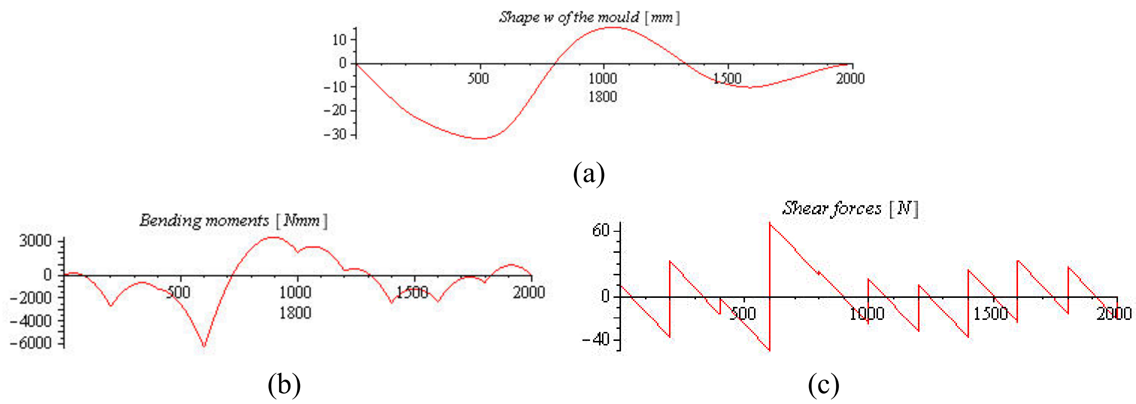

Fig. 10 Example of solution of forces using Maple: (a) desired shape is defined by filling in displacements of support points (b) bending moment and (c) necessary reaction forces in the support points

For the tests, the **local deflection** between every two support points (at a mutual distance of 200 mm) was **maximized** to 1 mm. This border condition lead to a lower limit for the bending stiffness *EI*. Respecting this condition, the bending stiffness was **minimized** as far as possible, so that no downward support forces (tension forces) were necessary to keep the deformed formwork in place. This lead to the beneficial situation that the formwork was more or less naturally sagging in the desired shape as a result of the weight of the concrete, an no extra forces on top of that were needed to pull the formwork into position[2]. This choice very much simplified the deformation process.

The first laboratory tests were performed using the model described above. Several formwork materials, thicknesses and concrete mixtures were used. The results of these tests are described in section 4.

3.2 Plate model – double-curved elements

Since the model discussed in the previous subsection can only describe single-curved shapes, a second structural mechanics model was used to describe **curvature in two directions**. For this purpose an existing finite difference model was used, described in [9]. This model, originally developed for the cold bending of glass panels, numerically models the behaviour of a thin plate under bending and subject to normal forces in plane and stretching of the plate due to extension. The model was in [9] implemented in an Excel worksheet, which was used for the research in this paper.

An important difference between singly and doubly curved shapes is that in the former normal forces do not necessarily occur, but that in the latter **in-plane normal forces** are inevitable. This is caused by the fact that the plane locally has to **stretch** to arrive at the desired shape. The model calculates these in-plane forces, as well as the perpendicular reaction forces necessary to deform the plate into its desired shape. The model was used for a number of purposes: 1) to find the right thickness and material for the formwork, 2) to determine and limit the reaction forces 3) to check whether the in-plane stresses were still on an acceptable level for the chosen material.

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[2] ***Note about normal forces in the formwork:*** *Since the developed length of a curved object is larger than the length of the flat original object, normal forces can develop in the curved formwork, resisting the deformation. It was for this reason that all support points were modelled (and built) as rolls, not hindering any horizontal movement of the formwork. Otherwise, the tension stiffness EA of the formwork would lead to axial forces in the formwork, a more complex differential equation, and large horizontal forces on the support points. This problematic effect was indeed found in tests by Schoofs and Huyge were the support points were hinges rather than rolls.*

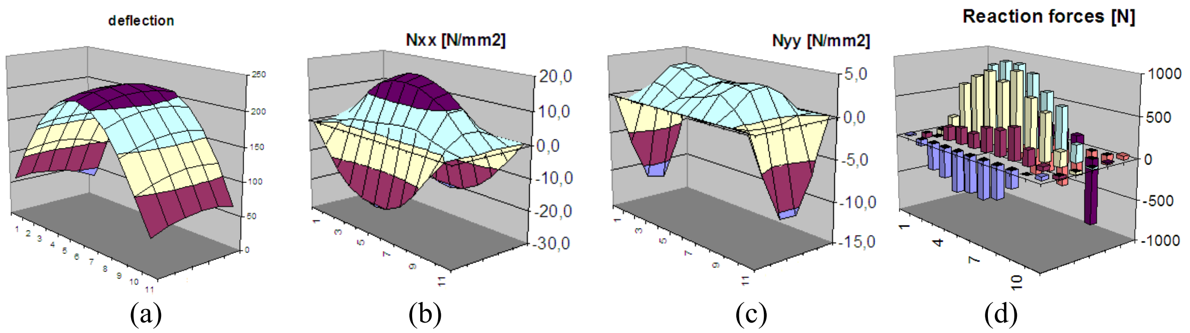

Fig. 11 Example of a double-curved shape (a), the resulting in-plane stresses in the formwork (b, c) and the reaction forces in the supports (d). The maximum forced deflection is 220 mm (mind: edges start on values > 0); for a timber formwork with a thickness of 4 mm this leads to the maximum compression stresses 21 N/mm^2 in the longitudinal direction (Nxx) and 12 N/mm^2 in the transversal direction (Nyy). Note that the maximum compressive stresses are in the edges of the panel. Calculated support reactions are not completely reliable due to inaccuracy of the numerical model, but the general image is positive reactions in the middle and negative reactions (tension) around the edges, which fits with the shape and was also found during the tests.

In section 4 the results of experiments with the double-curved plate formwork modelled in **Fig. 11** are described. The most important conclusion from the tests was that it was **not completely possible** to adjust the formwork in the shape modelled in Fig**. 11** as a result of **buckling effects** in the plate edges, that were probably the result of the calculated compressive stresses in the edges.

3.3 Strip model – double-curved elements

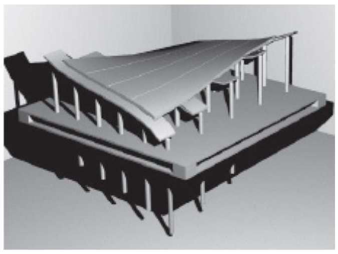

Fig. 12 Idea for a strip mould, sketched by Hansen (2004)

After evaluating the tests with the double-curved plate and the mechanics model, it was soon concluded that the buckling effects in the element edges form an obstacle inherent to the behaviour of a thin plate. This obstacle could in theory be overcome by using a system in which **in-plane stresses** are **diminished**. The solution was found in an idea earlier described by Hansen for the production of double-curved glass, and also mentioned by others in relation to the manufacturing of concrete elements. It is a **strip mould system**, consisting of flexible strips in two directions (see **Fig. 12**), were strips are bent in two principle directions: beam-like bending and torsion of the strip. Tensile or compressive stresses in the mould material as a result of the in-plane 'stretching effect' are avoided, because the strips can slightly slip over the supports, and among each other. After combining Hansen's idea with the structural mechanics model of section 3.1, it was possible to predict the support reactions and shape of the strip mould for a chosen mould material and thickness.

4 Laboratory experiments

4.1 Experiment setup

To check the validity of the structural mechanics models and find out the effects of deforming concrete after casting several tests were carried out. In the Stevin Lab facilities are available to mix most concrete recipes. In this stage of the research, we mainly used an adapted E2 mixture (f'_{ck} = 75 MPa) with the recipe as shown in **Tab. 1** on the next page. For mixing batches above 40 itres an Eirich force mixer was used. For small batches a simple freefall mixer was applied. For the mixture shown in **Tab. 1** it was determined that deformation is best performed after circa 45 minutes of initial binding.

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For the mould sub layer a variety of materials was applied: 3.8 mm plywood plate, 1 mm steel plate or 3.8 mm plywood strips with a 10 mm soft foam cover with silicone finishing layer to obtain water tightness. For the mould edges a flexible foam polyethylene SG 40 (extra firm) was used, with a silicone finishing layer.

For reinforcement a single mesh of thin rebar 4ø3 mm was used in the concrete elements of 200 mm width and 10ø3 in elements of 1 m width, just enough to de-mould and lift the elements without damage. In this stage no fibres were added; this will be done in future tests.

Tab. 1 Concrete mixture used in most tests: E2 adapted (fibres are left out), based on 45 litre batch

Cement type	Cem 1 52.5 R	26.865 kg
Filler	Fly ash	7.380 kg
Admixture	BASF Glenium 51	0.190 kg
Aggregates (dry)	Sand 0.125-0.25 mm	8.479 kg
	Sand 0.250-0.50 mm	11.305 kg
	Sand 0.5-1 mm	16.958 kg
	Sand 1-2 mm	14.131 kg
	Sand 2-4 mm	5.653 kg
Water		10.783 kg

4.2 Single-curved elements

In **Fig. 13** the test setup and resulting single-curved concrete element are shown. A simple timber lattice was used for initial support during casting and initial hardening in horizontal position. By lowering the lattice, the curvature was formed. The height of the curve after deformation was controlled by vertical stands of different height. The reinforcement in the element was bending along with the mould and the still plastic concrete. Using this setup, elements with a size 2.00x0.20x0.05 m3 have been manufactured, with a minimal radius of 2.5 m. After deformation no cracks appeared. In one test where a smaller radius was used (1.5 m), cracks appeared shortly after the deformation. In a repetition of this same test, the cracks did not appear. The structural mechanics model calculates the reaction forces, based on *EI* and *q* of the mould and concrete and the prescribed displacement. Although the reaction forces could not be measured in this simple setup, it could be observed that the mechanics model gave a good prediction of were positive and negative reaction forces occurred.

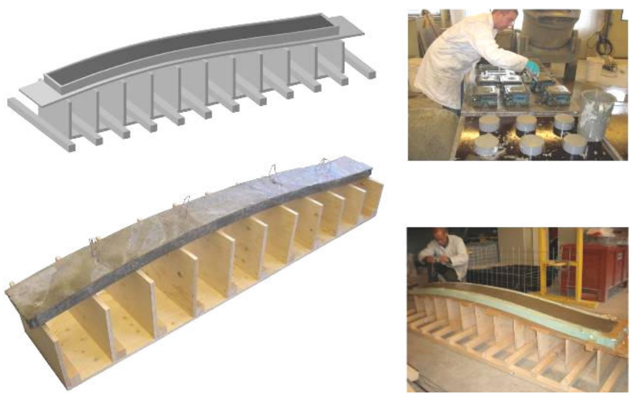

Fig. 13 Single-curved mould setup (top-left and bottom-right), slump tests to choose right moment of deformation (top right) and resulting concrete element (bottom-left)

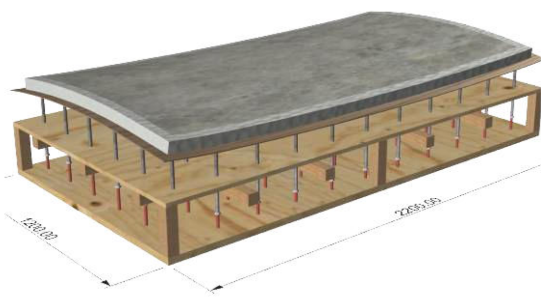

Fig. 14 Double-curved mould setup, using a plate. The concrete is cast when the mould is still in horizontal position. After 45 minutes the flexible mould is deformed in the desired shape by lowering the supports

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4.3 Double-curved elements

Based on the same principle, a 3D-setup was built for manufacturing double-curved elements: a pin bed of 6x11 pins, distributed over distances of 0.20x0.20 m^2. Each pin has two positions: an initial height for casting the concrete horizontally and a second height corresponding to the CAD model for the deformed situation. In the first tests, a thin plate was used as sub-layer formwork to cast the concrete on. In later tests, a strip mould was used. Three elements taken from the building in **Fig. 3** were chosen as example: one element with positive Gaussian curvature (shown in **Fig. 11a**), and two with a negative (saddle-shaped) Gaussian curvature (shown in **Fig. 14** and **Fig. 15**). As already mentioned in subsection 0, the thin plate was able to follow the deformed shape, but buckling effects due to internal stresses caused the plate edges to show a slight 'wave shape'. The strip mould did not show this undesirable effect, and accurately followed the required pin height. At some points around the edges the formwork had to be pulled slightly downwards to the pins, because a negative support reaction was needed (as indeed predicted by the mechanics model). The edge profile holds the concrete in the mould before and also after deformation, even though the concrete is still plastic. Under the horizontal load of the fluid concrete, the edge stays practically perpendicular to the mould surface.

For the element with size 2.00x1.00x0.05 m^3 100 litres of the concrete of **Tab. 1** was used. The surface quality of the different elements in some cases was quite uneven, as a result of both inequalities in the silicone finishing layer and difficulties in smoothening the casting side manually. The thickness of the element appeared not to change significantly as a result of the deformation process.

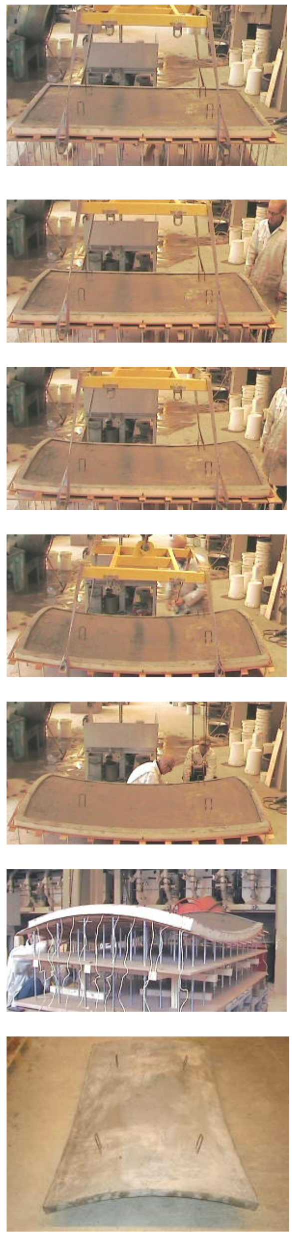

Fig. 15 Stepwise process of manufacturing a double-curved panel (size 2,00x1,00x0,05 m^3)

5 Conclusions

From the theoretical and practical work the following conclusions are drawn:

1. The manufacturing of single- and double-curved precast concrete elements is possible through the use of the flexible mould system described in this paper.
2. In order to control the process, it is necessary to predict the support reactions and exact deflection in the deformed shape by using a suitable structural mechanics model. One model for single-curved shapes and two models for double-curved shapes have been developed, that describe the behaviour of the flexible mould accurately. The beam and strip model gives better results than the plate model, as a result of buckling effects in the latter.
3. The strip mould test setup demonstrated in this paper can be used for the manufacturing of curved elements of 2.00 x 1.00 m^2 of various thicknesses, typically around 50 mm. Test were carried out with curvature radii as small as 1.5 meter, which is sufficient for realizing many freely formed building shapes. This kind of radii correspond with a difference in height within one panel of 100 to 200 mm.
4. The thickness of the element itself does not significantly change during the process. The edge profile of soft flexible foam meets the requirements of holding the concrete in the mould before

and after deformation. The elements' edges stay practically perpendicular to the mould surface, which makes it possible to fit the precast panels in the building geometry;

5. Using a 3 mm steel reinforcement mesh allows the mesh to deform along with the flexible mould and concrete during the process.
6. The surface quality of the elements ranged from good to rather poor, and has to be further improved in future tests.

In 2011 further work is planned on the following topics:

- experiments with thinner concrete panels;
- apply concrete mixtures with fibre reinforcement;
- experiments with SCC in order to improve surface smoothness and colour;
- cast structural elements applicable as plank floor, e.g. with strands as reinforcement;
- work on joints and interfaces between elements;
- work on fixings.

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