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.

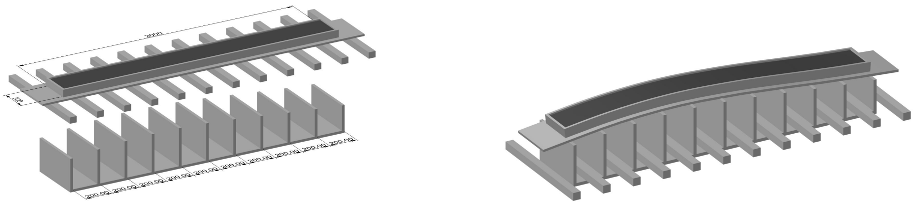
Keywords: Precast, Shells, Panels, Formwork, Free-form, Curved

1 Curved elements in architecture

The use of curvature in architecture results in **richer and more expressive designs**. An illustrations of the effect of curvature in buildings is given in **Fig. 1**. The new generation of architects that recently 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. Co-author Bas Janssen worked on an Msc-thesis research on the topic of precast double-curved concrete elements under guidance of prof. dr. ir. J.C. Walraven. The work done for the MSc-thesis

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

contributes to the PhD research of author Roel Schipper under guidance of prof. dipl-ing. J.N.J.A. Vamberský.



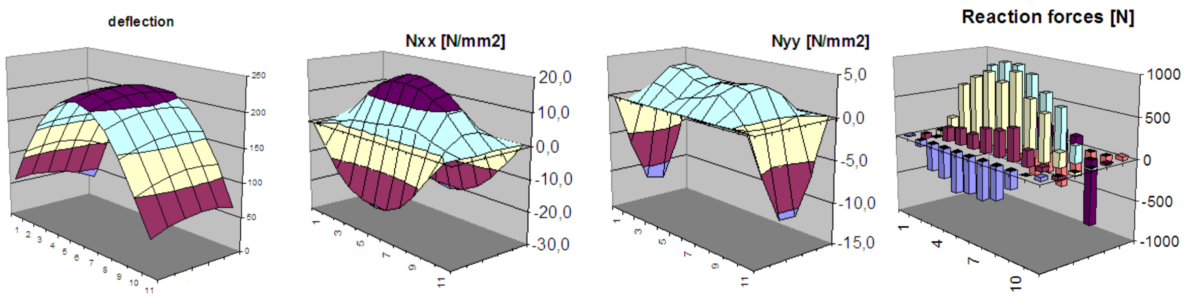
(a) first concrete is cast (b) then deformation takes place

Fig. 2 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)

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. 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. 2** shows an illustration of the principle of first casting and then deforming. To obtain the correct and desired shape of the mould, the behaviour of the mould has to be modelled first, using the theory of beams and thin plates from structural mechanics.

2 Structural mechanics modelling

Three structural mechanics models were used, a thin and flexible strip (beam) model, a plate model, and a model of crossing strips. For the tests, the models were implemented in Maple and Excel. An example of some results is shown in **Fig. 3**.



(a) (b) (c) (d)

Fig. 3 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; 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.

3 Laboratory experiments

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, an adapted E2 mixture (f'_{ck} = 75 MPa) with the recipe shown in the full version of this paper was used. For this mixture it was determined through tests that deformation is best performed after circa 45 minutes of initial binding.

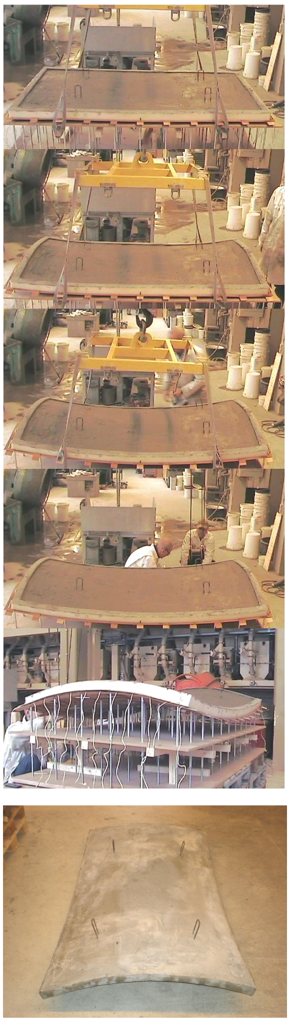


Fig. 4 Stepwise process of manufacturing a double-curved panel (size 2,00x1,00x0,05 m^3)

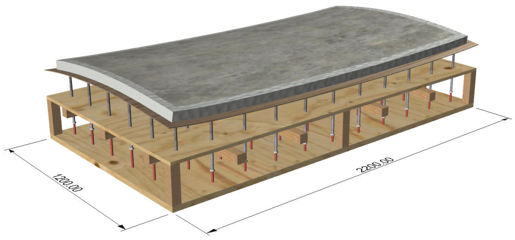


Fig. 5 Double-curved mould setup, using a plate. The concrete is cast when the mould is still in horizontal position. After 45 minutes the flexible mould is deformed in the desired shape by lowering the supports

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.

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 were taken from an example building: one element with positive Gaussian curvature (shown in **Fig. 3a**), and two with a negative (saddle-shaped) Gaussian curvature (shown in **Fig. 4** and **Fig. 5**). 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. 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.

4 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.

A more comprehensive report is given in the full version of this paper. 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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