



Kine-Mould: Manufacturing technology for curved architectural elements in concrete

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Abstract

The production of architectural elements with complex geometry is challenging for concrete manufacturers. Computer-numerically-controlled (CNC) milled foam moulds have been applied frequently in the last decades, resulting in good aesthetical performance. However, still the costs are high and a large volume of waste is produced. This paper describes the first outcomes of an R&D project funded by STW, the Dutch Technology Foundation, that was executed in close cooperation with industry. The work aimed at offering a viable alternative technology for CNC-milling, reducing cost and material waste at the same time. By constructing a prototype of a flexible mould system, and evaluating its viability in the production environment of a concrete factory, conclusions could be drawn concerning its feasibility. The context for the R&D project was a real ongoing project at the start of the research - a subway station in London - for which double-curved cladding elements needed to be produced. This paper discusses the principles of the technology, the construction of the prototype and the performance evaluation and accuracy. Some of the more fundamental technical aspects of the technology are discussed in a second paper in this ISOFF conference.

Keywords: Concrete, precast, complex geometry, double-curved, architecture, flexible mould

1. Introduction

1.1. Curved geometry in architecture

The use of curved geometry in architecture (Figure 1) challenges engineers, contractors and manufacturers in terms of material forming. With sheet-like cladding materials, such as metal, timber elements and glass, single curvature can be realised in a second manufacturing step after initial flat pre-production. By elastically deforming the material by cold bending or 'active' bending it is feasible to reach small radii if the ratio between flexural strength and Young's modulus is high [1]. Application of double curvature, however, results in in-plane stresses that easily lead to buckling or failure [2]. Various new technologies are emerging, using controlled plastic deformation of sheets into double-curved shapes. Recent examples are the production of curved glass elements for the Fondation Louis Vuitton pour la Création in Paris designed by architect Frank Gehry [3] and the forming of double-curved plate metal for the structure of the steel towers for the Thames cable car in London of Wilkinson Eyre Architects [4]. For the production of curved shapes in fibre-reinforced plastics or concrete, the option of moulding is a more obvious choice. Formwork in timber or foam can be realized in double-curved shapes by the use of skilled carpentry or CNC-milling. Some

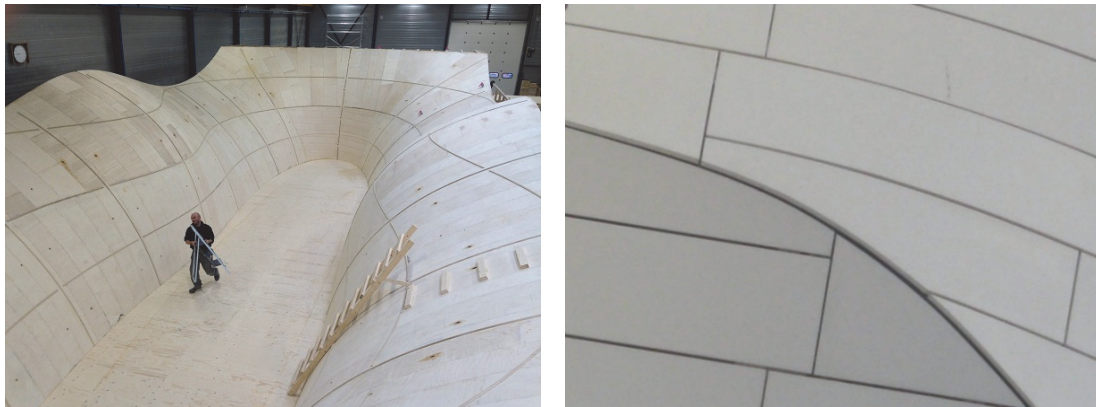


Figure 1: Left: an example of timber formwork for double-curved bridge parts for the Verlengde Waalbrug in Nijmegen, The Netherlands (Architectenbureau Zwarts & Jansma, Right: concrete cladding detail of Louis Vuitton Fondation pour la Création, Paris (Frank Gehry Architects).

examples of recent infrastructural projects are the Spencer Dock Bridge in Dublin of Amanda Levete Architects [5] and the bridge Verlengde Waalbrug in Nijmegen, the Netherlands designed by Architectenbureau Zwarts & Jansma Architecten (Figure 1, left). Generally, the price level of curved and double-curved moulds is significantly higher than that of flat and orthogonal ones, due to both the required skills, labour and equipment [6] as well as the difficulties in obtaining the required accuracy and tolerances. Since many complex geometry buildings do not have a large degree of repetition with regard to the shape of elements, this type of formwork often can be used only once, after which the mould material is treated as waste or, in the best case, source for recycling. A further complication is that the speed of production using CNC-milling for large projects is becoming a factor of importance [7]. For this reason, the feasibility of realizing a flexible formwork has been investigated by various research groups worldwide.

1.2. Flexible formwork technology

In the PhD research of the first author [8], patent and literature reviews are presented that show already first patents stemming from the first half of the previous century, and not only for architectural purposes. Automotive, aerospace and ship building industries have also developed similar concepts. Perhaps inspired by these other industries, already in 1969, architect Renzo Piano published in [9] a vision and the first practical results of an innovative manufacturing flexible formwork method for double-curved elements (Figure 2).

Piano manipulated a flexible surface by a grid of actuators to arrange the form of a predefined curved shape. After casting of a fibre-reinforced plastic (FRP) element on top of this flexible surface and a period of curing the FRP-element could be demoulded and the surface reconfigured into a different shape for the next FRP-element. Worldwide, the development of a flexible mould has remained under continuous attention of various researchers. Spuybroek [10] published a conceptual image of the flexible mould, but did not realize a prototype. Vollers and Rietbergen [11, 12] carried out research on a working prototype for glass and concrete and patented some of their ideas. Recently, Vollers completed a full-scale prototype co-funded by the Dutch Technology Foundation STW under the title 'pinbed wizard' [13, 14]. Raun et al. [15, 16] developed in Denmark a working system for materials such as (a.o.) concrete or thermosetting plastics; their system is at present commercially available.

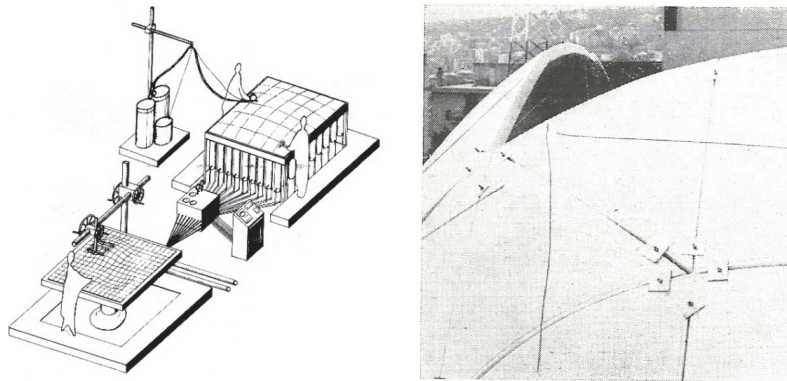


Figure 2: Pavilion (right) created with the 'Stampo deformabile' (left) of Renzo Piano, already published in 1969 [9].

Whereas the aforementioned publications aimed for the production of precast elements of a maximum size typically in the order of magnitude of about 2 by 2 square meters, Michel and Knaack [17] even investigated the use of a flexible mould for large cast in-situ free-form walls. Various Master students carried out research at the Faculty of Civil Engineering at Delft University of Technology [18-20] under the umbrella of the PhD research of Schipper [8] (Figure 3). Janssen explored the general feasibility of the flexible mould concept and elastic behaviour of the mould surface; Eigenraam concentrated on the kinematics and improved the accuracy for shapes with stronger curvature. Kok investigated the effect of textile reinforcement. The outcomes of all researches were promising, and were partially filed for patent.

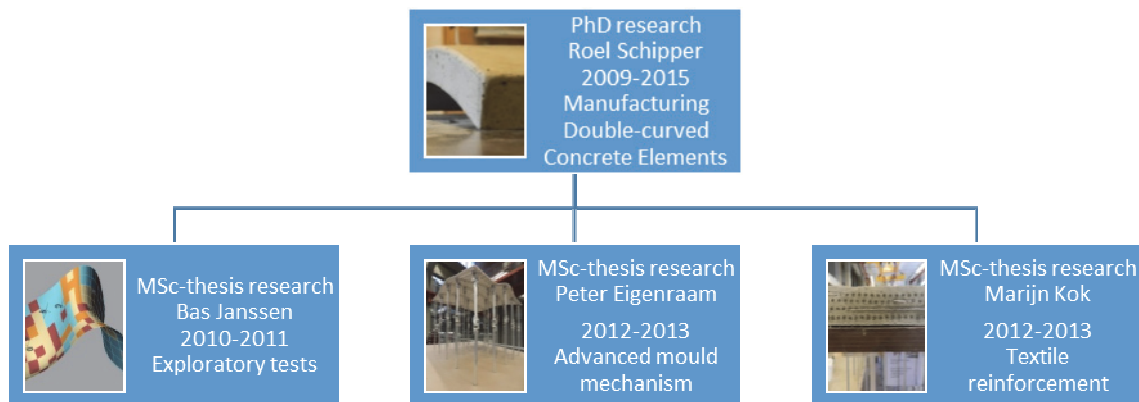


Figure 3: Hierarchy of various researches at Delft University of Technology.

1.3. Cooperation with industry and STW funding

Based on the positive outcomes of these researches, it was decided to initiate cooperation with industry, since the viability of the method had only been proved at small scale and in an academic context. The company mbX / Concrete Valley at that time was already the contracted manufacturer of precast concrete curved roof cladding elements for an impressive project in The Netherlands, the public transportation terminal Arnhem of architect UNStudio. In this project mbX uses technology closely related to the flexible mould method as described above. For new projects, the company was

investigating the possibility to manufacture elements with even sharper curvature and more complex shapes than those realised in the Arnhem project. At this point the cooperation between TU Delft and mbX / Concrete Valley started. As a first result a valorisation grant proposal [21] was rewarded by Dutch Technology Foundation STW with funding for building and testing a larger scale prototype for industrial application under the title *Kine-mould*.

1.4. STW Kine-mould project

The Kine-mould project consisted of a number of steps, from which the following will be reported in the present paper:

1. *Modelling, design and assembly of a larger scale Kine-mould*
A mould was developed for larger prototypes with surface sizes that would allow for production of realistically sized concrete elements. Parts of the larger Kine-mould were produced using similar materials as for the earlier prototypes. The larger scale Kine-mould was assembled and the mould surface prepared.
2. *Analysis and selection of concrete elements from realistic structures*
From an architectural structure, a small number of concrete elements was selected for production. The geometry of the elements was analysed to determine the curvature parameters and edge positions. Functional and structural requirements for the elements were determined.
3. *Concrete mixture design*
For the selected elements, a suitable concrete mixture, reinforcement and anchoring method was chosen. Rheological tests were carried out with the mixtures in order to establish the properties. Material tests were executed on the element level.
4. *Casting and deformation of concrete elements*
Using the larger Kine-mould, selected concrete elements were consequently cast and deformed into the correct geometry, using a scientific timing model.
5. *Performance evaluation*
The exact geometry of the elements was analysed using 3D-photogrammetry. The surface texture and finishing will be judged against industrial performance requirements.

The following section will discuss each of the abovementioned steps in more detail.

2. Project description

2.1. Modelling, design and assembly of a larger scale Kine-mould

The original prototype developed during the Master's thesis research of Eigenraam [18] had a mould surface size of 600 x 600 mm². A new and larger mould had to be developed with surface sizes that allow for the production of realistically sized concrete elements, in the order of magnitude 3 x 3 m². However, it was decided to first work out a *semi*-full-scale prototype with a mould surface size of 1080 x 1080 mm², in order to be able to evaluate its performance, since the necessary design choices on some aspects were still unclear. First, a geometrical model was setup with the parametric and associative geometry software Grasshopper™, a plug-in integrated with the 3D modeling software Rhinoceros™. To be able to assess the mechanical behavior of the flexible mould, a computational framework was set up by means of associating the geometric entities composing the mould with their relative mechanical properties in FEM software (Oasys™ GSA). In order to communicate the geometric characteristics to the FEM software, a third party plug-in integrated with Grasshopper was used (Figure 4) called GeometryGym, developed by Jon Mirtschin. Although the interface between the geometrical model in Rhino-Grasshopper and its mechanical counterpart in Oasys now could be implemented without difficulties worth mentioning, it appeared particularly complex to effectively use

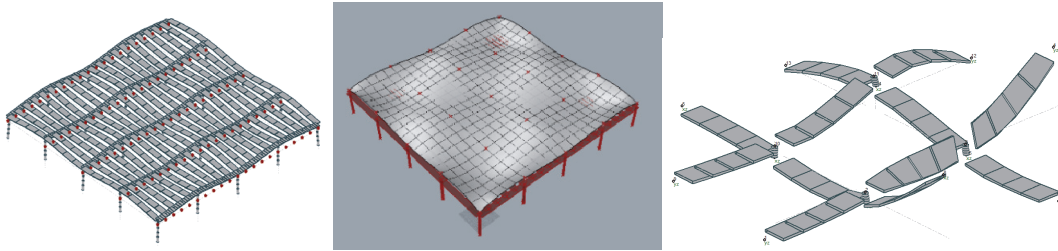


Figure 4: A deformed model in Oasys (left) and its associated geometry in Rhino/Grasshopper (middle image). Various deformations of the strips were modelled (right).

Oasys to optimize the strip dimensions. The very thin and flexible strips of the mould in combination with the relatively large displacements in various conditions resulted in convergence issues. After various attempts, it was decided to proceed with the construction of the mould prototype, choosing the dimensions of the strips based on earlier experience and available materials. Parts were produced for the mould prototype using similar principles as in the earlier prototype, but with stronger and improved hinges and strip system. The mould was assembled and the silicone mould surface prepared. Afterwards, it was transported to mbX / Concrete Valley for carrying out test castings (Figure 5).



Figure 5: Drafting, assembly and transport to the concrete product factory of the semi-full-scale prototype of the Kine-mould

2.2. Analysis and selection of concrete elements from a realistic design

From the architectural design of a new subway station to be built in London, a concrete element was selected for production. The design comprised the interior precast concrete cladding of a bored tunnel, more specifically the crossings between rail and passenger tunnels. After analysis of the full station, it became clear that for these areas of the station approximately 450 double-curved elements were needed, of which between 300 to 350 could be identified as fully unique, implying single use of a CNC-milled mould. It was apparent that application of a flexible mould could lead to a meaningful reduction of costs. The geometry of the elements was analysed to determine the curvature parameters and edge positions. Functional and structural requirements for the elements were determined. Figure 6 shows an example of an area in which unique double-curved elements were present.

The designed thickness of the concrete elements was 35 mm, with a joint width of 50 mm between the edge contours of each element and all neighbouring elements. Behind the joint, curved concrete strips were planned to cover this 50 mm joint on the rear side of all element connections; these strips had a width larger than 50 mm. All elements had to be produced within a tolerance of approximately 3 mm in all directions to achieve aesthetically smooth transitions from panel to panel.

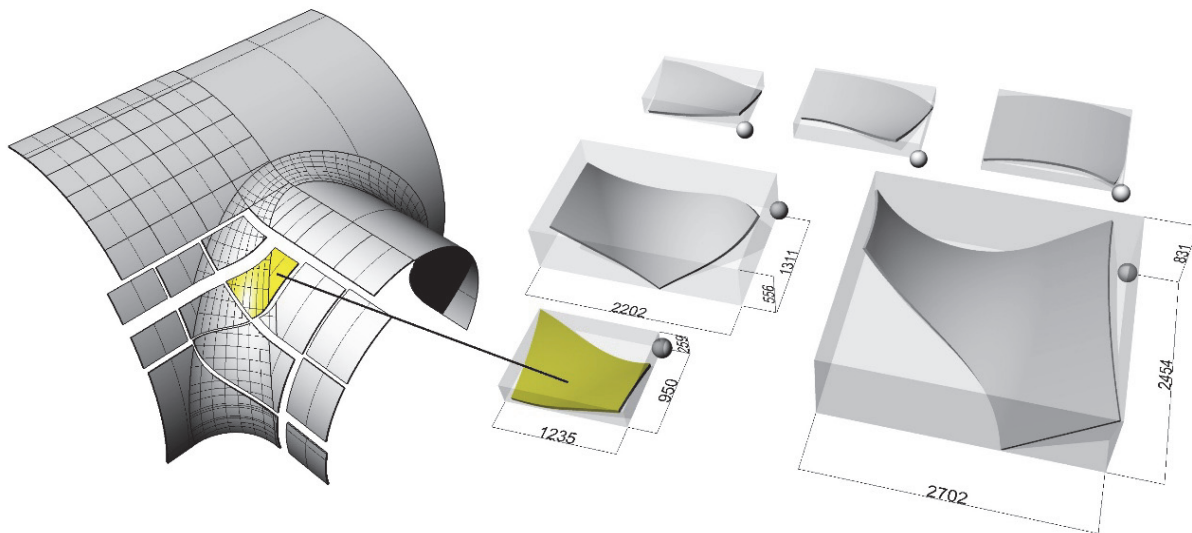


Figure 6: Fragment of the architectural design of a subway station to be built in London; in the exploded part of the view in the left image some of the interior cladding elements of a bored tunnel are shown. The radii of the smaller and larger tube are 2.72 m and 4.48 m, respectively. Both tubes are connected with a 1.25 m radius fillet. The yellow element was selected for the first experiment. The right part of the image show bounding boxes and x-y-z dimensions of six of the elements. The largest element has a bounding box of $\Delta x \times \Delta y \times \Delta z = 2702 \times 2454 \times 831 \text{ mm}^3$, the selected element has a bounding box of $1235 \times 950 \times 259 \text{ mm}^3$. The small spheres indicate the face of the element turned towards the interior of the tunnel.

The structural connection of the cladding elements was planned in steel anchors at the rear side of the elements, bridging a 600 mm cavity to the structural concrete of the bored tunnels. For the analysis of the geometry of the individual elements, first the smallest bounding box was determined (Figure 6), using the Rhino-Grasshopper genetic algorithm plugin Galapagos. It was clear that, due to their size, some of the largest elements could not be manufactured on the semi-full-scale flexible mould prototype shown earlier. Therefore, for the first experiments, an element with sufficient geometrical

challenges was selected (the yellow element in Figure 6), however, in a *scaled* version to fit the flexible mould prototype. If this test would be successful, confidence in the method would be gained, opening the way to building a larger prototype. The limitations of the prototype mould were a x-y size of 1080 x 1080 mm², although a size of 900 x 900 mm² would be preferable, since the accuracy of the outer fields of the prototype mould was already known to be limited [18]. Therefore, a uniform scale factor of 60% was chosen.

2.3. Concrete mixture

The elements were initially planned to be executed as shotcrete (sprayed mortar) with chopped glass fibres on a static, CNC-milled mould made of either foam or timber. However, the innovative principle of the flexible mould is that the element is cast in flat, horizontally deformed shape, which has two main advantages: 1) it allows the use of a single mould with edge profiles to restrain the fluid concrete and 2) by using a self-levelling, self-compacting high performance concrete (HPC), very good aesthetical and structural quality can be expected. Table 1 shows the mixture composition of a HPC-mixture that was used for various tests in the present paper. For the first element, a mixture used by mbX for another project was chosen, which, however, appeared to remain fluid for a too long period of time to be suitable for the flexible mould method. Thus, for later experiments, a self-levelling HPC with white cement and limestone filler as shown in Table 1 was chosen. Rheological tests were carried out with the mixture in order to establish the rheological properties. Tests were executed with the Abrams slump cone: a steel cone is filled with fresh concrete and lifted, after which (for fluid mixtures) the diameter of the concrete layer is measured (slump flow). For stiffer mixtures the reduction in height compared to the original cone is measured (slump value). The development of these values over time provide valuable information: the mixture from Table 1 has a slump flow in the range of 550 tot 650 mm directly after mixing, depending on the dosage of superplasticizer. Due to the high dosage of cement strength class 52.5 and the use of a fine limestone-filler, a rapid stiffening of the mixture occurs in the first hour after casting. By measuring the slump at regular intervals, the moment of deformation was estimated. The correct value for the slump depends on the shape of the element that is produced: if it is curved sharply (small radius) the slope between the horizontal plane and the edge of the mould surface is steeper compared to a flatter element. At this slope, some stiffness of the concrete is required to prevent it from flowing out of the mould, since a single mould is used (without top cover). These aspects are described in more detail in [8].

Concrete component	kg / 1000 litres
Cement CEM I 52,5 R white	600
White limestone powder (Betoflow D, Omya)	180
White pigment	6,0
PVA fibres L=8 mm (Kuraray)	5,2
Superplasticizer Glenium 51 (BASF)	3,2
Water	228
Sand 0,125-0,25 mm	229
Sand 0,25-0,5 mm	408
Sand 0,5-1 mm	637

Table 1: Concrete mixture used for later experiments. The mixture can be characterized as a self-compacting HPC. The average cube compressive strength (28 days, cubes with 150 mm ribs) was 76 MPa. The average prism flexural strength (28 days, prisms 40x40x160 mm³) was 13 MPa.

2.4. Casting and deformation of concrete elements

The digital shape file of the selected element was used to derive the proper actuator heights and edge contours. A correction was needed for the actuators that, apart from a vertical displacement, also showed a horizontal displacement. The principle of this procedure has been described in more detail in [18]. On top of the strips a silicone membrane with a thickness of approximately 1.5 mm was applied to smoothen the mould surface. During the first cast carried out in the concrete factory, this membrane did not have a foam surface support. In later tests, a polyether foam surface support of 10 mm thickness was used in order to improve smoothening. The actuator heights were prepared by adjusting the nuts on the threaded bars to the correct height and the edge contours were projected using a laser projector (Figure 7). After positioning of the edge profiles, the mould was brought back to a flat position, HPC was cast on the flat mould and covered with a plastic foil to prevent evaporation. After a stiffening period of approximately 45 minutes, the mould was deformed by gravity to its pre-installed actuator set-up (Figure 7). Small weights were attached to some actuators to pull them down to the installed height at those positions where the self-weight of the element was not sufficient to overcome the elastic springback of the mould strip surface. After deformation, a hardening period of 24 hours was respected, after which the element was demoulded, and the flexible mould cleaned.

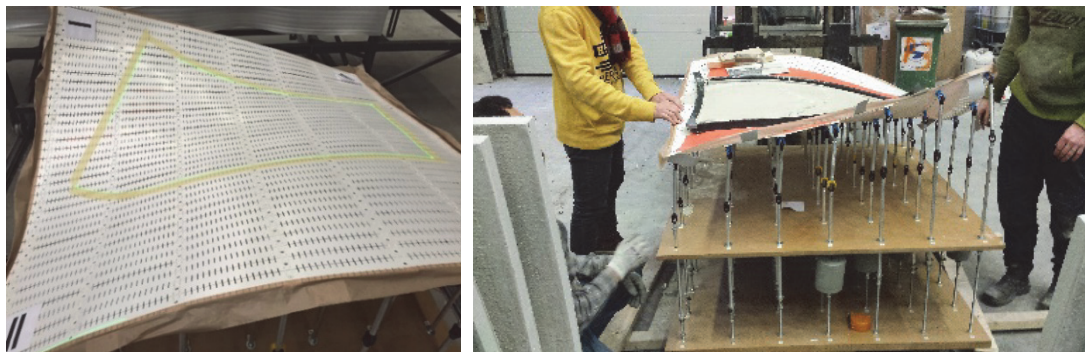


Figure 7: Left: mould strip surface with laser-projected edge contours;
right: adjusted actuator heights and first test casting.

2.5. Performance evaluation

After a first visual inspection, the element appeared to have an overall geometry that was corresponding to the predefined shape. However, on a more detailed level, the position of strips and actuators could be seen in the slightly reflective surface of the concrete element, which was unacceptable from an architectural point of view. To quantify the accuracy of the cast element in comparison to the original architectural shape, the resulting geometry of the element was digitized using 3D-photogrammetry (Autodesk 123D Catch™, freely available). By taking approximately 70 photo's at high resolution that are imported by 123D Catch, the software is able to capture a 3D model. This 3D model was compared to the original Rhino-model in another software, called CloudCompare (also freely available). The histogram in Figure 8 shows that the best fit of the two shapes resulted in an error of between 1 and 5 mm for the largest part of the surface, whereas local errors of 6.4 mm were measured. Visually, these errors can be detected, especially if light reflected from the panel reaches the eye after a small reflection angle with the element. With respect to the required 3 mm tolerance that was defined in the beginning of the project, the resulting geometry could be considered not too bad, but aesthetically the 'wobbling' or 'ponding' of the surface is disturbing.

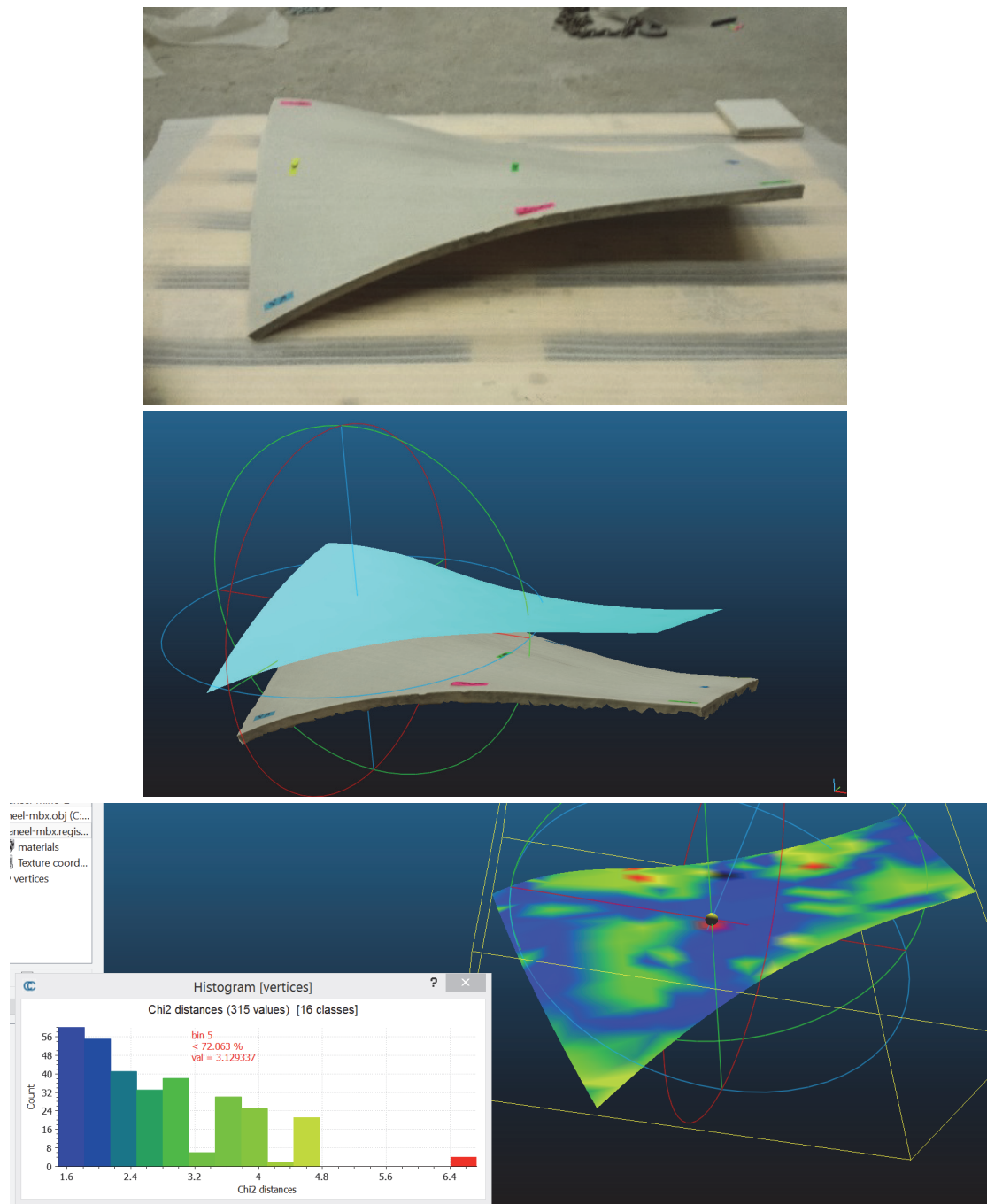


Figure 8: The demoulded element with coloured markers (top);
the digitized 3D image of this element with above it the original architectural shape (middle);
the calculated discrepancies between both shapes (bottom).

3. Conclusions

The Kine-Mould prototype was developed to investigate the possibility to replace CNC-milled moulds by a reconfigurable flexible mould system. Potentially, this opens the opportunity to manufacture elements for double-curved shapes in a more economic way. The project has demonstrated the following:

1. Casting concrete in a flat shape on a single-sided mould and deformation after a certain stiffening period is possible and does not lead to flow of the concrete out of the mould or cracks in the concrete;
2. A self-compacting high performance concrete can be applied, leading to an aesthetically smooth surface and a good structural performance;
3. The overall geometry of the element, after deformation, hardening and demoulding, corresponds roughly with the architectural geometry of the defined element;
4. The detailed geometry, though, shows visible uneven areas in the surface of the element, especially under specific light conditions and angle;
5. These uneven areas are the consequence of the strips being too flexible, leading to ‘ponding’ of the concrete between the actuator tips; it is expected that the use of stiffer strips will reduce this effect.

In the mean time, other experiments were carried out. It is expected that the flexible mould technology in the near future can be applied for single- and double-curved elements in real projects as the one described in this paper. For the subway project, the case study of this research project, it was decided to only use flexible moulds for the single-curved parts. The flexible-mould technology was considered not yet feasible for complex and strongly double-curved shapes as the ones chosen from the subway project. This was also the result of additional requirements that were not directly related to the outcomes of the present research.

4. Further work

An improvement of the prototype is planned to overcome the issues observed. After replacing the strips with stiffer ones and switching to another technology that is presently under investigation (steel wire mesh) new tests will be carried out to bring the technology closer to application in a real project.

5. Acknowledgement

This work was carried out with the help of a Valorisation Grant provided by Dutch Technology Foundation STW. Our gratitude also goes to Jon Mirtschin for providing a license of GeometryGym, to Conovation for providing Omya BetoFlow D and superplasticizer and to ENCI Rozenburg for providing white Heidelberg cement.

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