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DOUBLE-CURVED FORM APPROXIMATION WITH IDENTICAL DISCRETE PANEL GEOMETRIES

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Abstract. To reduce the costs of manufacturing multiple moulds for double-curved facade construction, this research suggests a method of approximating the desired envelope with identically formed panel geometries. The panels can then be fabricated by only using two double-curved moulds. In a second step, individual segments are cut out of the identical base geometries. The method has been successfully tested with the construction of a prototype. The result is an intricately textured free-form geometry. The installation was built at a reasonable cost compared to other ways of fabricating double-curved geometry. The strength of the panels was utilised as the sole structural system of the prototype.

Keywords. Architecture; façade; double-curvature; discrete components; panelisation.

1. Introduction

The main challenge in the construction of double-curved facade geometry is the cost of manufacturing individual panels (figure 1). Except in few cases, a seemingly double-curved facade is rarely actually constructed double-curved; more often it is rationalised into flat or single-curved elements that approximate the intended double-curvature (Ceccato 2012). The economic challenge lies in the costs of manufacturing moulds against which the façade panels are formed. For the fabrication of panels from various materials, such as aluminium, glass, fibre concrete or polymers, usually a separate mould needs to be manufactured for each panel (Lee & Kim 2012). Alternatives such as Multi-Point Forming offer savings but are still relatively costly (Lee & Kim 2012).

In order to allow for an affordable manufacturing of complex form, architects have proposed geometries that are based on a limited amount of identical discrete components (Sanchez 2016; Retsin & Jiménez García 2016). While this may provide an answer to the economic issues of the construction, it very often leads to geometric systems that appear pixelated rather than flowing.

Figure 1. Sahya.

We therefore propose a method of double-curved façade construction that utilises identical discrete panels during the forming process, which are then trimmed in order to align to the desired free-form envelope. The method has been tested with a prototype and was evaluated for its aesthetic and economic performance. It was shown to cost significantly less than a fully double-curved construction while resulting in a dynamically flowing, textured geometry.

Figure 2. Anisotropia, at the National Museum of China, Beijing.

2. Related Work

Previous research by the authors utilised individually trimmed, single-curved panels in order to approximate a double-curved geometry (Klemmt 2012). The installation Anisotropia used bamboo veneer strips hung in tension from the ceiling. Similar to the proposed system, the bamboo panels were trimmed in order to align to the desired free-form envelope geometry. The result was a dynamically flowing, textured geometry with similarities to the prototype of this research, however with all panels extruded along the same axis (figure 2). The methodology proposed in this paper therefore is a 3-dimensional generalisation of the previous work.

Aesthetically, some projects of Justin Diles and Neri Oxman have similarities to the constructed prototype, especially due to the free-form geometries in contrasting black and white colours they are based on. Eigenforms by Justin Diles uses double-curved panels to construct an indoor pavilion (Diles 2014). The sculptures Minotaur and Leviathan 2 by Neri Oxman are manufactured using 3d printing (Oxman et al. 2012).

Figure 3. Pattern generation.

3. Proposed Panelisation System

We propose a system similar to that of our previous research (Klemmt 2012) in order to approximate a desired envelope geometry, which in this case uses discrete panels that are double-curved in two repetitive shapes, rather than being single-curved as in the previous work. The panel fabrication therefore uses only two moulds so that the costs of mould fabrication can be minimised. The panels are then CNC-cut to custom shapes in order to align to the overall double-curved envelope geometry and to generate architectural detail and complexity at the same time (figure 3).

The system is based on the desired free-form envelope geometry and on the geometry of the repetitive discrete panels. The panels need to be able to connect laterally to their neighbours. In the arrangement that has been used for the prototype the panels connect to the adjacent panels in a tangential manner, which results in a seemingly continuous surface morphology within each layer of the system. The adjacent panels are arranged in a shifted grid with curved rather than straight edges. In the third direction the panels connect to the neighbouring surface layers also in a tangential manner, with the layers touching along the length of a curve.

The panels are then repeated in their arrangement to fully fill the desired envelope geometry. Any panel that intersects with the envelope geometry is trimmed along the intersection curve. If all panels connect in tangential manners and if the envelope geometry is free-form without any sharp edges, the resulting morphology will likewise be free-form without any sharp edges.

The connection hardware between panels can use various details depending on the materials used and on the design intent. The adjacent panels within the same surface layer can be designed to overlap.

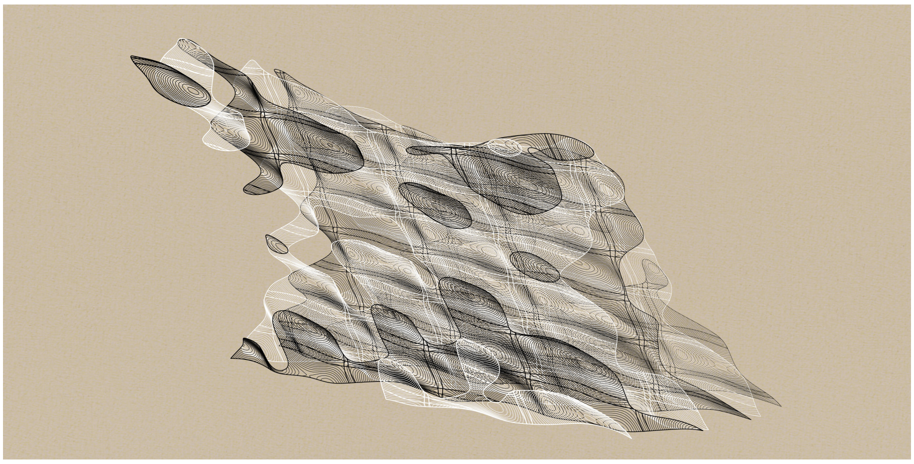

Figure 4. Prototype Design.

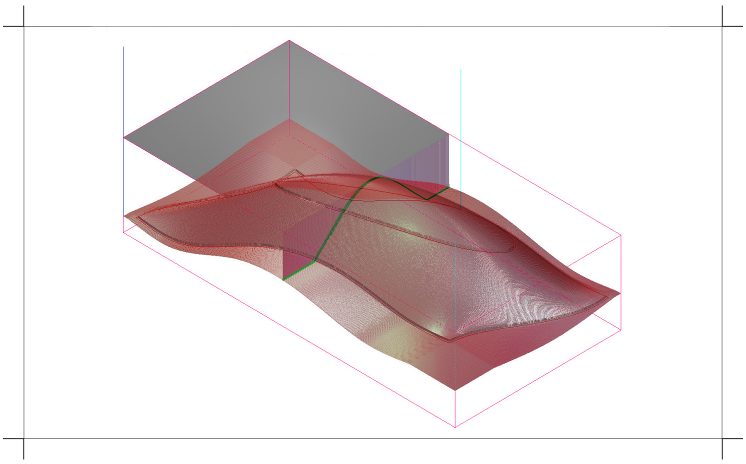

Figure 5. Toolpath for the moulds.

4. Prototype

The proposed methodology was tested with the construction of a prototype, titled Sahya, at the Venice Biennale 2016. The overall geometry was designed as a double-curved volume with dimensions of 3m x 1.5m and 1.5m height (figure 4). The resulting assembly is based on fully double-curved panels and on curved separations between those. The repetitive arrangement of the individual components becomes imperceptible against the overall geometry and its patternisation. The panels form the visible surface of the prototype while at the same time act as the structural system of the self-supporting installation. The fabrication of the panels for the prototype was carried out in three stages:

- manufacturing of the moulds in aluminium and wood
- vacuum forming of Acrylonitrile butadiene styrene (ABS) sheets
- CNC-cutting of the individual panels

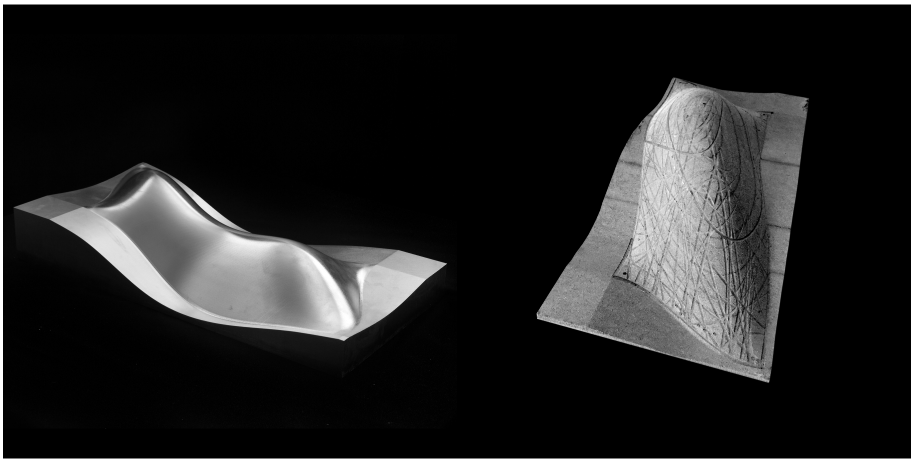

Figure 6. Aluminium mould and the wood mould as base for the CNC-cutting.

4.1. MANUFACTURING OF THE MOULDS

Two sets of moulds were made for fabrication. The first set of moulds, one for each panel type, were made using solid aluminium. Two blocks of aluminium of size 300x600 mm and 150 mm thick were CNC-cut into the geometry of the two panel types. 0.1 mm holes were manually drilled into the moulds for air extraction during the vacuum forming process (figures 5 & 6).

The maximum curvature deviation of the double-curved mould surface is 150 mm. Owing to the vacuum formed panel's relative thinness of 4mm, additional CNC moulds in wood had to be manufactured to hold the panels in place during CNC cutting. Like the aluminium mould, the wooden moulds were re-usable and allowed for precise cutting. Six layers of 25 mm thick MDF were laminated to create two solid blocks of 300 x 600 and 150 mm thick, which were then CNC-cut into the geometry of the two panel types (figure 6).

4.2. VACUUM FORMING OF ABS SHEETS

The ABS sheets were made to order from ABS pellets. The custom order was made to achieve equal glossiness in finish on both sides of the panel as typically, ABS sheets available are glossy on one side only. 150 kg of ABS pellets were formed into 150 sheets of ABS of size 400x700 mm and 4 mm thickness, in both black and white colours. The weight of each sheet was 1 kg. An extra margin of 50 mm on all sides served as a grip for the vacuum forming.

The panels were heated to 120 degrees for one minute to achieve plasticity in the ABS and subsequently vacuum-formed over the aluminium moulds. The panels were allowed to cool for 3 minutes over the aluminium mould before detachment to avoid shrinkage. Both aluminium moulds were used to cast panels in white and black colours producing four types of panels: Type 1 in black and white and Type 2 in black and white.

4.3. CNC CUTTING OF INDIVIDUAL PARTS

The cast ABS plastic panels were secured to the wooden mould with clamps and aligned to the CNC machine using registration points. The custom profile of each panel was cut and numbered based on the roll-out drawing. Wherever possible, more than one piece could also be cut using the same panel if the geometry of the cut lines of the two profile had no interference. A total of 200 panels were cut for the two mould geometries with two colour variations. In addition, a minimum of three and a maximum of eight 4.2 mm diameter holes were drilled in each panel to allow for fixing (figure 7).

Figure 7. 3d Cutting Schedule.

4.4. DETAILING

The panels were fixed to each other in layers. Each layer contained panels from both moulds but always the same colour to produce alternating layers of black and white panels. Built ground up, alternating layers of black and white panels were place and bolted together with pre-cut threaded rods with custom-made panel-coloured hexagon cap nuts, separated by EPDM gaskets.

5. Evaluation

5.1. AESTHETICS

The panelisation methodology results in a very intricate free-form aesthetic. The different curved layers in contrasting colours result in a flowing geometric overlay against which the repetitive arrangement of the panels disappears (figures 8 & 9). The proposed method does not result in a geometry that follows the desired envelope very closely but only ever actually touches it at the intersection curves with the panel geometry. It does manage to avoid any flat or single-curved geometry and any straight edges or joints. In comparison to the projects by Sanchez or Retsin and Jiménez García that utilise identical discrete components, the proposed method uses identically formed but individually cut discrete components. This allows for a much more dynamic aesthetic than the often pixelated morphologies that result from using identical components (Sanchez 2016; Retsin & Jiménez García 2016).

Figure 8. Sahya.

An aesthetic issue of traditional double-curved façade construction is the necessity to panelise the façade, which very often is done along straight lines for cost reasons and in order to optimize material usage (Ceccato 2012). The straight joint lines may in many cases be counterproductive to the creation of the dynamic that the curved envelope geometry may wish to achieve. In the proposed method, the curved panel edges come at hardly any extra cost. Any secondary structure along the curved edges or other relating architectural components will follow the identical curvature at every edge and can accordingly be mass produced.

As applied in the prototype with alternating layers in black and white, the geometric aesthetic appears to have similarities with Eigenforms of Justin Diles or Minotaur and Leviathan 2 of Neri Oxman (Diles 2014; Oxman et al. 2012).

However, a single-colour application is likely to appear much more homogeneous. While the aesthetic is different and more textured than constructing the desired envelope as a single, double-curved surface, this specific aesthetic may be suitable for many projects.

Figure 9. Sahya, detail.

5.2. COSTS

Four methods of manufacturing the desired envelope geometry were explored to develop a relative cost comparison table. In addition to the proposed system of fabrication using a pair of identical double-curved panels, costs for fabricating the geometry using flat panels, Multi-Point Forming and double-curved single surface panels were compared. Fabricating the geometry using flat panels requires the triangulation and rationalisation of the form. The product of the surface area of the geometry and the cost of panel per square meter were used to determine approximated flat panel costs at EUR 400 in 4 mm thick ABS plastic.

The production of the prototype using double curved, single surface panels requires the rationalisation of the geometry into 80 panels. The cost of raw material, moulds, 3d forming and panel cutting was calculated based on the same costs as the identical double-curved panels of the constructed prototype.

The relatively new technology of Multi-Point Forming has been applied to aluminium façade panels. A set of movable pistons is set to the desired geometry from above and below the sheet, which is then pressed against it (Lee & Kim 2012). Multi-Point Forming can be used on heated polymer sheets, however, care must be taken that the pistons do not leave individual marks on the material. The costs for this have been estimated based on research by Lee and Kim (Lee & Kim 2012).

Any costs towards packaging, transportation and on-site assembly have been excluded from the cost comparison table. However, the proposed system allows for panels to be stacked, so that the complete set of elements for the prototype could be transported in two standard suitcases. The costs and estimated costs in table 1 show that the proposed methodology is significantly cheaper than a construction of the geometry as a single double-curved and panelised surface. However, the methodology is still more expensive than approximating the geometry with flat panels.

In comparison, the construction systems used for the example by Diles utilises individually cut moulds as is therefore commercially not feasible (Diles 2014). The example by Oxman was 3d printed and a commercially feasible 3d printing technology for similar large scale applications is yet to be developed.

Table 1. Cost Comparison for different Construction Methodologies.

	Approximated Flat Panels 800 panels 20 m² material	**Double-Curved Single Surface** 80 panels 32 m² material 80 moulds	**Multi-Point Forming** 80 panels 32 m² material multi-point press	**Identical Double-Curved Panels** 200 panels 80 m² material 2 moulds
Raw Material	€ 250	€ 400	€ 400	€ 1,000
Alu. Moulds	-	-	-	€ 2,350
Wood Moulds	-	€ 48,000	-	€ 1,750
3d Forming	-	€ 480	€ 6,400	€ 1,200
Panel Cutting	€ 800	€ 400	€ 1,200	€ 1,000
TOTAL	**€ 1,050**	**€ 49,280**	**€ 8,000**	**€ 7,300**

5.3. STRUCTURE

It was found that the panel assembly was able to withstand a significant load. At the scale and the dimensions at which the prototype was constructed it easily formed a self-supporting structural system. Because of their double-curvature, the panels had a significant inner strength.

Architectural large-scale aluminium panels are expected to perform similarly in regards to their structure. It is expected that, depending on the scale and material thickness, stiffeners may not be required. Depending on the main structure of a building, the secondary structure could possibly be reduced to local connections at each fixing point. The possibilities of the panels as the sole structural system of a façade or complete small-scale building would have to be investigated in detail for the specific project. The proposed method can easily provide building enclosure, insulation and waterproofing along the panels within one surface layer. This innermost layer of the façade could directly be constructed from insulated double-curved panels.

6. Conclusions and Future Work

The proposed methodology for the construction of double-curved volumes based on identically double-curved panels has proven reasonably affordable. The system has shown to have intricate aesthetic qualities that have not been built yet at a larger scale at a commercially affordable cost. The methodology and design aesthetic appear very suitable for an application as building scale aluminium façade system (figure 10).

The prototype sets out new directions to be explored: The system can be tested using aluminium instead of ABS plastic and suitable detailing needs to be developed to realise the system as a building facade. The multiple layering of the tiling systems could be developed as a passive thermal control system in the form of a self-shading facade or to channel air to regulate temperature around the building envelope. Due to the successful structural behaviour of the prototype, the system should be explored as a self-supporting structure in form of a larger pavilion.

Figure 10. Sahya.

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