From Shape to Fabrication

Closing the Digital Chain for Free Form Shapes Formwork with a Focus on Ruled Surfaces

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Abstract. There is a close relation between building design and fabrication. However still it is mostly a sequential process where the fabrication with its geometric chances and limitations is only to a small extend taken into account in early design phases. In this paper we describe a prototype form work project, realized out of styrofoam cut out with a CNC hot wire-cutting system and coated with the Claraporon coating system. Due to the linear nature of hot wire cutting the surfaces that can be created are ruled surfaces. They are discussed in a more general way as well as first exercises with ruled surfaces in teaching.

Keywords: Digital fabrication; Form work; Ruled surface.

In contemporary architecture free form shapes become more and more common. The increasing number of digital and parametric designs cause a high number of buildings with free form shape elements. For the design phase there are numerous software packages available ranging from classical CAD packages like AutoCAD or Microstation to animation software like 3D-Studio MAX, Softimage or Maya and parametric modelers like Generative Components that make the design phase as well as the design of free form shapes very easy. However what is easy to digitally design often still causes a lot of craftsman’s work in the production and realization phase. So the production costs tend to be somewhere in the range of prototypes and thus only affordable for prestigious projects.

The digital chain for e.g. steel work from design to final fabrication (e.g. laser- or plasma cutting) works quite well, also due to its application in other disciplines like automotive and mechanical engineering. In contrast to that the digital chain in surface based free form shapes like concrete form work up to now is still not closed. Especially due to the one time usage of the form work, it has to be very cost effective by reducing the amount of craftsman work, replacing it by digital production and nevertheless minimize machine time which due to machine costs is still a major factor.

In form work choosing the right production method is essential for the quality of the final concrete as well as the cost effectiveness. As architects are more and more involved into the production process by e.g. delivering 3D data directly to the manufacturer, a profound knowledge of the production
method, the relation of the production method to the possible geometry and the relation to the design is essential. Because by thinking about the production method in early stages might influence the decision on the possible geometry. Sometimes minor changes in the design geometry, not decreasing its design quality, can significantly reduce the production costs.

These experiences were made in a new production method from B&T that was applied and realized in a prototype project, a concrete form work for a convoluted concrete staircase by Kieferle & Benk architects.

**The geometry**

The three stories high stairs which had to be built within an existing cubical space are designed with an elliptical walking path and an accordingly elliptical, chamfered stairs eye. This geometry generates wound surfaces both on the view from below as well as the stairs eye. As each story has a different height, the form work for each story has to be different.

So to make the design more sculptural and, as the production method was not chosen at that time, the wound surface was transformed to a folding out of triangular and quadrangular flat surfaces, mainly seen at the view from below (figure 1). The intention was to be able to use conventional, even manual production methods with flat board material.

**Comparison of possible production methods**

For the final decision two production methods have been analyzed,
- cleat form work and
- hotwire cutting Claroporon system.

The company B&T has a sound experience both with cleat form work, as it supplied most of the form work for the new Mercedes museum, as well as now with their newly developed coating system, a fiber reinforced coating of styrofoam.

For cleat form work, the surface as well as the cleats are cut out of wooden boards. Depending on the concrete load, the distance of the cleats is about every 30 - 40 cm. Due the irregular geometry of the stairs there are no two equal flat surfaces of the form work. To calculate the necessary work the surface geometry was laid out flat. It showed that for the 62 treads and 4 landings there were about 325 form work plates of triangular and quadrangular shapes necessary. This sums up to more than 1100 different beveled angles of the edges. As a support more than 42 vertical cleats would be necessary, each with different angled and beveled stairs like looking top edges. So even with a 5-axis CNC the effort of programming, milling and mounting each flat surface with its beveled edges showed to be very inefficient.

In the Claroporon coating system the geometry is cut out of styrofoam blocks measuring up to 1 x
1.25 x 5m, either with standard CNC milling technology or with hot wire cutting. The hot wire cutting system used, the PC-CUT 5000, is a 4-axis CNC system with a range of maximum 5 x 1.7 x 5 m (length x height x width). It has two portals, left and right, where the two sides of the hot wire are moved with step engines in the x- and y-direction. A wire tensioning keeps the hot wire under a constant tension also if its length due to diagonal cutting is changed (figure 2).

Depending on the surface shape the CNC milling especially for larger surfaces and deeper z-dimensions e.g. with a standard 20 mm milling cutter can take hours per square meter due to several runs of roughing plus the final finishing. However the shape of the surface is hardly limited with this method.

In contrast to that cutting with the hot wire system limits the surfaces to ruled surfaces due to the straight line of the wire. If geometry allows, it is a very fast and thus affordable method which was chosen for this project. Cutting straight through the styrofoam blocks runs with a speed of 20 - 40 cm per minute without any need for roughing and finishing.

**Production process**

For the production the form work was divided into 24 parts to fit the size of the styrofoam blocks, limitations of transportation, space on site as well as production of the CNC styrofoam hot wire-cutter. A typical partitioning of the form work of one floor is shown in figure 3. The 3D-model was created both in Autocad and 3D-Studio MAX. As the S4CUT software running the hot wire-cutter is unable to create cutting paths out of 3D data, the projection of the cutting path on left and right side either of the styrofoam blocks or the portals was created in AutoCAD and the two contour lines were exported as 2D DXF.

The first tests (figure 4) showed a lot of problems which had to be overcome:
1. Length of wire and cutting speed have to be optimized to create proper chiseled surfaces
2. Hot wire cuts in holes if it stays in one position for a longer time like at one vertex of triangle surface
3. Synchronisation between two portals is essential

So the distance of the portals was adjusted from 5,0 meters to the shorter distance of 3,5 meters allowing to cut all figures. The shorter distance even made steeper angles of the hot wire between left and right portal possible, as the vertical range of the machine is only 1,70 meters.

To avoid burning in of the hot wire, the triangular
surfaces were extended to quadrangular surfaces into the unused parts of the styrofoam blocks so the cutting speed was about the same on both sides of the styrofoam blocks. This created a kind of “rolling” cutting path (figure 5).

Manual synchronization between the vertices on the left (n) and vertices on the right (n’) portal showed to be very difficult especially to the limited capabilities of the software. So when modeling the cutting paths special care was taken to create a minimum of 5° change of angle, so that the software automatically could recognize vertices. For the automatic assignment the number of vertices on the left and right portal has to be exactly the same.

Due to the limited range of the hot wire, the angles are restricted by the production space of 3.5 x 1.70 x 5m, the more complex elements had to be re-positioned. In general 2-3 positions were sufficient, the most complex element needed 5 re-positionings (figure 6).

The final styrofoam forms were then coated with the Claroporron system as shown in the first mockup (figure 7).

Due to the flat, uncurved surfaces the sheet material HPL (high pressure decorative laminates), based on thermosetting resins was used. Depending on the shape of the form work further coatings are available.

**Ruled surfaces in design**

Two aspects of working with complex geometric
forms encourage us to develop particular methods and processes of designing and manipulating these forms: the design process itself, often requiring modifications to the forms as new information is acquired which affects the form (so, for complex designs, parametric modeling tools, or a parametric way of thinking, where ‘design rules’ can be defined and manipulated, is becoming a more standard way of working); and fabrication, balancing the complex form with what is possible and economical.

Ruled surfaces, part of our architectural vocabulary for centuries, are a way to address both aspects, particularly with the development of recent fabrication technology described in this paper. Simply defined, a ruled surface can be generated by a straight line moving continuously in space.

We can use two geometric ‘curves’ to define the paths of each endpoint as it moves through space. If the ‘curves’ are two parallel lines in space, we will get a plane; if the curves are two lines which are not parallel but are skew, we will get a hyperbolic paraboloid (figure 8a).

If the curves are two circles separated by a central axis which is perpendicular to both circles (so the circles lie on two parallel planes, separated by some distance - the length of the axis), moving a line with endpoints on each circle will result in a cylinder. If we rotate or twist one of the circles about the central axis, the result is a hyperboloid (figure 8b). The circles may be different sizes; one curve may even be a point which will give a cone.

More interestingly and complex, if one of the surface-defining curves is a straight line in space, and the other is a helix which wraps around the straight line, we will get a “helicoid” (figure 8c).

The surfaces, and process for generating surfaces, explored in this chapter, which are producible on the foam wire-cutting device described, are generally created by defining curves on parallel planes, or being able to project the resulting forms to two curves on parallel planes (figure 9).

The shapes as well as their arrangements on portal A and B have a basic influence. A simple example, creating an extruded square; numbers at the vertices indicate which parts of the curves on the two faces

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**Figure 8**
a) Hyperbolic paraboloid, b) Hyperboloid, c) Helicoid

**Figure 9**
General setup of plane paths

**Figure 10**
Same shape at A and B

**Figure 11**
Same shape at A and B, different size
correspond to each other, and, as we will see shortly, this can affect the final form (figure 10).

Changing the curve on one face, the volume changes as well (figure 11).

Rotating curves against each other creates twisted surfaces (figure 12).

Depending on the correspondence between points (vertices between portals A and B) the same shapes can create different volumes (figure 13).

Even quite simple contour lines can produce complex shapes (figure 14).

**Student course work with ruled surfaces**

In order to teach students the advantages and limitations of curved surfaces, a hot wire-cutter was recently installed at the FH Wiesbaden and a first 4 hours workshop was held to gain experiences. The course goal was to design a high rise building based on the contour lines on ground and top. They were drawn in Illustrator, then exported as DXF and finally prepared for cutting in the S4CUT software. Whereas...
the general approach was quickly understood by the students, some items were not easy for them to understand:

- shapes have to be closed
- hot wire can only cut straight lines, no cavity in line of wire
- synchronization between vertices of contour lines defines shape (at starting points as well as synchronization between different vertices)

The results (figure 15) are very promising and a first feedback from the students showed, that if they can apply production methods already within the design phase, this will influence the design. However future research is necessary to proof this assumption.

**Conclusion and outlook**

With CNC / digital production shape variations can be produced without a major increase in production costs. However a greater amount of work has to be invested into precise modeling for the production geometry, sometimes even in early design phases.

Whereas for “normal products” drawings are sufficient and all machine programming is made by the manufacturer, now with the increasing complexity in shapes the architect is much deeper involved into the production process. In the stairs project even most of the CNC code was generated by the architect. Though this integrated collaboration between architect and manufacturer in general is very positive, it means a shift of responsibility from the manufacturer to the architect. Who should take over the responsibility if production errors occur, e.g. if the final product does not fit on site? Is it the architect, who programmed the CNC code or the manufacturer owning the machine and producing but not really being able to control the CNC code?

Up to now one of the major drawback is that mostly first a shape is designed and then a production method chosen. Many production methods, their advantages and limitations, are hardly known by architects. So in the future, especially in architectural education, there should be a profound introduction into production methods and their geometric results. It would be best, if the manufacturers
could describe the geometric impact of their production methods as shown in this paper. This could make the production process easier, more appropriate and cost effective. Thus the production method could not be seen as limitation but even at early design stages as inspiration.

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