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Strategies to Design with Curved Creased Surfaces

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Abstract: *This paper shares findings from the project DevA (Developable surfaces in Architecture), a research by design based project developed a collaboration between academic and industry partners. The project aims to investigate the use of curved sheet material in architecture using hybridised 3D modelling and pattern cutting techniques. The project investigates how digital design and fabrication technologies enable the development of new structural concepts through the new means of material specification and detailing at unprecedented levels of precision. The paper presents speculative research project as well as the demonstrator Reef Pattern (Figure 1).*

Keywords: *Complex surface design; CAD, material behavior in design; industrial and interdisciplinary collaboration; practice based research.*

Project background

Architecture is mainly made of planar elements. Sheet materials form the basis for most building elements both as direct planar materials such as façade claddings and interior walls as well as folded materials such as steel profiles or rolled materials such as air vents. The ability to bend and fold sheet material has been exploited mainly in metal based formwork. Where some examples from early ship making and furniture design have developed techniques for bending and laminating wood, it is in the steel industry that huge advances have been made through complex form making.

Figure 1
Reef Pattern: front elevation

Figure 2
Reef Pattern: side elevation of the final installation

Recently bent metal sheeting has found new application in the cladding of complex formed buildings. High profile projects such as Frank O. Gehry's Guggenheim Museum in Bilbao or Ben van Berkel's Mercedes Benz Museum, are characterised by their complex formed external skins. These projects rely on the development of sophisticated techniques by which the overall geometry can be defined through single curvature tiles (Shelden 2002, Kilian 2003).

These projects are defined by a clear hierarchy between skin and substructure. Here, the substructure is an independent construction that carries the skin. Other disciplines, such as the sail-, aeronautic- or ship-industry have invented ways of creating more complex relationships between skin and structure. In construction systems such as the monocoque or the semi-monocoque the skin is structural either independently or in dialogue with a rigid armature. Here, the skin acts as a tensile counterpart to a compressive substructure. Where mono-coque systems are common structural systems in the car and aeronautic industry they remain rare in architectural design (Kolarevic 2003).

The starting point for the DevA research project is an interest in structural skins. The aim is to investigate how developable surfaces and the techniques for unrolling these surfaces can be used to develop structural membranes. Choosing steel as a material allows the project to engage with an architectural scale of investigation as well as material knowledge from the building industry. The project asks: what are the structural behaviour of bent steel sheet and how can it be used in architectural design? What are the appropriate material traditions and how can we learn from other disciplines such as textile flat pattern making? Are these techniques scalable and what happens as be move from compressive to non-compressive materials? And finally, what are the design potentials and embedded expression of bent steel constructions?

More than developable surfaces: Developing an interest in creased surfaces

Developable surfaces are special surface types defined as sections of cone geometries. Their mathematical description makes it possible to unroll the single curved surfaces on to planar materials and as such can be used to develop material specifications for semi-stiff sheet material such as metal, acrylic or fibre based materials (Shelden2002). Where developable surfaces are commonly implemented in the shipping industry they remain rare in architectural construction (Berkel and Bos 2006).

A second interest in the DevA project lies with the creasing of surfaces to improve structural performance. Here, our interest lies with the way in which creases, known as curved folds, can be generated from single planar sheets, without tearing or stretching of the material. Learning from early work by computer scientist David Huffmann (Huffman 1976). as well the works of lamp designer Le Klint (Jakobsen 2008) and artist Ilhan Koman (Agkun 2006) our approach combines structural investigations with formal inquisitiveness.

The third interest lies with the possibilities for material specification and digital fabrication. Where many software programmes have particular functions for unfolding developable surfaces these are often imprecise. In our work we have a dual approach merging mathematical investigations into the description of creased surfaces with more crafts

Figure 3
Developing the crease line, double twisting and clustering of the components

based approaches learnt from textile pattern cutting using an iterative process of prototyping and pattern tracing to refine the final pattern. This dual approach has also enabled us to integrate particular textile based understandings of material manipulation. Here, special interest lies with dart design, the process by which material is subtracted from the flat pattern so as to generate the cone based geometry. Where dart design is simple in an analogue realm, it is highly complex in digital modelling. Our interest is to find ways of incorporating traditional crafts based knowledge into digital specification and fabrication.

DevA research project

DevA aims to engage an architectural scale. Developed in collaboration with the Copenhagen based architectural office MAPT, our ambition has been to develop a temporary shelter in the form of a canopy construction (Figure 2).

A first decision in developing DevA is a negotiation with the scales set by the material thickness, the size of steel sheeting and the bed size of the steel laser cutter. Materials come in finite sizes that are scaled in respect to their tools and manipulation. Our interest in DevA is to use the materials own inherent performance, working with the inherent flexibility of the material. In DevA our approach has been to work with the natural bending curvature of the material rather than shaping it through processes of pressing, rolling or hammering. In this way a core criteria for the project has been to use materials of a thickness as well as size that allows for manual bending. This first focus led us to an understanding of the structure as an aggregated surface made of multiple cells. As a shell construction, DevA is made of multiple components that stiff jointed together so as to find its overall structural performance.

Design process and material investigations

The initial ambition for DevA was to develop the material specifications, or patterns, for the singular cells through the digital unfolding of 3D surfaces. Working in both Rhino3D and CATIA we were able to develop solid models of single curvature surfaces with no crease lines. These primary surfaces were empirically tested in cardboard models (Fig. 3). Using an iterative process of digital and material design refinement this first level of investigation explored how discreet single curvature cone based surfaces can be combined into complex forms that strengthen the overall structural performance. Each time a surface is joined with another the structural performance of the whole is increased.

This early structural investigation led us to explore creasing and double twisting as ways of maximizing structural performance. Our aim was to develop the component out of one single sheet material rather than introducing weld lines. Scoring the cone based geometries allowed to crease the surface creating a folded curvature. The creased surface is defined by the inverted angle of the main surface. In a second range of investigations we investigated the double twisting of the cones. Here, the material is tightened creating a layered structure that we can further strengthen by joining the outer with the inner layer.

Creating a digital three-dimensional model of the twisting double cone with an irregular spiral base and tip line posed a surprisingly hard problem to CAD tools. This as they created none or non sufficient surfaces, which couldn't be unrolled. Although some tools came with quite advanced unroll tools, we had to find out that actually none could deal with spiraling surfaces which overlay in the top view.

Instead we developed an iterative design process testing parametrically defined 2D patterns continually in physical models. The 2D patterns formed the basis of a series of tests in order to achieve an understanding of the interplay of crease, curvature and cut outs. The tests were carried out in flexible cardboard allowing us to score the material to develop the creases. We found that these manually produced physical models provided more efficient information than digital models.

Embracing deformation

Where the introduction of creases in the surfaces improve the tectonic strength it also causes deformations of the surface. According to the amount, nature, curvature and positions of one or multiple creases in relation to the cones center line of the cone is deformed.

This has a mathematical explanation as well as a material consequence:

By intersecting a cone with a plane we get a conic, that in our case will be either a circle or an ellipse. Let us assume for simplicity that it is a circle. This circle traces out a curved folding on our paper, and we want to describe the resulting developable helicoid as a ruled surface[1] , with our folding curve as a directrix. In space the folded line takes the form of a helix, with the height as the variable, and height zero corresponds to the original cone. Since no forces act upon our surface, the dihedral angle _ along the fold is constant. Hence it is possible to determine the angle of the rulings with the tangent to the directrix by the following formula:

$$cot(\alpha) = \frac{\alpha' - \tau}{\sin(a)\kappa} = c\tau$$

where c is a constant and κ,τ is the curvature and torsion respectively of the folding curve in space. Hence, since the torsion τ is proportional to the height of our helix, we see that the rulings form a constant angle, and the case of the cone corresponds to $\alpha = \pi/2$. For the general case of an ellipse, the angle α will not remain constant, but rather vary according to the curvature of the ellipse. But the same procedure works in this case too. When we attempt to add more creases around the boundary, by connecting the different cones for example, the description given above breaks down. Since the fold would attempt to be planar in space it would affect the angles the ruling make with the curve on both sides of it, and hence a global deformation will occur.

In our work we found that digital design tools are not capable of predicting the deformation that appears from the fine interplay of these disturbances. In order to generate an understanding and establish a parametric control over the geometry we pursued a series of test with creases in cones. As simple cones with crease line resulting from the projection of straight lines perpendicular to the cones rotational axis led to creases with almost no deformation to the original conical shape. Any other crease line on the surface results in more severe deformations.

To counter act the deformation we introduced carefully defined cut outs in the pattern that release the material tension in the surface.

Clustering: Cellular logic of assembly

The clustering of the components is structured around two nested layers. In the first layer, three components are joined in a "pod". The pod is structurally integral joining the three components by introducing further convex creases into the surface. These creases allow the components to pack

Figure 4
The hexagonal clustering of Reef Pattern

together tightly assemble together so that they can be bolted together. By lengthening on side of the pattern we furthermore developed a central core, or "column", that is used to strengthen the connection between the components.

At the secondary level the pods are packed together in a hexagonal matrix (Figure 4).

The pods are bolted together using the same system of secondary crease lines. During the testing of the assembly we found that the pods were slightly twisting the overall surface creating further tension. To compensate we reversed the bending of every second pod using the backside of the pattern. In this way the tension is dissipated rather than accumulated each pod slightly twisting against the next.

Reef pattern – a 1:1 prototype

The final demonstrator Reef Pattern is made of 27 components arranged in 9 pods along a hexagonal matrix. The Distortion Festival in Copenhagen served as public venue for making of a 1:1 prototype. Following our established research method (Thomsen, Tamke 2009) a full scale prototype in steel enables physical evidence and insights into the process of making.

Working in close collaboration with a small scale steelwork company the 2D pattern were laser cut in 0.7mm steel sheets. Through material testing we found that thin steel could bend in ways that were comparable to the cardboard models generated in the design process. We developed a stitch like pattern replacing the scoring of the material allowing for a frictionless bending of the steel sheeting (Figure 5).

Reef Pattern was used as a suspended canopy for the festival. The "column" created in the middle of the pods allowed for a connection point to a set of steel wires that were to hold the construction. Although the assembly of 9 pods is structurally integral the general considerations of the festivals audience moving beneath the structure led to secure the construction with a safety net of steel wiring.

Conclusion

Material performance can be introduced in a novel way into design using computational tools and digital fabrication. Yet these tools are to be developed further and underlying processes and mathematics

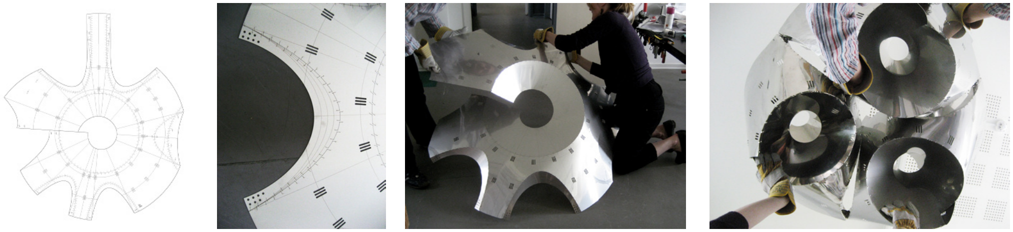

Figure 5
Developing the pattern and material manipulation

have to mature. To better be able to explore the structural potentials of self bracing construction we need tools that can support the complex interplay between design intent, geometric definition and material performance, as well as tooling and making.

In DevA we have found that the modelling of curved creases show great potential for further development The curved surfaces of DevA are an example of how materiality and process challenge the traditional design process and the existing tools. Empirical approaches seem to be inevitable as the mathematical simulation is not available at state. Yet only the production of models and the experience of the materials behaviour allowed the devA project to become real.The interdisciplinary work with mathematicians showed approaches how to find general solutions for the problems. Further work will allow a combination of material properties with computational strategies.

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