

Tool to design masonry double-curved shells

Tom van SWINDEREN*, Jeroen COENDERS^a

*Structural Design Lab, Delft University of Technology
Stevinweg 1, 2628 CN, Delft
tjvanswinderen@gmail.com

^a Arup, Delft University of Technology
Naritaweg 118, 1043 CA Amsterdam, Stevinweg 1, 2628 CN Delft
jeroen.coenders@arup.com

Abstract

This paper introduces a new application to design masonry double-curved shells. It uses the theory of Thrust Network Analysis (TNA) to analyse a parameter based force network model. One goal of the application is to optimise the communication between the architect and engineer and reduce the time needed to create a conceptual design. In order to achieve this, the application is made interactive: after any change made in the force network the analysis and results are updated instantly.

In this paper the four main steps of the application as well as the applied theories will be presented.

Keywords: Conceptual design, masonry shell, Thrust Network Analysis, Catmull Rom splines, Processing, interactive, form finding.

1. Introduction

Design and optimisation of a double-curved shell is often time-consuming because the shapes are complex, the architect is very specific in the desired shape and the engineer has to perform an elaborate analysis.

Block and Ochsendorf have proposed a new theory to analyse shells, the Thrust Network Analysis (TNA) [1]. The authors of this paper propose and have developed an interactive design tool, with which masonry double-curved shells can be rapidly designed and analysed. The new tool uses the TNA theory, which is based on three-dimensional equilibrium of force networks.

After designing and analysing the conceptual shape of the shell, it has to be materialised. Following examples by Eladio Dieste [4] (Figure 1) the tool is able to generate masonry patterns and takes into account manufacturability constraints for this material.

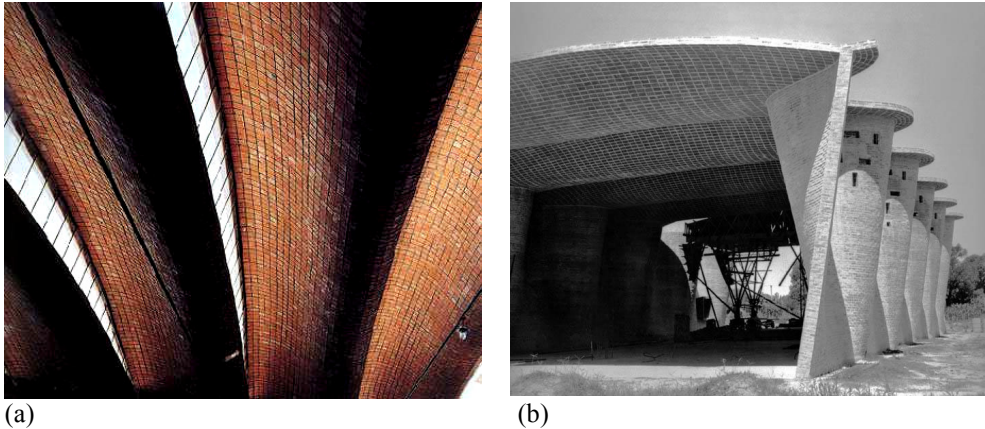


Figure 1: Double curved masonry structures by Eladio Dieste. (a) Roof of 'Julio Herrera & Obes Warehouses', Montevideo, Uruguay and (b) 'Church of Christ the Worker', Atlantida, Uruguay.

2. Theory

Below the theory will be discussed which has been the basis of this tool.

2.1. Thrust Network Analysis

The Thrust Network Analysis uses the method of force polygons to determine forces in networks. Another relevant aspect of this theory is the reciprocal relationship of grids and networks [3]. The analysis is performed to check the force flow. Stability checks, such as buckling behaviour and displacements have not been regarded.

The initial goal was to analyse free form designs. These shapes are often characterized by a combination of tensile and compressive forces. TNA bounds the design of the masonry shells to be compression-only and therefore the application is mainly used to design masonry double-curved shells with positive Gaussian curvature, instead of free forms.

2.1.1. Force polygons

When the sides of the polygon are representations of forces in a network, the resulting closed polygon is regarded as a force polygon. The lengths of the sides represent the magnitude of the corresponding force (Figure 2).

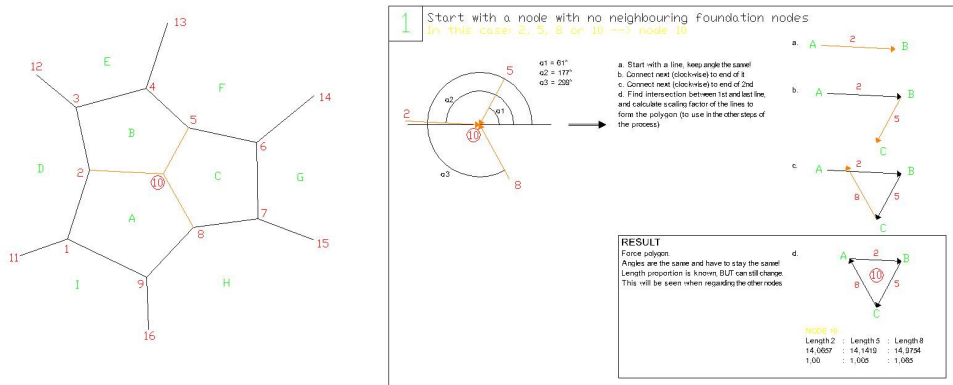


Figure 2: An example of a closed force polygon, which assures equilibrium of forces in node 10.

2.1.2. Reciprocal relationship

The relation between the primal and dual grid can be described as lines connected to a node in the dual grid form a polygon of forces in the primal grid and vice versa. This two-way relation is known as a reciprocal relationship. The mechanical property of reciprocal diagrams is expressed in the following theorem by Maxwell [3]: ‘If forces represented in magnitude by the lines of a figure be made to act between the extremities of the corresponding lines of the reciprocal figure, then the points of the reciprocal figure will all be in equilibrium under the action of these forces.’ (Figure 3).

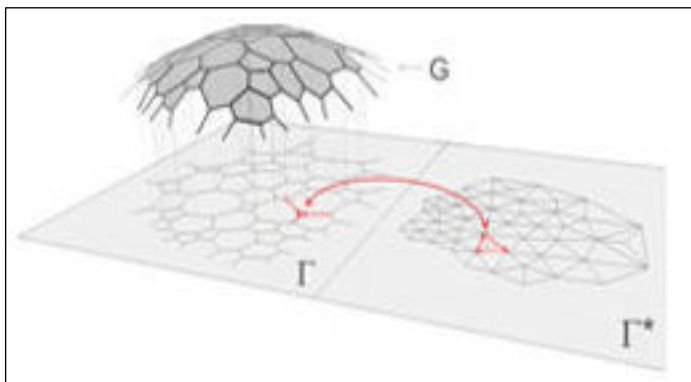


Figure 3: Reciprocal relationship in the Thrust Network Analysis by Block and Ochsendorf [1] (Image courtesy of Philippe Block).

2.2. Catmull Rom splines

This theory is applied to determine the height and angles of each individual brick in the brick pattern. The theory uses the coordinates and tangent of control points to determine the curve between these points [2]. This curve is described by a formula, consisting of the coordinates of the four points and a factor τ :

$$p(s) = \begin{bmatrix} 1 & u & u^2 & u^3 \end{bmatrix} \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\tau & 0 & \tau & 0 \\ 2\tau & \tau - 3 & 3 - 2\tau & -\tau \\ -\tau & 2 - \tau & \tau - 2 & \tau \end{bmatrix} \begin{bmatrix} p_{i-2} \\ p_{i-1} \\ p_i \\ p_{i+1} \end{bmatrix} \quad (1)$$

The curve always passed through these points and the curve is adapted according to the position of each of the four points. (Figure 4).

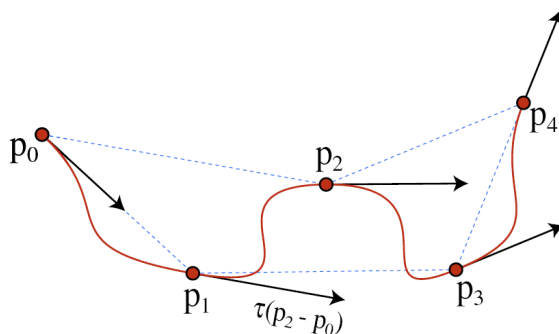


Figure 4: An example of a Catmull Rom spline.

3. The new application

The place of the application in the design process is the overlapping area of the architectural and engineering phase, because the architect and engineer form a team during the phase of finding a conceptual shape (Figure 5). The tool has been created in Processing, an open source programming language and environment [6] & [7].

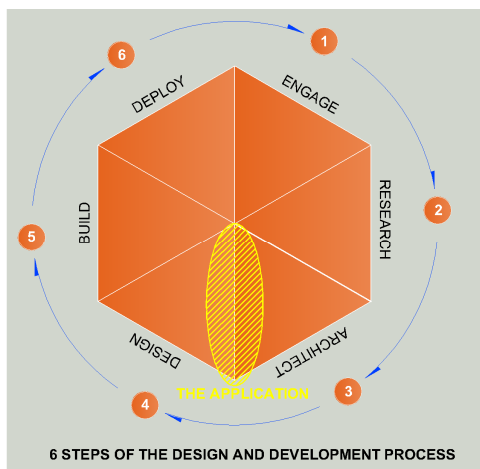


Figure 5: Place of the application in the design process.

3.1. The four steps

The new application is operated using four tabs, located at the top of the user interface. These four tabs represent the four main steps. When these steps are completed, the design of the conceptual shape is finished and can be exported to use it the continuation of the design process.

The four steps are and will be discussed below:

1. Setup of the initial force network model;
2. Analysis and optimisation of the network model;
3. Generate the brick pattern;
4. Export the final model.

3.1.1. Setup of the initial force network model

There are two options to generate a force network model: (a) create a parameter model or (b) import a model.

Create a parameter model

Five parameters are used to generate a start shape and they are all manually adaptable. The model can either be based on a rectangular or spherical grid. The three common parameters are the shell height, base width and base depth.

The two extra parameters for the rectangular grid are the number of rows in X and Y direction, to determine the density of the grid and the amount of compression lines.

For the spherical grid the two extra parameters are the number of bays and rings density of the grid and the amount of compression lines.

Import a model

In the current version the only implemented file format to import is .OBJ. This format only consists of vectors and it is complex to generate the correct line elements which does not make it the ideal candidate for implementation, but because of the ease of implementation this format was chosen. Moreover the surfaces imported as .OBJ files are polygon surfaces, which have no relation with a structural system, force distribution and network.

It is advised to use the imported model only to approximate it with a parameter model and do the analysis with this parameter approximation model.

As a result additional steps have to be taken after importing, before to continue with the analysis and pattern generation.

3.1.2. Analyse, adapt and optimise the force network model

In the application several elements are adaptable to be able to design and optimize the shell shape. The analysis is performed automatically every time the model is adapted. To be able to see every part of the model it is possible to zoom, pan and rotate the 3D model at any time.

The force network is determined by the parameters in tab 1. In addition there are two more options to adapt the model: (a) relocate nodes, by selecting a node and moving it around or adapt its height and (b) add or remove line elements.

The loading on the nodes, which determines the outcome of the analysis, is adaptable in two ways: (a) adapt the loading on one node, by selecting a node and adding or lowering the loading and (b) adapt the loading of all nodes at once, e.g. to define a load case, such as snow.

3.1.3. Create brick pattern

The final conceptual network model can have two types of patterns: (a) a linear pattern or (b) a spherical pattern.

The linear pattern consists of lines of brick, all placed next to each other. They form the centre line for the brick. This spherical pattern consists of elliptical rings, which form the centre line for the brick (Figure 6).

When the base plan is rectangular, it is convenient to use the linear pattern. In the case of an elliptical base plan, a spherical pattern is more convenient. The appearance of the two options differs significantly, even when the design parameters in tab 1 are the same.

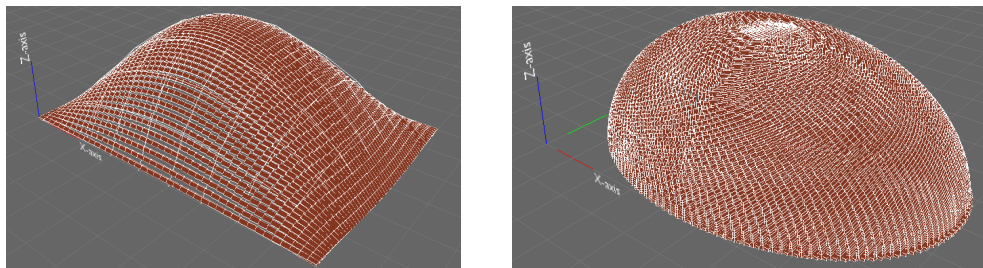


Figure 6: Difference in appearance of a rectangular (left) and an elliptical pattern (right).

Besides the two patterns, described above, there is an option to only see the force network lines filled with bricks. After improved technological developments, regarding for instance pouring liquid concrete in an exact pattern, it might be a good option to show this network as concrete ribs.

3.1.4. Export the final model

Several layers are created when the application is used, so that the results are available for all actors that are active in the continuation of the design process. For the structural engineer the force network model layer is of importance, for the architect the surface models and the contractor might be interested in the masonry pattern layer (Figure 7).

- The force network model (for the structural engineer)
- The surface model, consisting of curves (for the architect)
- The surface model, consisting of polygons (for the architect)
- The brick pattern (for the brick producer and layers)

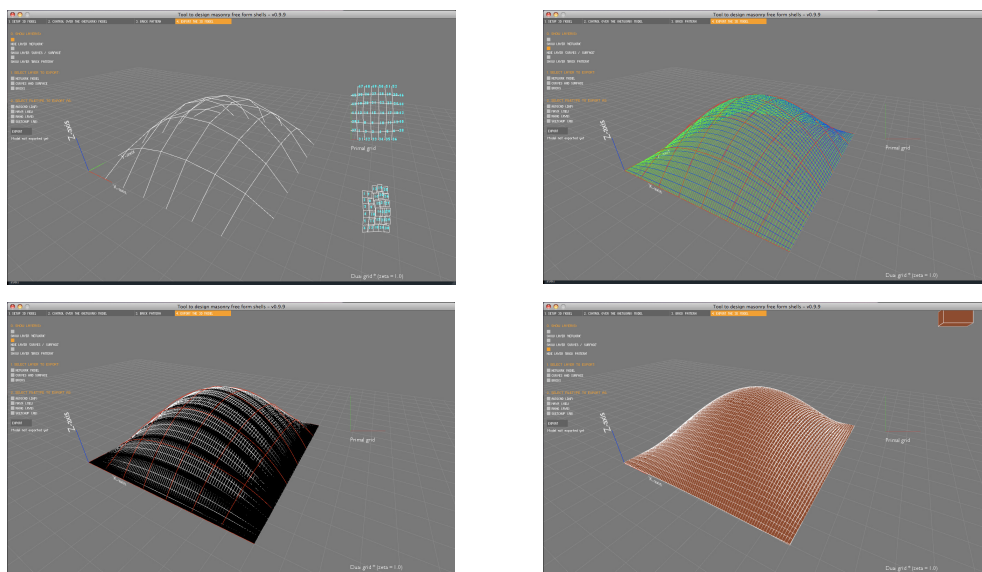


Figure 7: The four layers created by the application. In clockwise order, starting at the left top: the force network, the lines-surface, the brick pattern and the polygon-surface.

Companies use different software programs; Rhinoceros, Maya, 3DMax, AutoCAD and SketchUP are most commonly used. To assure widespread use the tool supports a wide range of export formats, such as:

- .dxf (for AutoCAD and 3DMax)
- .rvb (for Rhinoceros)
- .mel (for Maya)

- .rb (for SketchUP)

3.2. User interface

The interface is user-friendly and has to have a good performance. As mentioned before the main life-line of the user interface is represented by the tabs at the top of the screen (Figure 8).

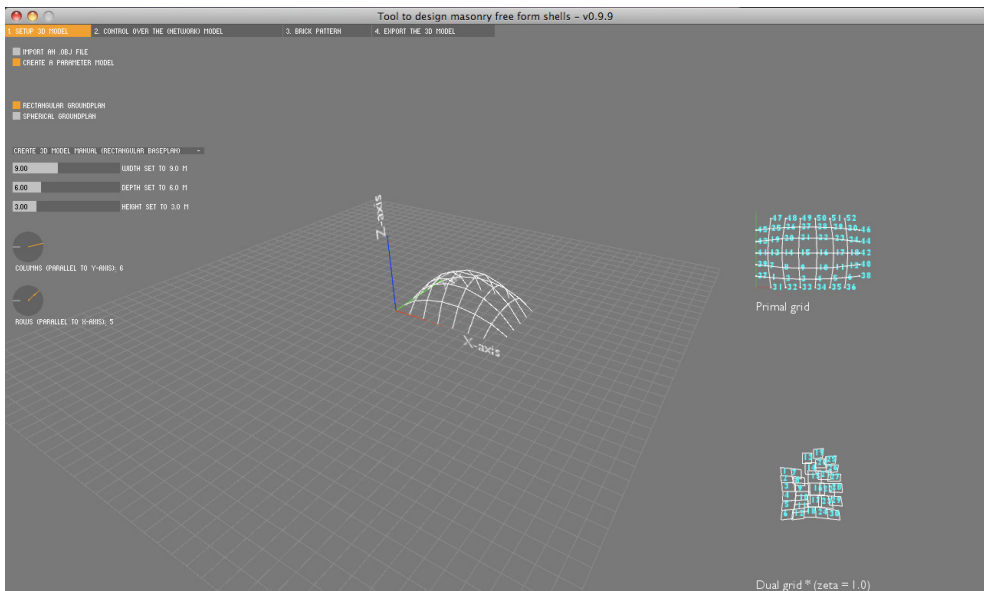


Figure 8: A screenshot of the user interface, with in the top the four tabs which represent the four main steps. In this screenshot tab 1 is selected, dealing with the setup of the initial force network model.

4. Discussion and conclusions

One of the main goals was to create an interactive tool, with which the architect and engineer can rapidly generate a conceptual shape for a masonry shell. Using the theory of Thrust Network Analysis [1] in combination with Catmull Rom splines, has provided the right conditions to design a first prototype for this tool.

The tool performs a force flow analysis of a shell shape. The stability, such as buckling behaviour, and the displacements have not been considered. To improve the results and increase the range of possible shapes to analyse, several recommendations are given:

- Two recommended extensions are the ability to choose several forms of brick and the ability to choose colours for the brick;

- Research into extending and improving the Thrust Network Analysis, so that it can deal with tensile forces as well. With these tensile forces the required reinforcement can be calculated and included in the design. This significantly increases the possible shapes and forms of the shell.
- Research into generating an initial force network model, according to the imported .obj model. As a result the approximation is not necessary anymore and any imported model can be analysed with the application.
- The script code of the application must be looked at by a professional tool developer, so that the performance of the application is improved.

Acknowledgements

The author would like to thank Philippe Block and John Ochsendorf for their approval to use the Thrust Network Analysis [1], of which they are the authors. This theory has been applied in the tool as described in the article for the IASS 2007.

References

- [1] Block, P. and Ochsendorf, J., Thrust Network Analysis: A new methodology for three-dimensional equilibrium. *Journal of the International Association for Shell and Spatial Structures*, 2007; 48: 167-173.
- [2] Catmull, E., and Rom, R., *A class of local interpolating splines*. In Computer Aided Geometric Design, R. E. Barnhill and R. F. Reisenfeld, Eds. Academic Press, New York, 1974, 317–326.
- [3] Cremona, L., *Graphical Statics - Graphical Calculus and Reciprocal Figures in Graphical Statics*, 2007.
- [4] Pedreschi, R., *The Engineer's Contribution to Contemporary Architecture: Eladio Dieste*, 2000.
- [5] Pottman, H. Asperl, A. Hofer, M. & Kilian, A., *Architectural Geometry*, Bentley, 2007.
- [6] Reas, C. and Fry, B., *Processing* - <http://www.processing.org>, accessed September 2008 – May 2009.
- [7] Reas, C. and Fry, B., *Processing - A programming handbook for visual designers and artists*, 2007.