A MINIMAL TENSION CANOPY

Through investigations of self-organised systems

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Abstract. The dynamics of a physics-based algorithm which acquires its complex organization through a number of localised interactions applied over a prescribed network can be described as a self-organised system. This in turn has the capacity to define explicit form and space based upon behavioural computational processes with an embedded structural logic. This paper discusses the way in which physics based algorithms can be used to inform the organisation of a compressional structure in a case study. Its structure is based on Hooke’s law of elasticity; which establishes a three dimensional catenary logic through a number of localised interactions applied over an entire network. This is applied to a project with specific constraints to site, boundary conditions and maximising solar gain whilst maintaining structural rigidity. The methodological approach describes the design to assembly process in which the project has been developed. This includes the applied generative design tools in order to establish the self-organised logic, the form finding process, the techniques of design documentation, the fabrication process and the logistics of construction and assembly.

Keywords. Digital fabrication and construction; generative; parametric; simulation.
1. Introduction

Self-organised systems can be described as a dynamic and adaptive process through which systems achieve and maintain structure without external control (Hensel et al., 2006). These systems allow for a computational exploration of a high level of structural performance, and can then be intrinsically linked to the material system of which it will ultimately be fabricated. Albeit analogue, Frei Otto’s pioneering work within the field of minimal surfaces and lightweight high tensile membranes went far beyond traditional methods of calculating structural stresses. His work includes clear examples of self-regulating building elements developed through the specific material organization of their interrelated parts. This technical approach to understanding natural systems makes use of the physical laws which were discovered in order to develop new strategies for design (Gruber, 2008).

A process of form finding is established through computational methods which are not bound by the composition of subjective criteria, but instead a product of qualified feedback through parametric and multi criteria controls. These investigations lead to new and unbiased understandings of architectural space and geometry which permit a dynamic and adaptive interchange between concept, organization, structure, materiality and its resulting space.

Algorithmic design through the use of software environments such as McNeel’s algorithmic editor Grasshopper and its custom Visual Basic scripting component enables the development of rule sets. Different criteria can be played out using timers that simulate the generative process of self-organisation. Thus, a logical framework emerges during the schematic stage of design, which may be adjusted and repositioned as the intrinsic part of a generative design process. Focus on such an analytical methodology seeks not only to document pre-existing design nodal types or ancestral trees, but also provides an opportunity to investigate diffuse typologies of hybrid process & multi-material performance through a recombination of scripts and algorithms.

Exploration of design via scripting and making techniques seeks to identify a universal language of code assembly and accessing digital technology as part of everyday practice (Burry, 2011). Rather than the serial progression of macro code which executes one line after another, scripting language introduces loops, conditional statements and other forms of checking to control the flow of construction in the development process.

Within the framework of the case study presented here the scripted environment allows for a number of factors to be considered which have explicit relationships between each other. The project has been developed using a particle system which sets out the criteria for form finding, the programmatic influences
of the proposal, the constraints of the site and the restrictions of the material applied. The optimization between each of these elements results in an explicit outcome derived from a logical framework of inputs.

2. Case Study Minimal Tension Canopy

The use of a physics based algorithm for developing a self-organised structural roof canopy is discussed in the following via a design proposal for a 3rd floor constrained apartment terrace located in Sydney’s CBD. The site is defined by a number of constraints: it is approximately 10m x 5m and is located to the rear of the building. The building has a total of 34 storeys and the terrace receives the brunt of debris which the neighbours above throw from their balconies. The terrace contains two large skylights which filter light to the communal gym area below which cannot be obstructed. Limited penetrations can be made on site particularly to the tiled flooring in order to maintain a waterproof seal to the levels below. In addition site access is limited to a 2.1m x 2.1m lift restricting the size of structural elements that can be delivered to site. Overall the terrace was seen as unsafe for the client and his family to use and therefore the brief called for a lightweight canopy that would filter debris into safe collectable containers, maintain solar amenity for the level below and create a safe outdoor space for entertainment (Figure 1).

The design challenge was to build a structure using a number of serialised components which could be assembled easily and efficiently on site. The structure needed to be self-supporting and allow for breaks or holes within the network in order to maintain the solar amenity to the level below. The design intent was to develop a canopy which was an informed relaxation membrane and one which did not exert any lateral loadings to the building. Precedents for this system came in the form of Otto’s Mannheim grid shell structure and in particular the British Museum Great Court developed by Chris Williams (2004).

![Figure 1. Diagram describing the constraints of the site.](image)
3. Catenary Logic

The logic of a catenary curve suited the design intent in which a self-regulated arch could be produced supporting its own weight at its ends. Hooke’s law of elasticity provides an approximation stating that the extension of the spring is directly proportional with the load applied to it. This could be applied to the catenary curve allowing varying degrees of elasticity to be exerted depending on its positioning and forces applied.

The catenary curve is a one dimensional cable network whereby a line or curve is split into a series of straight segments, with each segment acting as a spring member. In this case a number of parameters can be controlled which includes spring, damping and gravity effect on each node within the network. This exact organisation forms the building block for a two dimensional structure in which each node in the structure has effect on neighbouring nodes with respect to its topological order. In addition, further relationships between nodes such as diagonal referencing can be introduced to attend shear force moments. With the introduction of gravitational force applied to each node, a catenary surface may be developed. Creating a customised surface with breaks and edge boundaries additional characteristics need to be added. Within the sheet typology loops are created and the diagonal shear springs pull to specific nodes on each loop according to their proximity. In addition, the perimeter of the loops and overall surface are constrained in order for the surface to begin organizing itself around the given constraints (Figure 2).

![Catenary chain and resulting diagrams describing the catenary network logic.](image)

4. Structure

This technique provided a clear framework in which a generic canopy structure could be organised around a number of varying constraints. The application of the
algorithm to the specifics of this particular site could then be mapped which included the non-orthogonal site boundary, the two skylights situated in the middle of the space and a low height plane dictated by the strata lot. Once the Grasshopper definition was executed, the catenary network organized itself around its parameter constraints and settled into a self-organised and self-supporting structure (Figure 3).

Once the overall formal arrangement of the network found it’s equilibrium a number of modifications were applied in order to verify the fall and angle of the surface always directed towards the skylights so to prevent debris and water collecting on flat planes. The next step was the application of a material logic that could be fabricated in an efficient manner and at a reasonable cost. The panelisation of the surface could be achieved in a number of ways but due to the restrictions of using a 3 axis CNC router and laser cutter the final components needed to be fabricated from a flat sheet.

Dividing a surface in its U and V directions so square panels are generated works for a single directional curvature. As soon as this is curved in a secondary direction the result is a splitting or fracturing of the edges. This is still achievable if the resulting structure can adopt the overlaps in its design but in this particular case a sealed and water proofed contact edge was necessary. By dividing the panels into triangles allowed for multi directional curvature of the surfaces without the splitting of the edges (Figure 4). The resulting structure was a triangular panelised surface which radiates in a polar array from each skylight.

The triangular component arrangement solves panelling a doubly curved surface, but does not resolve the structural integrity of the canopy which requires thickness for rigidity. A minimal depth of 50mm along the structural radial lines and a 50mm width to each panel was required by the engineer. The approach,
within the constraints of the fabrication tools, led to cutting the triangular panels with a 50mm tab on each side which are folded to the correct angle using a brake press thus producing an L section profile. When connected, the triangular elements form a series of radial beams maintaining structural efficiency throughout the canopy. Earlier models allowed for a variable internal cut out for the triangular components which then control the amount of solar gain throughout the structure. This would work for a larger scaled structure which was orientated differently, however the project site is constantly overshadowed so the resulting apertures for each component had to be maximised throughout the canopy (Figure 5).

5. Documentation for Fabrication

A stick model structure was tested in the finite element analysis program Strand 7 which highlighted a number of weak points and bending moments (Figure 6). The model was optimised so that no length of any triangular component was greater than 1.5m. Each component was fabricated using 6mm aluminium sheet. Due to the constraints of the brake press each component had to be cut back 50mm from its corner point in order for the folded tabs to fit into the break press and not affect each other. The result of this was a series of gaps at each nodal point of the structure which left the radial structural paths weak. Additional stiffener plates were sandwiched between these gaps to maintain the structural rigidity of the canopy.
Mapping all of this information as a parametric construct was essential in maintaining precision throughout the design and documentation phase. A three dimensional scan was taken of the site so millimetre tolerances could be maintained.

As the design developed information from the fabricator on the radial bending of the aluminium panels changed. An internal radius of 12mm was required for bending the tabs in the break press. Additionally these tabs needed to maintain their 50mm depth so that the depth settings on the break press did not have to be adjusted for each panel. This needs to be described mathematically in the parametric model which can then be updated on the fly if any of these parameters change at a later stage.

The Grasshopper definition was divided into a series of VB scripted components in order to work on the front end of the definition once key elements had been resolved. This reduced refresh time of the script allowing for parts to update quickly. Information within the model could then be broken down into segments and manipulated dynamically. This would be assemblies of part, layers, groups and geometry.

These adjustable parameters were applied to the depth of the tabs, size of bolt and rivet holes between components and connections to the perimeters walls. The number of connection holes between elements was controlled via the length of each part. If a length was less than 300mm it was allocated 2 holes. If it was more than 300mm it was allocated pairs of holes which would match its neighbours.

The three dimensional geometry was then unfolded in order to produce flat nested templates for fabrication. Each edge of each component was mapped according to its position in the model and single line fonts were applied to each edge with a bend angle (Figure 7). These were mapped as two halves, the left and the right and then sequentially from the centre of the skylights outward. This topological mapping of each components position equated to a hierarchy of parts which when assembled on site were easily read, organised and assembled.
The fabrication of this project is relatively straightforward. Cutting files were supplied for both the aluminium and steel components with all parts nested with layers with lines for cutting, scoring and bending. All the aluminium components were laser cut and the steel CNC routered. The aluminium components tabs were then folded on the brake press at the correct angle for each tab (Figure 8). Steel parts were then galvanised and then all components powder coated white.

6. Assembly Logistics

Once delivered to site all of the components were organised according to their numbers and radial neighbours. A drawing indicated the order of the assembly
sequence and a 1:10 physical model described each labelled component with the order of radial families of parts (Figure 9).

Firstly in the assembly sequence the gutter collars were positioned around the skylights. From there the central components which affixed to the gutters were positioned, bolted and pop riveted. From here these two sections were joined or bridged and once in position strips of elements were built in a radial sequence in an order which maintained structural stability. All of the components where finally tightened forming the final fitting of the structure (Figure 10).
There were a number of issues that came to light during the construction process. The appointed engineer allowed for a 1mm tolerance around each pop rivet and bolt hole. This was the only tolerance within the entire structure. The result of this was as the structure grew in the number of parts connected we would have to loosen and leave components together which was often tough work and quite time consuming. However the result of this was an extremely ridged structure. The second issue was sealing of the polycarbonate panels. Attaching each panel was extremely quick using double sided glazing tape but the application of silicon between each panel is a job and cost which we did not anticipate taking so long. This is a result of the distance between each panel varying greatly. Certain panels are up to 20mm apart which means that applying the silicon needs a lubricated backing strip which can be removed once the silicon is dry. Often the silicon will sag as it dries and creates perforations which then need a reapplication of silicon.

7. Conclusion

The work explores the potential of using physics based algorithms to describe and produce structural solutions for a constrained site which is specific to its conditions and characteristics. Although this paper describes a particular project, the framework of the system that has been scripted and the process of documentation and fabrication enable this project to become an adaptive typology, which can be developed for another program and location. The powerful nature of the parametric tools implemented throughout the project has allowed for live manipulation and adaption from design phase to documentation without loss of information or the need to laboriously redraw and reorganise information. This parametric process has resulted in a smooth sequence from design to construction through the use of customizable tools and standard fabrication processes. The case study finds a medium whereby these tools are used in a pragmatic manner to not only understand a form driven by its site constraints but though integrating constraints of structure and material logic.

References