



SUTD Library Extension

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1 Introduction

Compelling architectural forms frequently stray far from the rectilinear. Numeric form finding algorithms, modelling programs specifically designed for irregular architectural curved surfaces and advances in structural analysis and design programs provide ready means for structural engineers to partner with architects in designing these ambitious forms. A typical program stack might include an implementation of Dynamic Relaxation (numeric form finding), Grasshopper (parametric design), Python (scripting), and finite element analysis programs with programming interfaces such as Oasys GSA. While perhaps not standard practice, this design workflow is a relatively mature design process capable of keeping pace with rapid design iterations and of accurately modelling innovative forms, enabling creative experimentation with highly curvaceous structures.

However, such designs must eventually be built, which can be an expensive and complex proposition. An exciting new possibility is the increasingly prefabricated and automated manufacturing of building components. The implications on design of Computer Numerical Control (CNC) fabrication are significant, exemplified by a library extension and event space constructed at Singapore University of Technology and Design (SUTD).



Fig 1 SUTD Library Extension

The origin of this project was as a student design competition, in which an intriguing doubly curved surface was conceived to span a lecture area and open to a patio reception area, with an entrance hall connecting to the existing library. Placed in an unused corner of the university next to the car park, the concept was a compelling addition to the campus and the design was further developed in collaboration with SUTD City Form Lab (architect), Arup (engineer) and Arina Hogan (contractor). In 2014 the project won a Singapore President's Design of the Year award.

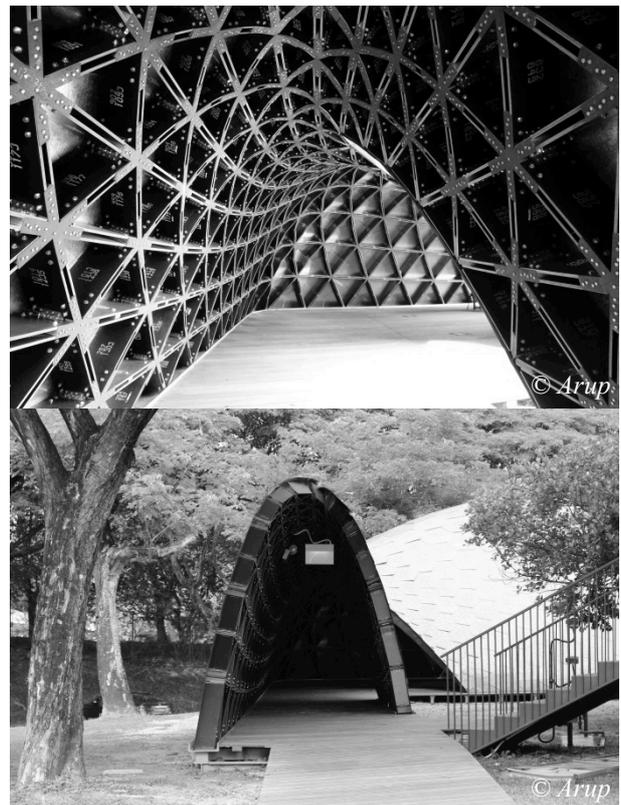




Fig 2 SUTD Library Extension

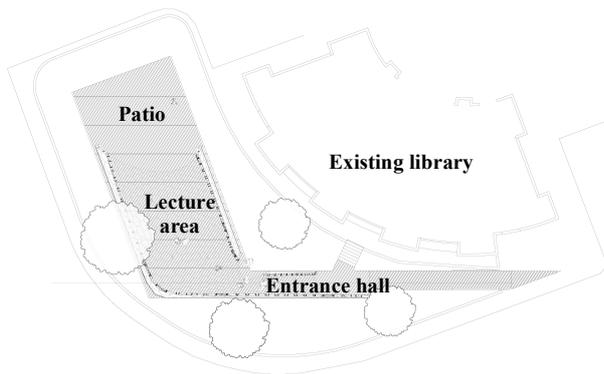


Fig 3 Site Plan

2 Design

2.1 Form finding

While this particular project employed a freeform shape, other strategies exist to define the form of lattice shell forms. However, it is frequently the case where project requirements and the stage at which the structural engineer is engaged dictate one or another method being necessary. A general overview is listed below in descending order from the structural ideal to the architectural ideal.

Funicular Shape – Continuous Members

The traditional method of forming a gridshell, using flexible timber lathes laid in a 2D grid on the ground before being pushed from the boundaries into a 3D form. This archetype ensures a highly efficient structural form relying on membrane action, but is less easy to adapt to arbitrary architectural geometries. The necessary out-of-plane flexibility requires careful consideration of the connections if brittle cladding such as glass is to be used.

Hanging chain models of the Frei Otto era were originally used to analyse the final shape, but have been superseded by numeric form finding algorithms such as Dynamic Relaxation and Particle-Spring systems.

Examples include Multihalle Mannheim and Chiddingstone Castle Orangery

Funicular Shape – Discrete Members

Members are fabricated as discrete sections and moment connections provided at the nodes. Construction requires scaffolding and for the lattice to be constructed in the near-final position. Numeric form finding is used to achieve a funicular geometry under uniform distributed loading, and additional constraints such as approximately planar facets can be set.

The efficient funicular structural geometry is retained, but irregular shapes are more easily accommodated. To achieve these benefits it is important that engineer controls the form finding, ensuring that proper member stiffness, boundary conditions and loads are used.

An example is the Dutch Maritime Museum.

Rational Shape

Form is specified analytically, varying from simple shapes such as the cylinder, sphere or torus, to more complex shapes derived from differential geometry. The grid is either created by subdivision or by relaxing a mesh on the surface using numeric form finding. An alternative strategy is to use translational surfaces, defining the shape and grid simultaneously.

Analytically defined shapes are advantageous in that desirable attributes such as rationalized curvatures, symmetry and planar quadrilateral facets are easily achievable. This often results in a more buildable design when using traditional construction methods, while balancing structural efficiency and architectural freedom.

Examples include Gardens by the Bay, British Museum Great Court Roof.

Freeform Shape

Freeform general refers to continuous curved surfaces, usually convex and generally generated using a Non-Uniform Rational B-Splines (NURBS) modelling program such as Rhino. Especially in cases where an initial architectural concept exhibits poor structural properties, an iterative process is necessary to balance the structural efficiency, buildability (ie planar facets and symmetry) and aesthetics. Close architect-engineer-builder collaboration and rapid design iterations are essential.

An example is the SUTD Library Extension roof.

For the SUTD Library Extension, an initial NURBS surface was created in Rhino, and tweaked to ensure sufficient shell and arching action could be engaged over the main event space and entrance hall, respectively. Openings were framed with stiff steel sections and a triangulated grid employed for stability.

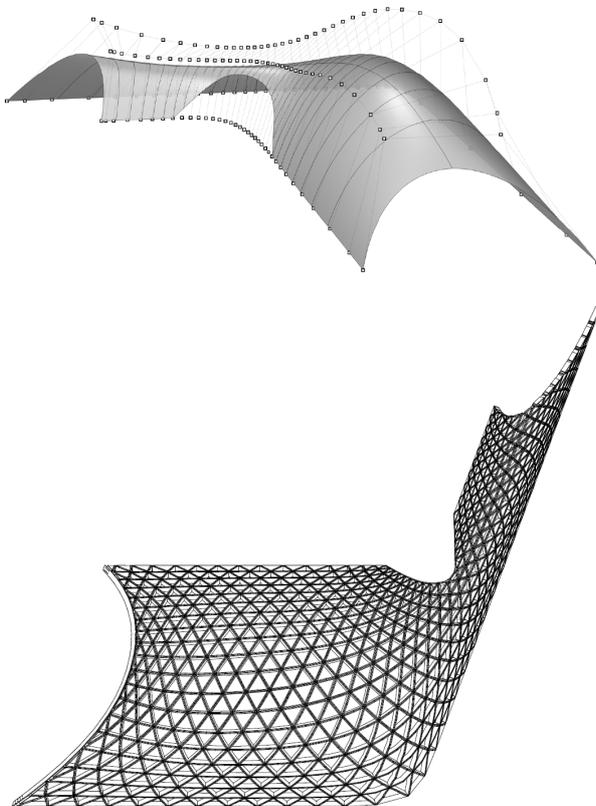


Fig 4 Roof control surface and grid

Further reading of numeric form finding implementations (Adriaenssens, et al 2014), the translational surface strategy (Glymph, et al 2004) can be found in the references.

2.2 Materials and Topology

For the SUTD Library Extension, *high tech fabrication – simple construction* was the mantra. The design was crafted to ease construction on site, while taking advantage of the resources locally available: cheap marine grade plywood and computer controlled fabrication facilities.

With plywood as the primary material, it was determined that offset pairs of slender plates would serve a good axial members and that global out-of-plane flexural stiffness could be provided by member in-plane bending action. The concept of preassembled hexagonal units was established, each composed of individual triangular assemblies bolted together with erection shear tabs. Moment continuity was to be provided through the cladding and additional tension straps fixed at a later stage.

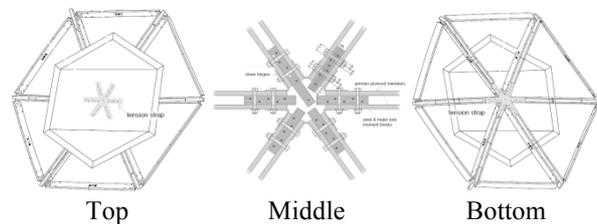


Fig 5 Preassembled components

This assembly is slightly unusual, but effective for the specific constraints of this project. As discussed later in Section 3, detailed design, and particularly modelling for fabrication, of this complex assembly was easily achieved with the parametric, scripted workflow. Generation of the form, member orientations and full connection details was divided into a logical series of simple geometrical operations starting with the local element dimensions and orientations.

2.3 Connections

Connections are one of the most important aspects of gridshell design. Full axial member capacities must be transmitted, a

relatively large number of connections are required, and cumulative construction tolerances are significant. Rationalization and simplification is therefore highly desirable.

The SUTD Library Extension connection detail transfers load to a central block bolted between each pair of plywood members. The galvanized steel cladding and a strap on the inside face was then screwed into the blocks, acting as axial members with short effective lengths and providing moment transfer through push-pull action.

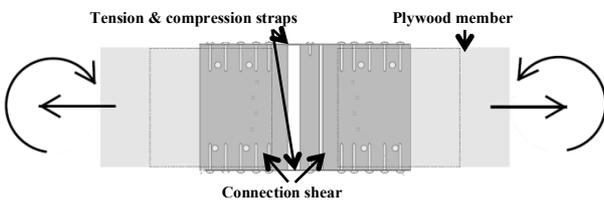


Fig 6 Connection moment transfer

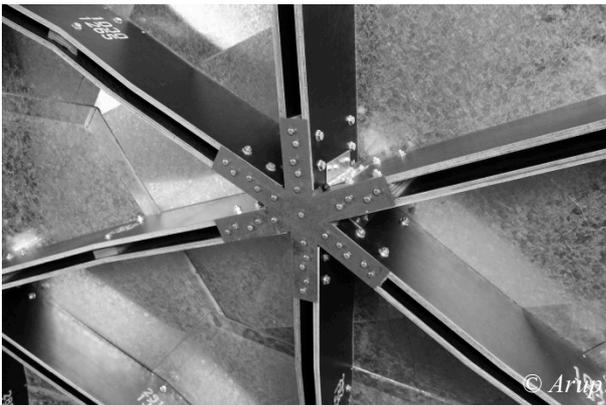


Fig 7 Connection detail

3 Construction

3.1 Design Documentation

A key lesson from this project is the potential of fully utilizing the information built into the 3D design models. When models are built with care, so that centerlines node out and the final details fit together, the design model can be used directly in fabrication and construction.

This refers to the popular concept of Building Information Modelling (BIM). In the case of the SUTD project, Rhino and a few Python scripts proved sufficient to embed the design knowledge into the model and make use of

this dataset throughout multiple design stages, fabrication and construction.

All geometry was defined parametrically in the master model, generated from simple Python scripts. Other scripts generated the structural model, defined bolt hole locations, laid out efficient cutting patterns for the plywood members, and generated the construction drawing.

An interesting point is that as the design model was used to directly generate the fabrication files, and virtually all relevant information was able to be directly embedded. This meant no human error, no need for 2D drawings and no complex tender packages for the contractor to decipher.

The 3D model was provided to the contractor to design the scaffolding and convey the intended form, but only a single “map” was provided as the construction drawing. The precision fabrication effectively eliminated cumulative construction tolerance issues.

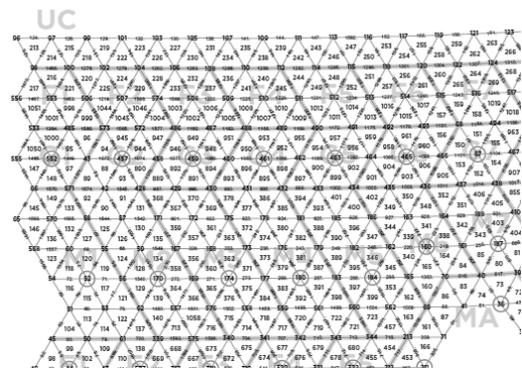


Fig 8 Part of the construction drawing “map”

3.2 Fabrication

Full advantage was taken of CNC fabrication, with all components predrilled and cut to a precision only achievable by computer-controlled fabrication. Even the steel cladding panels were prebent and predrilled to the precise geometry specified in the design model.

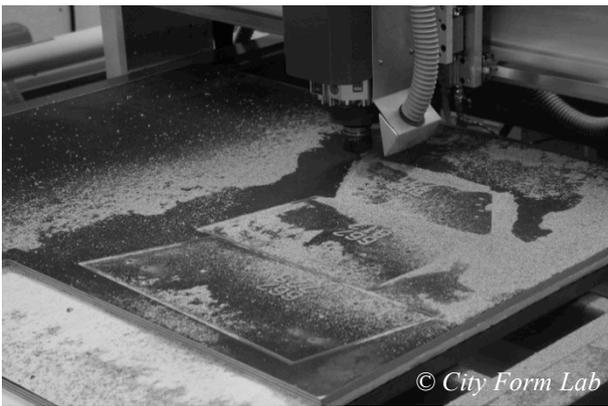


Fig 9 Fabrication

The implications of generating fabrication drawings for the CNC machine directly from the design model go beyond reducing human error on site. As cutting layouts were directly produced using scripts, efficient algorithms could be used to pack member outlines onto the minimum number of plywood sheets, minimizing waste.

Conversely, so that cheaper CNC machines could be used, the geometry had to be rationalized so that all members could be fabricated using orthogonal cuts. Far greater modelling detail was required down to the smallest bolt hole and there was little scope for changes after the fabrication files had been issued.

Generally, the vastly improved accuracy on site and increased confidence that the design is built exactly as specified outweigh the additional modelling effort involved.

3.3 Construction on Site

The contractor's response to the design was generally positive within the context of the inherent complexity of gridshell structures. Construction tolerances were impressive; the predrilled holes meant that any errors were immediately implicitly corrected as adjacent members were bolted together and the last few pieces fit without issue.

Given the unusual form, the final built structure was subjected to load testing by Singapore Construction Authority's request. This was conducted by comparing suspended

point loads to the predicted deflections, achieving close correspondence. The numeric design, engineering and fabrication process thus not only delivered high construction tolerances and ease of on-site assembly, but also closely matched the predicted structural behaviour of the shell.



Fig 10 Construction on Site

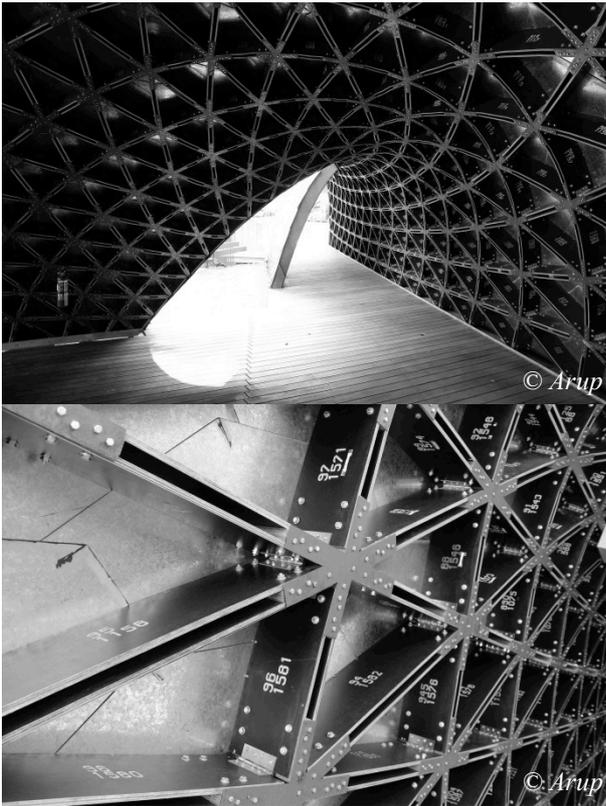


Fig 11 As Built

References

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James Glymph, Dennis Shelden, Cristiano Ceccato, Judith Mussel, Hans Schober : A Parametric Strategy for Freeform Glass Structures Using Quadrilateral Planar Facets, Automation in Construction, Vol.13, Issue 2, pp.187-202, March 2004.