

## A SYSTEM FOR COLLABORATIVE DESIGN ON TIMBER GRIDSHELLS

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**Abstract.** The bent timber laths of the *Sound Bites* gridshell create two types of performance space over an area of almost 100 m<sup>2</sup>. Such post-formed gridshells are a well-established design solution for creating curved forms from linear elements. Extending principles developed since the 1970s, contemporary digital tools have been utilised to drive a renewed interest in them, primarily through so-called form-finding techniques which connect digital and material models through a simulation of shape under bending loads (Nettlebladt, 2013) and the definition of efficient structural geometry acting under compression loads only (Hernandez et. al., 2012). This paper describes the workflow conceived and implemented for the *Sound Bites* structure. A central challenge of the research was for such a workflow to allow for the principles of gridshell design to be engaged in parallel to other tight constraints and design drivers. As such it needed to facilitate close collaboration between architectural, engineering and fabrication experts. This workflow was tested in the design and realisation of the full-scale structure within a six-week period. The gridshell design was developed through the manipulation of the shape of two edge profiles and the shell form spanning between these. Architectural and fabrication constraints were met and the workflow allowed for a sufficient level of structural analysis to be fed back to inform the design.

**Keywords.** Digital Workflow; Collaborative Design; Digital Form-finding; Digital Fabrication.

## 1. Introduction

This paper reports on the workflow conceived and implemented for the design and fabrication of a temporary structure, the *Sound Bites* shell. This installation was commissioned for an exhibition of sound art and provided performance spaces and infrastructure inside an existing gallery.

A post-formed timber gridshell structure was proposed as an appropriate solution for the project. Such gridshells have been identified as having exceptional design qualities and are considered cost-effective through ease of assembly and efficient material use (Otto, 1974).

Following project commissioning, a design team of experts in architectural and structural design was brought together with timber experts to lead the project, supported by a class of masters level students. This group was given six weeks to design, fabricate and assemble the structure in time for the exhibition. A workflow was conceived to allow for aspects of the design to be developed in parallel and subsequently brought together for collaboration on a final proposal.

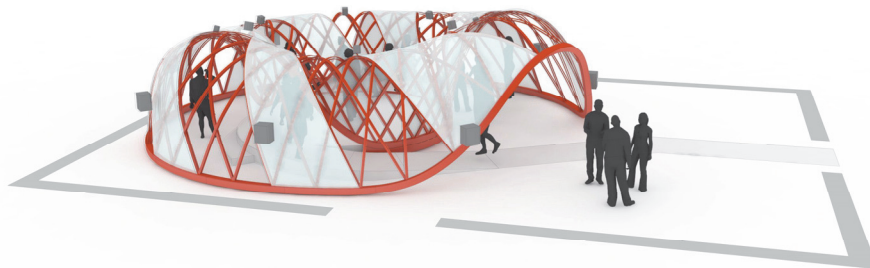


Figure 1. A computer generated image of the *Sound Bites* structure.

## 2. Background

### 2.1. PROJECT BRIEF

The *Sound Bites City* exhibition was the inaugural presentation of a major collective of sound art works. The brief for the design of an installation called for an architectural proposal of approximately 100m<sup>2</sup> that would provide two spaces for audiences: (1) a primary performance space in which groups could gather for a piece to be played through a 24-channel audio system and; (2) a 'promenade' space through which an audience could move between individual listening stations and displays. A torus-like arrangement

was proposed as a spatial device, providing a central, 'external' performance space and other program elements enclosed by a continuous form around this.

The gallery which hosted the exhibition was comprised of two spaces with the major installation proposed for the larger of the two, approximately 14m x 11m in size. Within this, a number of architectural and spatial constraints needed to be met. It was required that existing walls and floors be left without any damage, essentially requiring a structure that was fixed other than with temporary adhesive. Suspended lighting tracks located at just higher than four metres above floor level provided a limitation on overall height and during installation. Furthermore, a series of access ways needed to be maintained for the duration of the exhibition.

The architectural installation was also to provide a support structure for the audio speakers that defined the performance space. Through discussion with the exhibition curators a preferred speaker layout was identified. This was designed using radial grids to set out speakers equidistant from the centre of the performance space. They were arranged at three heights, with large speakers and subwoofers concealed under a raised central platform. This scheme was utilised to help drive the spatial arrangement of the architecture, with speaker locations defined but given tolerances for movement which would not diminish the spatial quality of the sound and art performance.

## 2.2. POST-FORMED GRIDSHELLS

A post-formed timber gridshell was identified by project researchers as offering a solution which is light-weight and rapidly assembled, as well as holding significant research interest. As one of the first instances of such principles, the term gridshell was defined by Frei Otto (1974) as a grid of timber laths that is double curved over its extended area and described by bending and twisting these timber members and adjusting angles between elements at intersection points. In order to fabricate and assemble such a structure, a lattice is built with strips that are of developable geometry. This allows for elements to be laid out as a flat grid and then pushed into a final shape.

Timber gridshell structures are elastic, premised on the fact that wood is anisotropic and open to elastic deformation. Further, wood has relatively low torsional stiffness which allows the design of double curved structures and the relatively easy connection of straight elements (Harris, et al, 2004). In a gridshell arrangement, all members find an equilibrium state and the overall erected frame becomes self-supporting and capable to carry a minimum of external loads.

There exist a number of permanent structures which provide examples of such post-formed gridshells. These include the Multihalle of the Garden Exposition in Mannheim (Germany, 1975), the Japan Pavilion for the Universal Exposition in Hannover (Germany, 2000), the Weald and Downland Museum in West Sussex (United Kingdom, 2002), the Savill Garden Building in Windsor (United Kingdom, 2006). More recently, a number of temporary pavilion structures have used the same principles, exemplified by the work of Sergio Pone at Università degli studi di Napoli or the gridshell tectonic investigations by Cabrinha (2008).

This project sought to extend these precedents in two related aspects. Typically, the shapes of gridshells are symmetrical around at least one axis. This project sought the design of a form without any axes of symmetry. Secondly, and to help achieve this, the workflow of the project sought to provide real-time structural analysis within the design workflow, in order to enhance the designers' understanding of structural behaviour.

### 3. Design Concept and Collaborative Approach

For the *Sound Bites* project, the limited space of the gallery made difficult a conventional approach of a flat grid which is pushed up in its final shape. A variation was identified in which two edge beams would be built first and laths subsequently installed to span between these. Both edge beams were continuous loops, creating a torus-like spatial arrangement. A similar arrangement has been used by Cabrinha, Shook and Kudless in the SmartGeometry workshop 2012, which utilise minimal surfaces between two edge curves as a reference surface for the design. These result in a layout of laths in an irregular spacing. As has been discussed (Hernández et. al., 2012), this reduces the curvature of each lath both locally and globally.

Departing from precedents, the design ambition here was that both the edge profiles and spanning elements would be able to take a range of free form and asymmetrical geometries. The design of these shapes was the focus of a collaborative research process which sought to explore potentials for trade-offs between architectural form-making and the form-finding techniques associated with gridshells.

Trade-offs are common in gridshells and have been documented on projects such as the Great Court Roof of the British Museum (Williams, 2001). Specifically, the *Sound Bites* project required trade-offs between three key aspects of the design:

- **Architectural form**, providing for spatial requirements including sufficient height for inhabitation, requirements of the building code and access within the gallery. As well, a desirable aesthetic outcome was sought.

- **Structural performance**, providing a form which performs efficiently through acting as a shell, a minimisation of local loading as well as the reductions of all deflections to be within small tolerances.
- **Fabrication constraints**, providing for the bending of timber members without failure, the utilisation of members within available sizes and the minimisation of difficult to assemble components.

Recent research focusses on how best trade-offs could be achieved by utilising parametric design and ‘lightweight’ analysis tools which provide the right level of resolution of the data to be analysed and communication of results (Fischer, 2012). The inclusion of structural analysis through such lightweight tools is novel for gridshell design. The approach here proposed simple structural analysis early in the workflow, with results verified utilising commercial structural software packages. This was considered particularly useful as the proposed form and loadings were asymmetrical and stresses would be difficult to predict and attempts at optimisation impossible without it.

Further to this, researchers sought to utilise parametric modelling tools to enable different aspects of the design to be addressed in parallel. The team identified a series of dependencies, for example the requirement of form-finding simulations of an initial state as an input. As such, each aspect was developed in parallel with design and analysis at each stage providing a loop. These plugged into a linear chain, which allowed for information to flow both in both directions along this (see Figure 2.).

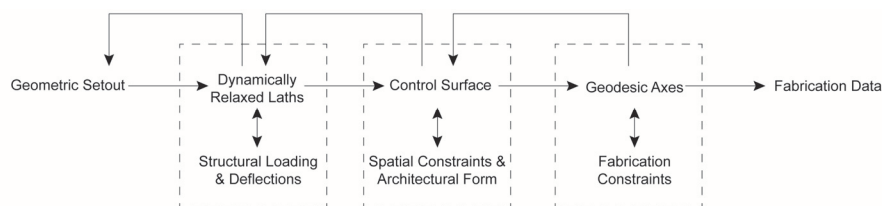


Figure 2. The elements of the Sound Bites project workflow.

#### 4. Implementing a workflow

In order to enhance potentials for collaboration, the research team sought to minimise issues of interoperability by employing a common software platform, *McNeel Rhinoceros (version 5.0)*. This was utilised by all working on architectural design, structural design and analysis and fabrication. The parametric modelling environment *Grasshopper (version 0.9)* was used to set

out elements and relationships of the workflow. A further plug-in, *Karamba (version 1.03)*, provided structural design and analysis tools.

#### 4.1. DEFINING SETOUT GEOMETRY

Initial NURBS geometry was explicitly modelled and acted as inputs to the parametric schema. This was most easily generated by the architect and components were set out in an arrangement as described above. It was further necessary to consider a range of requirements at this stage including the design of access for the movement of people around the structure and audio speaker layout.

Initially it was hoped that setout geometry could be comprised of edge profiles curves as well as points at which these intersected with a series of vertical planes used as inputs to a topology of grid elements. As the research progressed, however, this proved to be an inadequate interface to the form-finding process and a guide surface was added as an initial approximation from which to drive a final form.

#### 4.2. EMPLOYING TECHNIQUES FOR FORM-FINDING

A number of techniques have been integrated into the form-finding tools used for such timber gridshells. Relatively widely known is the study of the behaviour of physical models, exemplified in the work of Frei Otto (1974). A common approach with contemporary digital tools is *dynamic relaxation*, which involves simulating the displacement of the profile-intersection points of a planar predefined grid system under loads to identify a state of equilibrium (Kilian and Ochsendorf, 2005). These two form-finding methods rely on imposed boundary conditions. A second subclass without such fixed boundaries uses an imposed surface geometry within which equilibrium of a mesh is found (Bouhaya et. al. 2009).

In the case of the *Sound Bites* gridshell we utilised a mixed method (see Figure 3.). As described above, a guide surface was generated to initiate simulations. The network of members was generated using this, with initial intersection nodes lying on this surface and later released from it.

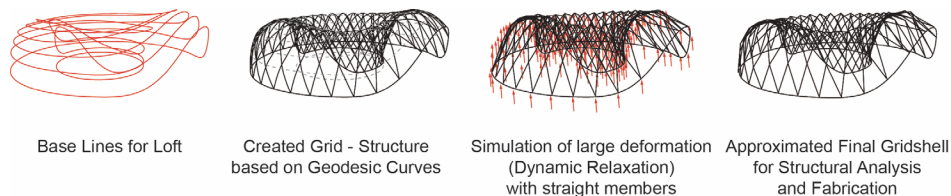


Figure 3. Steps used for form-finding and structural analysis of gridshell proposals.

The large deformation method of *Karamba* was used to apply forces, an approximation similar to the dynamic relaxation process. Further point loads were also applied to represent the weight of speakers mounted to the structure. With all of these forces applied, members were free to move in response to loading typical for shell design.

Upon reaching a stable state, material properties were applied to resultant members and structural analysis of the given arrangement undertaken. While still using the same parametric model and *Karamba* plugin, areas of high local stress could be easily identified and deflections calculated. With analysis undertaken in the same model, results could easily be fed back to inform the design through adjustment of topology, and input geometries.

#### 4.3. EVALUATING SPATIAL, FORMAL QUALITIES, AND MEETING FABRICATION CONSTRAINTS

Following the generation of lath axes, a series of further aspects needed to be evaluated. It was necessary that the mesh of linear members used for structural design were related back to the curved and continuous shapes of timber laths and further that these could be achieved from straight elements bent into shape. A new reference surface was required for this and a method was chosen in which a loft surface was generated which contained all nodes from the form-finding mesh.

This surface was used by the architects to check that spatial requirements for access were met and that collisions with existing structures were avoided. The surface also allowed the architects to consider qualitative aspects of the shape. As mentioned earlier, an asymmetrical form was sought and it was considered important that range of formal and spatial effects within this were achieved for a variety of audience experience. Visualisations of the structure from a series of key audience points were generated and considered.

The reference surface was also used to generate and analyse the geometries of the timber laths. The central axis of each lath was defined as a geodesic curve on the reference surface, allowing that curved paths could be achieved from straight elements. A series of properties could then be analysed: the length of each lath; the minimum bending radius of each lath at any point; the twisting ratio of any lath any given point. These three measures were related to the material properties of western red cedar, a timber chosen as appropriate for the project due to its availability of long lengths and its good bending properties. Through tests with the material, limit values for each of these was identified.

Analysis of these architectural and fabrication properties was again used to inform design at early steps in the workflow. For example, where fabrication constraints were not met or undesirable form generated, these were used to inform subsequent form-finding iterations, with attention paid to the specific areas of the form as required. Where a result could not be achieved which met all constraints and design goals, further adjustments were made to the setout geometry.

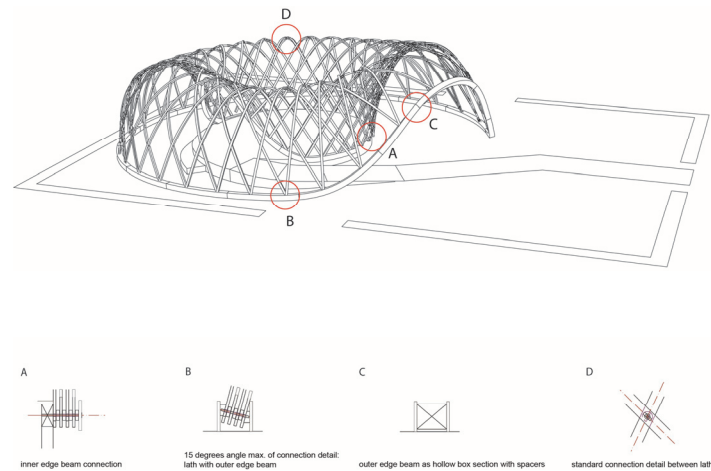


Figure 4. Typical connection details of the structure.

## 5. Discussion

The *Sound Bites* timber gridshell was successfully designed and installed for the opening of the exhibition, a timeframe of six weeks from commencement to completion. The implementation of all aspects of the workflow within a single software environment allowed for a significant number of iterations in the design process and facilitated collaboration between experts working on separate aspects of the design. Through this, material and structural properties were effectively integrated into a digital model.

Useful trade-offs between architectural, structural and fabrication concerns were required for a successful outcome. It was expected that this could only be achieved through regular discussions between experts to propose and test approaches in response to a range of criteria. The workflow comprised of a linear series of parts with clearly defined interfaces, and applied through a parametric modelling environment, allowed for this to occur rapidly. The single modelling environment avoided issues of interoperability. Together these expanded the scope which the project team could address in a short timeframe and the reduced risks of failure to deliver a desirable result



Several unexpected advantages of the collaborative approach also became apparent. One key example is that the aesthetics of the original architectural concept were enhanced through the form-finding process. This produced desirable forms which could not be easily modelled by hand. Further, the understanding of the structural performance of specific shapes was extended through responses to architectural proposals.

Beyond these successes, it quickly became apparent that some requirements were more difficult to meet than others. Of paramount difficulty were fabrication constraints, as a majority of the proposed forms contained areas in which bending radii were smaller than the material could achieve, and laths which were longer than available lengths. Refining the design to avoid these unbuildable areas was not straightforward. Conversely, the structural design objective of keeping deflections below 5mm was relatively easily achieved. As a result, significant time and design iterations were spent in utilising form-finding tools in order to satisfy fabrication requirements.

It should be noted that these last conditions were specific to the scale and form involved in this project and may or may not exist in other scenarios. Useful further research would explore the potential for such a workflow to facilitate the design of a project in a larger scales and geometric arrangement.

## 6. Conclusion



*Figure 5. The completed Sound Bites structure, focussing on the central performance space.*

This paper has presented the collaborative workflow conceived and implemented on the design and fabrication of the *Sound Bites* gridshell. This workflow utilised parametric models within a single software platform to facilitate collaboration between experts and through this, the negotiation of trade-offs between architectural, structural and fabrication issues. Such an approach allowed a series of significant design challenges to be met including the realisation of a freeform and asymmetrical shell structure while utilising principles of form-finding to define an efficient shape. Further, material properties abstracted in the digital model ensured that fabrication of a selected design would be possible.

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