The UWE Research Pavilion 2016

The UWE Research Pavilion 2016

John E. HARDING*, Scott HILLS[a], Cecilie BRANDT-OLSEN[b], Stephen MELVILLE[b]

* University of The West of England

Bristol BS16 1QY, UK

john3.harding@uwe.ac.uk

a University of The West of England

b Format Engineers

Abstract

This paper describes the design, fabrication and assembly of an elastic gridshell by staff and students at The University of The West of England (UWE) in collaboration with Format Engineers. Whilst timber lath gridshells are traditionally formed from a fixed topology with hinged connections, here all laths are bent and installed sequentially on-site. Whilst this method requires a more complicated assembly, a wider variety of freeform shapes could be explored to suit the constrained site location. The gridshell is formed from single layer thin timber laths following surface geodesics. This constraint enabled simple fabrication methods to be used despite the resulting doubly-curved form, which was partly shaped to counteract buckling. Non-linear analysis of the elastic gridshell is described, made possible using K2Engineering (K2E), a new plug-in for Rhino Grasshopper based on the Kangaroo 2 Physics engine. By integrating modelling and analysis in a common environment, critical buckling issues could be addressed by altering the gridshell topology live, resulting in a materially efficient but stable structure.

1. Introduction

Traditionally, elastic gridshells involve first laying an unstressed planar grid of elements which are then pushed into a non-planar shape via bending and torsion. Double curvature is achieved by allowing in-plane rotation at connections, which are subsequently fixed and/or braced when the desired shape is found (Harris et al. [8]). Forming high curvature whilst maintaining suitable member capacity is commonly achieved by doubling laths and post-fixing shear blocks at regular intervals. Well-known structures using this method include The Mannheim Budesgartenshau (Burkhardt et al. [4]), the Weald and Downland Museum (Harris et al. [7]) and the roof of the Savill Building (Harris et al. [9]).

This classic method allows for a relatively simple assembly of the initial lath grid, however resulting geometries are limited in scope, with possible solutions form-found using either physical or computational models (Douthe et al., [6]). Methods to counteract this limitation have recently been proposed by Hernández et al. [13] by discretizing the gridshell into separate parts, and/or using non-standard grids as described by Winslow et al. [20] for example, although these methods still maintain a bi-directional topology for ease of assembly.

With this structure however, the gridshell was assembled from a sequential bending and installation of each and every lath, thus meaning that a wider variety of both freeform shapes and lath patterns (aside from bi-directional grids) could be explored suitable to the confined site, albeit at the cost of requiring a more complex assembly. This type of sequential lath assembly therefore sits outside the classification of gridshells defined by Mesnil et al. in 2015 [15], namely either a gridshell with no pre-stressed elements at all or traditional elastic gridshells formed from a planar layout as described above.

A similar approach of sequential lath assembly of bending-active elements has been recently used for both the Faraday Pavilion [16] using GFRP tubes and the Ongreening Pavilion [10] with flat timber laths, albeit the former using circular sections and the latter within a controlled internal environment. To the

author(s)' knowledge, this is the first such sequentially assembled timber gridshell to exist in an outdoor environment, requiring new challenges in both modelling and analysis.

2. Geometry and Topology

The pavilion was to be located on a sloping green field site, occasionally used as a pedestrian cut through with three main points of access. Existing planting including native orchids were to be left untouched, thus determining the approximate footprint of the design (fig. 1). In addition, a small tree was to be respected, thus resulting in three entrances to the pavilion which was designed as a shaded meeting place, helping to make use of an otherwise neglected area of the university campus. During the design process, this gave rise to an initial design with three-fold rotation and mirror symmetry, helping to reduce the number of unique lath types and repeating assembly sequences.

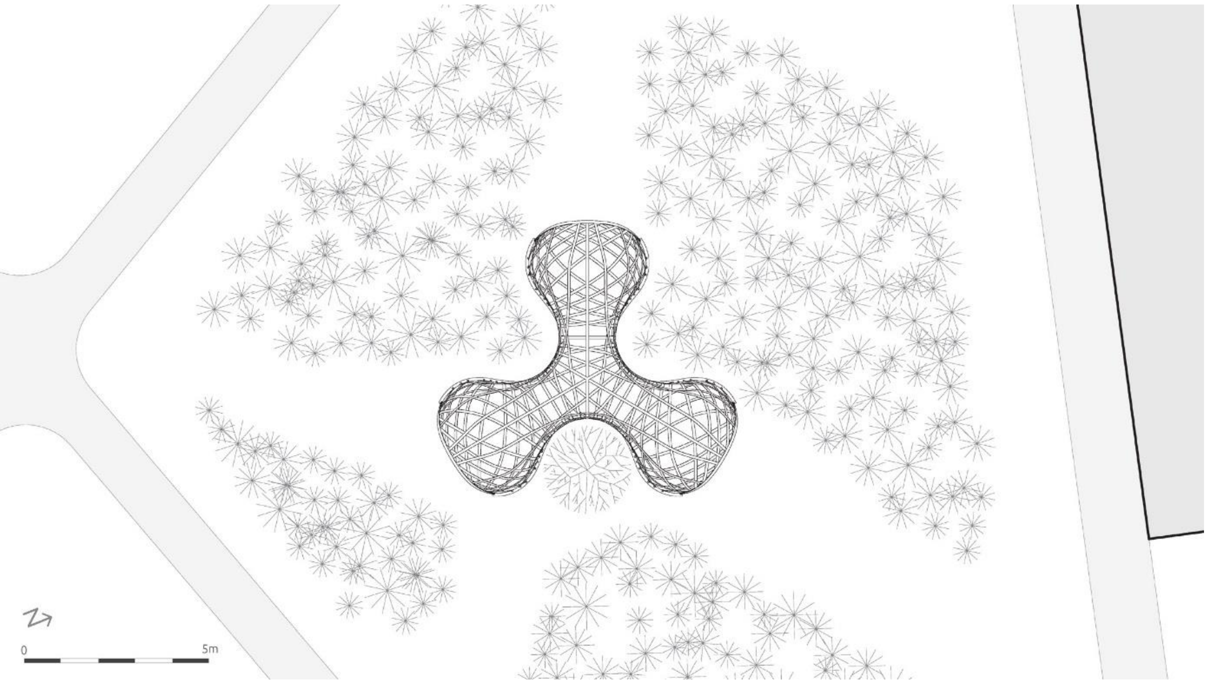

Figure 1: Site plan (showing final design)

2.1. Surface form

The gridshell consists of single layer bending active timber laths in a multi-direction configuration, i.e. without an underlying set of predominant member directions. A reference surface for the shell was created by performing three lofts through sets of splines, defined parametrically from perimeter base curves and heights. These three NURBS surfaces were combined using surface blending whilst maintaining continuity of curvature. Possible lath patterns were then constrained to geodesic curves on this surface form, in the knowledge that any lath following a geodesic is straight when unrolled flat.

As opposed to using elastica curves or any sort of form-finding to set out the initial surface shape, in this project the aim was retain a more freeform approach to the modelling, enabling the design team to introduce curvature where necessary (see Section 3.1) and gain sufficient height within the confined site. This latter point ruled out funicular 'compression-only' designs, which do not allow surfaces to curl back on themselves in the global z-axis.

2.2. Iterative geodesics

At least one geodesic curve can be found between any two given points on a closed surface, however this is not guaranteed with an open surface and there is no control over curve tangents using this

method. However, a geodesic or so-called plank line may also be generated using an iterative approach (Kensek et al. [14]). Using a seed point, initial direction and step size, a new point is generated that is then projected back to the surface. This point becomes the next seed, with a new direction vector found by combining the previous direction with the current surface normal.

The advantage with this method is that the initial vector can be defined, which simplifies the lath connection at the perimeter, as well as a guaranteed end point of the geodesic lying at the surface boundary). Seed points were thus defined by equal spacing along part of the base curve, with a starting lath direction in the positive-z direction. The curve is then integrated with a suitably small step size until a projected point lies beyond a surface boundary, at which point the curve ends (fig. 2). The overall gridshell pattern was then trimmed at the three entrances, in this case using a geodesic curve using the two-point method.

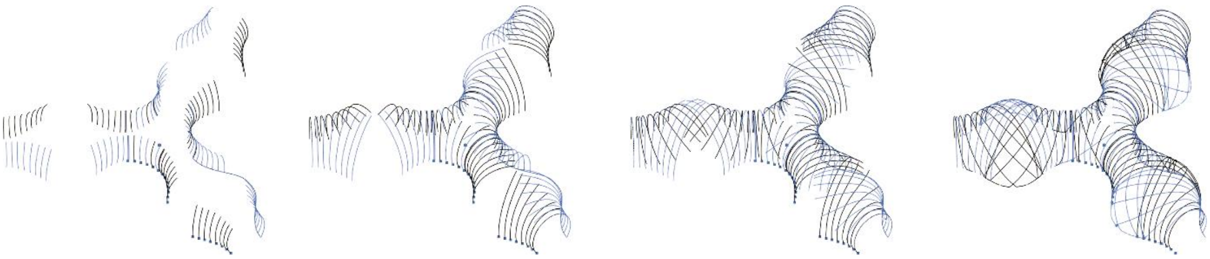

Figure 2: Generating surface geodesics using an iterative method from boundary seeds

2.2. Design refinement

The design process essentially required establishing a system of lath generation based on the above constraints, then steering the surface form following both aesthetic (qualitative) and structural (quantitative) guidance. However, controlling the surface parameters was not as simple as first expected. Subtle variations in parameters controlling the surface formed often led to large changes in the resulting gridshell, in particular the density of the lath pattern in areas of large double-curvature.

In order to arrive at a suitable pattern, dimensionality reduction using a Self-Organising Map (SOM) was therefore performed on the surface parameters to visually compare different designs on a 2D layout (fig. 3). This method allows a design space of possible options to be visualised associatively even for high-dimensional parametric models (Harding [11]). Essentially, designs are pre-calculated and can be visualised associatively at a lower dimensional space as opposed to the traditional ‘slider-tweaking’ manual method associated with visual programming environments such as Rhino Grasshopper. Gridshell options were then be assessed by the design team both aesthetically and structurally during the design process.

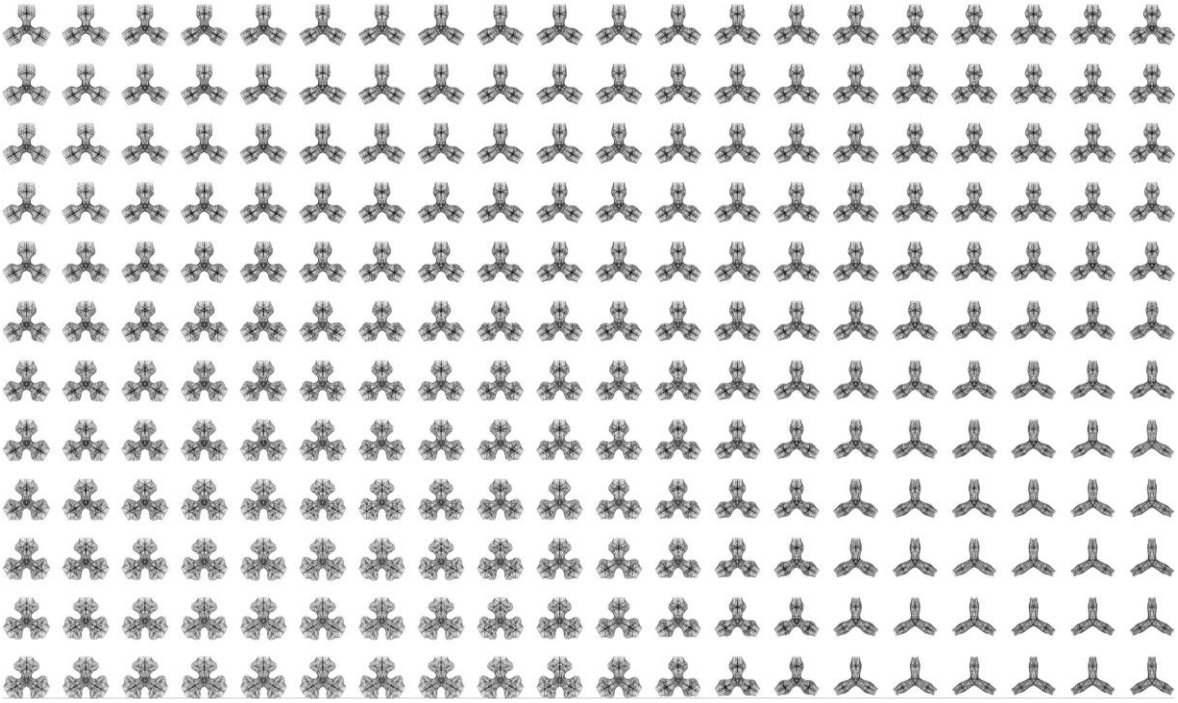

Figure 3: Visualising the design space of geodesic lath patterns using a Self-Organising Map (SOM)

3. Integrating structural analysis

The assembly of the gridshell using a sequential method (as opposed to form-finding from a flat grid for example) meant that the elements were already stressed in their rest state. It was therefore important to carefully control the thickness and curvature of the laths during the design process in order to reserve some capacity to resist additional external loads.

As gridshells are known to be particularly sensitive to buckling similar to continuous shells (Hernández et al. [12]; Mesnil et al. [15]), it is highly useful to incorporate feedback on buckling behaviour early in the design process. The short time period for the design and analysis of the gridshell required a fast workflow between the geometry modelling and structural analysis software to investigate and improve different design options. It was chosen to keep the analysis within the Rhino Grasshopper environment using plug-ins such as Karamba3d (Preisinger, [18]) and later incorporating K2Engineering (Brandt-Olsen [2]).

3.1 Initial Finite Element Analysis

Karamba3d is a parametric finite element analysis software based on the direct stiffness method, which assumes small displacements to describe the linear relationship between forces and displacements. Since the shaping of the gridshell involved large deformations, this software choice made it impossible to account for the influence of pre-stress on the deformation behaviour. However, the pre-stress was manually included in the strength validation by using the principle of superposition, similar to that used for the Ongreening Pavilion [10].

The scale of the pavilion suggested that a single layer of 6.5 x 100mm birch plywood laths would be sufficient to resist the wind pressure. However, the initial analysis of several early designs highlighted that the structure had critical buckling issues towards the free edges and supports (fig. 4). These areas had little out-of-plane stiffness due to the flatness of the sides of the initial surface which was in strong contrast to the curvature-rich top. It was therefore decided to stiffen the gridshell by adding more curvature to the shape along the boundaries (b). These more curvature-rich forms were much stiffer based on an evaluation of the deflection, however the Karamba3d analysis still highlighted that it was vulnerable to buckle despite the first buckling load factor increasing considerably.

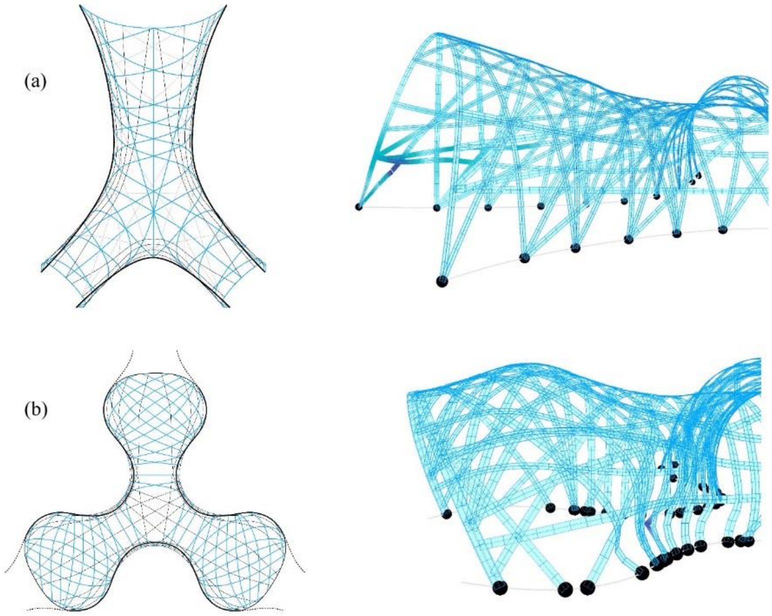

Figure 4: Initial (a) and higher curvature stiffened gridshell (b) with one of its first buckling modes shown

A number of initiatives were subsequently made in an attempt to resolve this issue. This included globally scaling of the pavilion, modifying the layout of the lath patterns (as described in Section 2) and stiffening of the free edges at the entrances by using a double layer structure with shear blocks. Additionally, the lath dimension was adjusted to 6.5 x 125 mm at the free edges and 4 x 100 mm in a few locations where the curvature had become too tight due to the scaling of the pavilion. These adjustments helped to further stiffen the structure but it was still not enough to avoid buckling problems according to the Karamba3d analysis.

3.2. Use of non-linear buckling analysis using K2E

It is known that the pre-stressed state of bending-active structures has an influence on the deformation and buckling behaviour (Mesnil et al. [15]). In most cases, the pre-stress will not have a positive effect on the magnitude of stresses and deflections but it has been observed to lead to a more ductile behaviour of gridshells, making buckling behaviour more vague [3].

The Grasshopper plug-in K2Engineering (K2E) was therefore used to investigate this pre-stress effect on the stability of the gridshell. K2E extends the functionality of Kangaroo2 (Piker [17]) with accurate structural behaviour. The underlying dynamic relaxation solver inherently deals with the geometric non-linearity related to large deformations of form-active structures (Quinn et al. [19]).

K2E has the bending model described by Adriaenssens and Barnes [1] implemented, making it possible to include the pre-stress effect of such a sequentially formed gridshell (i.e. not classically form-found), albeit with elements currently limited to circular cross-sections only. Well aware of this limitation, it was decided to model one third of the gridshell designs (due to rotational symmetry) and then calibrate the stiffness properties to match the deflections from the previous Karamba3D analysis (whilst disabling the pre-stress feature for comparison reasons).

When a reasonable coherence between the two models was obtained, the bending-active behaviour was activated and a non-linear buckling analysis under self-weight, pre-stress and wind load could be carried out for multiple design options using a bespoke script of the Kangaroo2 solver (fig. 5). The script was responsible for incrementally applying the load and using dynamic relaxation to find

equilibrium in each load step whilst tracing the displacements. Any sudden changes in displacements were used to evaluate whether the structure had buckled or not. The method is more thoroughly described in Brandt-Olsen [2].

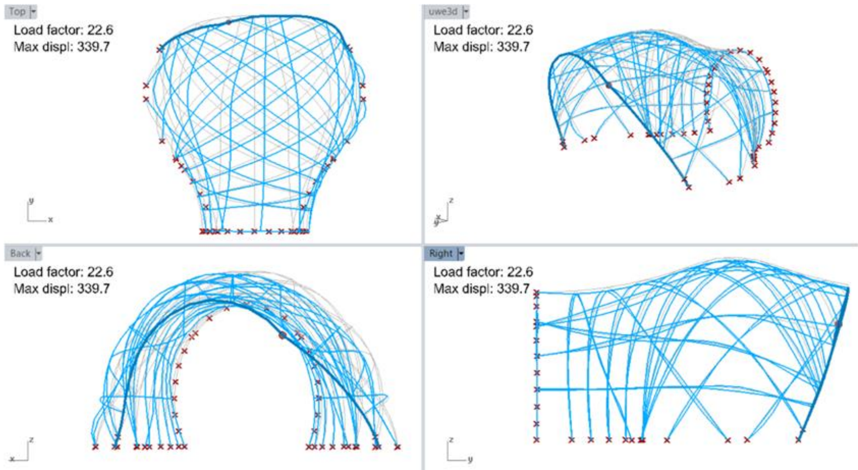

Figure 5: Buckling analysis of a design option using K2Engineering within Rhino Grasshopper

The gridshell designs exhibited a more ductile behaviour under the applied load than the Karamba analysis had signaled and it was concluded that no buckling tendency was noticeable up to a load factor of at least 1.5. The analysis highlighted that the free edge and the base of some laths were the vulnerable parts of the structure. In general, this study helped to increase the confidence that buckling problems could be avoided, resulting in the final layout for the laths shown in Figure 6. The gridshell is approximately 10m wide and just under 3m high, with the smallest lath radius at 1.05m.

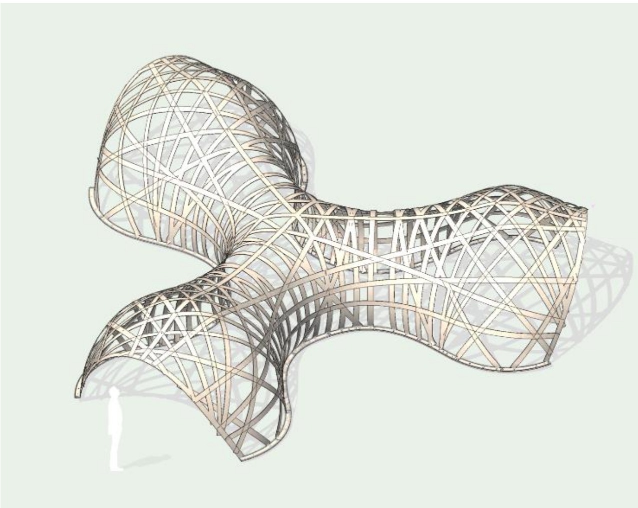

Figure 6: Final pavilion lath layout

4. Fabrication and assembly

Once the design was complete, a two stage process of fabrication and assembly began. The ethos was to where possible use relatively simple manufacturing methods whilst still achieving a stiff doubly curved shell. This aim was partly to provide an educational benefit to the students, noting that modelling complex geometry does not necessarily mean digital fabrication - rather advances in modelling and analysis can unlock potential of standard modes of fabrication and hands-on assembly by a community of human beings.

4.1. Lath fabrication

As opposed to using CNC machining throughout, the unrolled straight laths were very simple to manufacture using a vertical panel saw with holes then manually drilled using paper templates plotted at 1:1 scale. Where laths were to intersect, a simple reference was manually made in pencil using the templates. The rotation and mirror symmetry of the structure resulted in just 15 individual lath types, repeated six times (fig. 7). Splice connections were introduced to pre-fabricate laths up to 10m from standard sheet materials, which due to the straight cuts resulted in practically zero waste. These splice connections were located to avoid clashing with intersecting laths using the process first described by Harding et al. [10].

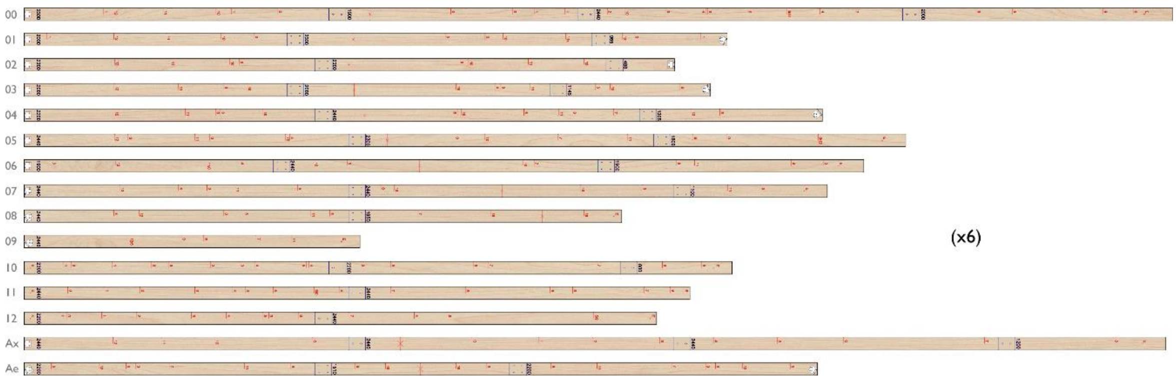

Figure 7: The 15 unique unrolled laths.

The use of a high grade Finnish birch plywood was essential to achieve the bending radii whilst still retaining the required shell strength at such a thin size. The fact the shell could be made from such thin plywood, also meant material use for this size of enclosure was minimised and costs were kept low. Due to the initial temporary nature of the pavilion, the final laths were left untreated and allowed to weather in the external environment. The perimeter base curves were the only CNC cut elements, allowing accurate setting out of the lath connections, fixed using simple stainless steel hinges and M6 bolts.

4.2. Gridshell Assembly

The gridshell took a small team of staff and students two days to assemble. Starting at the centre of the pavilion, straight laths were bent into place and then connected at each intersection in-situ using a single M6 stainless steel bolt. Some longer laths were split at splice locations to allow for easier handling, then fixed back into place as the pavilion took shape (fig. 8).

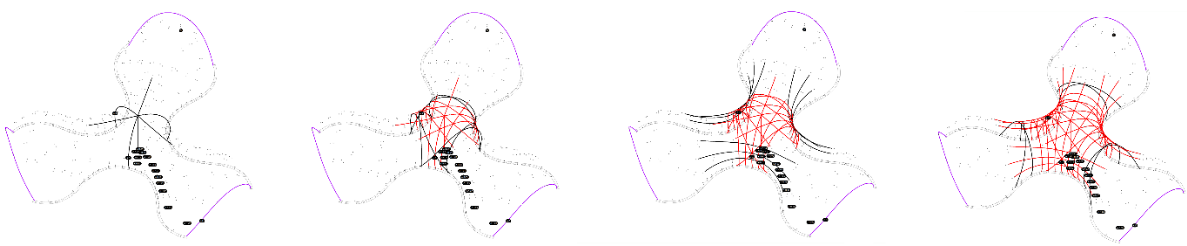

Figure 8: Initial assembly sequence

The tight tolerance of the pavilion and multi-directional pattern of the laths meant the form required no guidance in terms of setting out. Rather, as the laths were assembled the shell took on the only possible form it could for the given connections, with temporary support used only at the centre and the

three entrance free-edges. The resulting structure (fig. 9) was extremely stiff due to its high double curvature and unidirectional lath pattern, acting similar to a continuous monocoque.

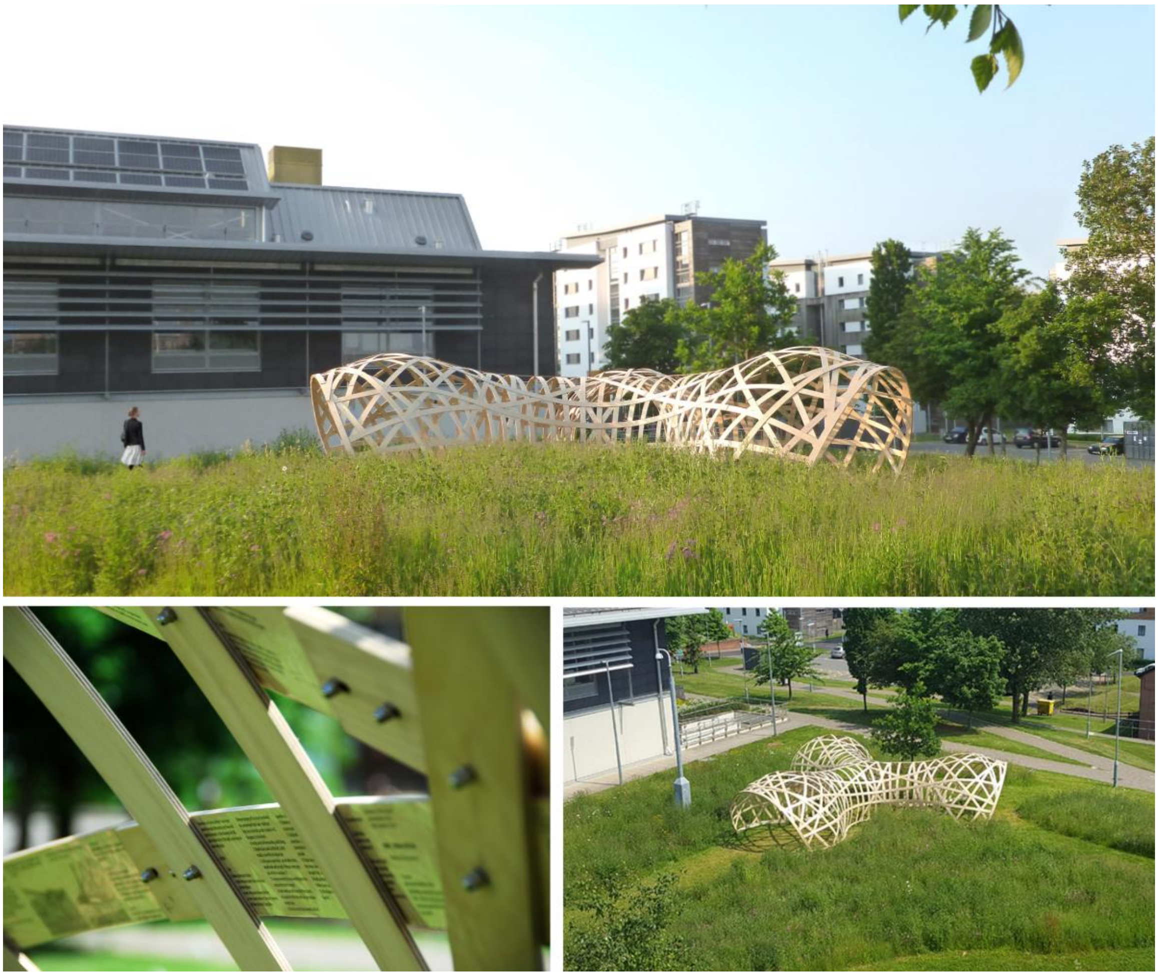

Figure 9: Realised gridshell at the UWE campus

5. Conclusions

This paper describes the design, fabrication and assembly of an elastic gridshell using a sequential installation of laths. The pavilion builds on the work of the earlier Ongreening Pavilion [10] by extending beyond form-found elastica shapes to completely freeform shells, albeit guided by aesthetic, functional and structural criteria. This integrated approach was made possible under a single modelling and analysis environment, offering an educational benefit to student participants learning parametric design techniques for the first time.

The pavilion is the first outdoor structure to be built using K2Engineering, a new structural analysis package for Rhino Grasshopper that integrates fully with the Kangaroo Physics engine. The benefits of using non-linear buckling analysis with pre-stressed elements for such structures is described, for which the pavilion is an early test-case. Integrating 6 DOF biaxial bending and torsion within K2E without calibration with additional finite element analysis (see Section 3.2) is the next step for the tool, similar to those recently incorporated into a dynamic relaxation solver by D'Amico et al. [5].

Although intended as a temporary structure, the pavilion remains in place to date (twelve months), showing the potential of geodesic gridshells made from readily available materials and using simple manufacturing techniques. Due to the initial intended lifespan of the pavilion being short (one month),

creep was not deemed to be an important design concern. The plywood was also left untreated, allowing moisture absorption and some minor delamination to occur, making meaningful long-term monitoring of the structure (for correlation with analysis) unfeasible. Much work is therefore required to investigate the long-term behaviour of such timber shells in an external environment in combination with developing analysis tools such as K2E.

Although a number of sequentially assembled elastic gridshells have been erected in recent years, their scale remains small. With the advent of digital fabrication and assembly methods, the prospect of sequentially assembled gridshells are larger scales becomes a real possibility and it is hoped that similar methods to those used here point the way to future structures at widespan scales.

Acknowledgements

This work was supported by the Department of Architecture and The Built Environment at UWE, UK. The author(s) would like to extend thanks to all those that helped during the project, with special mentions to Olga Kravchenko, Raymonde Bieler, Paul Cooper, Lee Bartholomew, Shadie Elyaei and Tom Barnes (KWMC).

References

[1] Adriaenssens, S. and Barnes, M. Tensegrity spline beam and grid shell structures. Engineering structures, 1999; 23, 29-36.

[2] Brandt-Olsen, C. Harmonic Form-finding for the Design of Curvature-stiffened shells. MPhil thesis, University of Bath, 2015.

[3] Brandt-Olsen, C. Calibrated Modelling of Form-active Structures. MSc thesis, The Technical University of Denmark, 2016.

[4] Burkhardt B., Bächer M. and Otto, F. Multihalle Mannheim: Dokumentation über die Planungs und Ausführungsarbeiten an der Multihalle Mannheim. Institut für Flächentragwerke, Stuttgart, 1978.

[5] D'Amico B., Kermani A., Zhang H., Shepherd, P. and Williams, C.J.K. Optimization of cross-section of actively bent grid shells with strength and geometric compatibility constraints. Computers & Structures, 2015; 154; 163-176.

[6] Douthe C., Baverel O. and Caron J.F. Form-finding of a grid shell in composite materials. Journal of the International Association for Shell and Spatial Structures, 2006; 150; 53.

[7] Harris R., Romer J., Kelly O. and Johnson S. Design and construction of the downland gridshell. Building Research & Information, 2003; 31, 6; 427-454.

[8] Harris R., Dickson M., and Kelly O. The use of timber gridshells for long span structures. In Proceedings of the 8th International Conference on Timber Engineering WCTE, 2004; 1001-1006.

[9] Harris R., Haskins S. and Roynon J. The Savill Garden gridshell: design and construction. The Structural Engineer, 2008; 86, 17; 27-34.

[10] Harding J., Pearson W., Lewis H. and Melville S. The Ongreening Pavilion. Advances in Architectural Geometry, 2014; 295-308.

[11] Harding J. Dimensionality Reduction for Parametric Design Exploration. In: Adriaenssens, S. Gramazio F., Kohler M., Menges A. and Pauly, M. (Eds.) Advances in Architectural Geometry, 2016; 274-287.

[12] Hernández E. L., Gengnagel C., Sechelmann S. and Rörig, T. On the materiality and structural behaviour of highly-elastic gridshell structures. In: Computational Design Modelling, 2011; 123-135.

[13] Hernández E.L., Baverel O. and Gengnagel C. On the design and construction of elastic gridshells with irregular meshes. International Journal of Space Structures, 2013; 28, 3-4; 161-174.

[14] Kensek K., Leuppi J. and Noble D. Plank lines of ribbed timber shell structures. In Acadia 2000: Eternity, Infinity and Virtuality in Architecture, 2000; 261-266.

[15] Mesnil, R., Ochsendorf, J. and Douthe, C. Stability of Pseudo-Funicular Elastic Grid Shells. International Journal of Space Structures; 2015; 30, 1; 27-36.

[16] Nicholas P., Hernandez E.L. and Gengnagel C. The faraday pavilion: Activating bending in the design and analysis of an elastic gridshell. In Proceedings of the Symposium on Simulation for Architecture & Urban Design, 2013; 21:1-21:8.

[17] Piker, D. Kangaroo: Form finding with computational physics. Architectural Design. 2013; 83, 2; 136-137.

[18] Preisinger, C. Linking structure and parametric geometry. Architectural Design. 2013; 83, 2; 110–113.

[19] Quinn G., Deleuran, A.H., Piker D., Brandt-Olsen, C., Tamke M., Thomsen M.R. and Gengnagel, C. Calibrated and Interactive Modelling of Form-Active Hybrid Structures. In Proceedings of the IASS Annual Symposium, 2016.

[20] Winslow P., Pellegrino S. and Sharma S.B., Mapping two-way grids onto free-form surfaces. Journal of the International Association for Shell and Spatial Structures, 2008; 49; 123-130.