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The TRADA Pavilion – A Timber Plate Funicular Shell

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Summary: This paper describes the design and construction of the TRADA (Timber Research and Development Association) Pavilion by Ramboll Computational Design. The design process combined a zero-length spring funicular form-finding approach with a planar polygon discretisation method, thus enabling the final structurally efficient but complex geometric form to be realised with low-cost materials. The timber plate shell is fully demountable and has been assembled at several separate locations since being completed in September 2012. To the authors' knowledge, the structure is one of the largest free-form facetted thin shell structures ever to be constructed. It is hoped that the project inspires a new approach in realising complex funicular shapes with low-cost materials and fabrication methods.

Keywords: *funicular form-finding, timber shell, surface discretisation, planar remeshing, digital fabrication*

1. INTRODUCTION

The TRADA Pavilion was designed and first constructed by the Ramboll Computational Design (RCD) team in 2012. The structure is a doubly curved compressive shell assembled entirely from flat timber panels and stainless steel hinges. Designed as temporary trade fair stand, the shell is fully demountable. This allows it to be used at various trade events across the UK, promoting the use of timber as a building material. At the time of writing, it has been assembled at three different locations.

The design of the pavilion was separated into two main stages. Firstly, the form-finding of a funicular compression-only shell was undertaken. The form-finding approach chosen was a zero-length spring system with dynamic nodal masses. Its use is explained in Section 2 of the paper.

Secondly, a surface discretisation into planar polygons with tri-valent nodes was made in order to cheaply and efficiently realise the doubly curved form with flat timber panels. This discretisation had to be sufficiently fine in order to maintain a similar structural behaviour to the continuous shell. This process is covered in Section 3 of the paper.

This combination of techniques meant that a structurally efficient compressive shell with a complex form could be realised using low-cost off-the-shelf materials and well known fabrication methods, as well as providing a demountable structure as required by TRADA.

2. FUNICULAR FORM-FINDING

The form-finding of funicular structures has long been desirable for compression and tension shells. Antoní Gaudi's original physical hanging chain models have inspired many designers to explore similar methods for finding efficient shells, with notable work by the engineers Isler, Candella, Torroja, Nervi and Otto to name only a few.

Physical hanging nets working in tension-only under self-weight are reversed to act in pure compression under the same loading, a principle first discovered by Robert Hooke in the 17th century. As the physical tension nets cannot carry bending, the resulting compressive forms that result also have zero-bending under self-weight, with the structure working axially with no out of plane forces thus enabling a thin structural depth for the shell.

2.1. Computational approach

Whilst using physical form-finding models give a real-life understanding of the behaviour of material subject under self-weight, the cost of having to model many design options individually can be both time consuming and constraining if the problem's boundary conditions are complex and/or the exact design requirements are not known *a priori*.

In response to these difficulties, recent efforts have been made to recreate the playfulness and intuition of 3D physical model interaction in computer software applications. Interactive software examples include directly mimicking physical models with stiff springs [1], as well as the more recent 'Thrust-Network Analysis' (TNA) method that combines linear optimization with projective geometry and duality theory [2].

2.2. Zero-length spring system

The computational method used for the TRADA Pavilion utilises a zero-length spring approach with dynamic masses [3]. Zero-length springs by their nature must always be in tension, and hence any resulting form in tension will result in a compression only-structure when used appropriately during structural form-finding.

An initial hexagonal zero-length spring system was established to the dimensions of the 8m x 6m site. Each node thus consisted of 3 springs meeting at a pinned connection. Nodal mass forces were then applied perpendicular to a reference ground plane, with equilibrium solved for using the dynamic relaxation method. With such an approach, funicular forms were able to be generated so long as the lumped nodal masses applied are updated at each time-step.

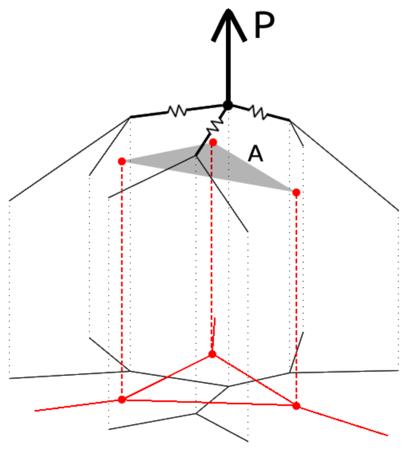

Fig. 1. The nodal point load applied perpendicular to the ground plane is proportional to the area of the adjacent panels' dual.

As the TRADA shell was to be a continuous surface as opposed to a lattice, the lumped mass applied at each node was proportional to the local surface area. This proportionality assumed that the material thickness was constant throughout, although exactly what thickness did not need to be known at this stage. The local area was easily approximated by using the hexagonal mesh dual which is a triangle. Within a gravitational field, the mass therefore exerts a point load perpendicular to the ground plane in an upwards direction, whose magnitude is proportional to this local area. This force is therefore resisted by the adjoining springs, see Fig.1.

Because this applied nodal force vanishes to zero when projected to the ground plane, the system is statically determinate for 3-valance nodes,

so long as *all* of the applied nodal forces are indeed perpendicular to the ground plane. This condition is true for the form-finding of funicular structures where self-weight is the dominant load case, a fact also utilised by the TNA approach when unique solutions are sought.

The static determinacy of the hexagonal system is useful during the form-finding process, as it enables the designer to view local forces in real time whilst the model is altered and new designs are explored. If the springs are replaced with rigid bars after equilibrium is found, the forces in the elements must remain as per the spring model in order to resist the applied nodal point loads due to the uniqueness of the solution. By reversing the direction of the point loads after finding a tensile form, a purely compressive shell with zero-bending is the result (Fig.2).

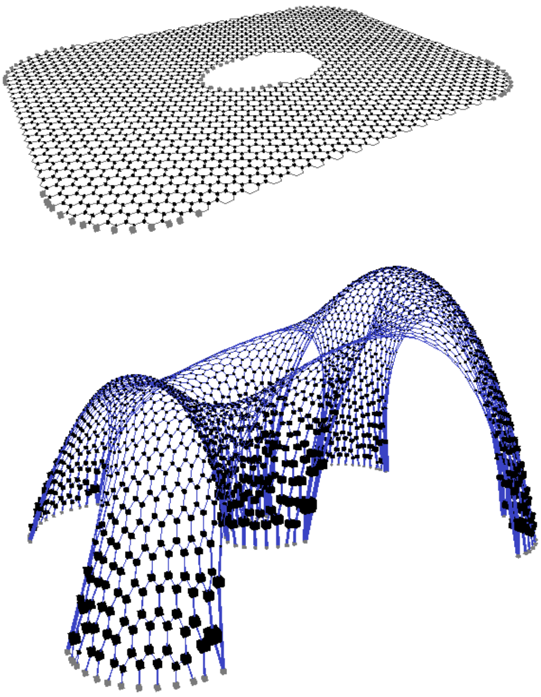

Fig. 2. Initial condition and the final equilibrium after relaxation. Larger nodal masses can be seen towards the base of the structure as expected as the springs become stretched under greater load.

2.3. Software application

By incorporating the form-finding method into a Java application, spring stiffnesses, the gravitational constant and boundary conditions could be adjusted on the fly during design development by the RCD team. Various funicular forms could therefore explored during the early design phase. This included the introduction of a negatively curved area at the centre of the site, and the 4 free edges around the perimeter of the shell.

By using zero-length springs, not only were all elements guaranteed to be in tension, but also a much smoother shell resulted than was the case by using natural lengths set by the initial line lengths with no gravitational field applied, i.e. on the ground plane.

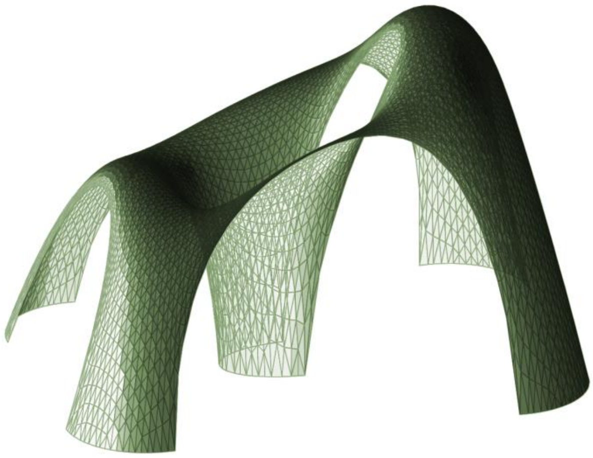

Fig. 3. Final fine triangulated mesh sent for remeshing.

A real-time approach meant that the effect on curvature could be quickly assessed by changing the boundary conditions. For example, one of the main problems of the design was to ensure a sufficient amount of double curvature was present in the 4 corner legs to counter buckling effects. However, the support areas were limited by their size as the structure had to be accessed by the public. By adjusting the size and shape of the legs as they meet the ground, the overall effect on the shape could be assessed quickly until a satisfactory compromise was found.

Once the form was finalised, rather than having to painstakingly measure a complex physical model, a fine triangulated mesh could be exported ready for the next stage of the process (Fig.3).

3. PLANAR REMESHING

Due to their double curvature, compressive shell structures have traditionally been constructed from concrete or masonry. For the former, bespoke formwork is required in order to accurately provide a reference surface before the pour is made. Reinforcement is also necessary to resist live load cases due to concrete's poor performance in tension, and must follow the curvature of the shell - often a complex and time-consuming process. Such cost implications have seen the popularity in thin concrete shell structures fall in recent decades.

Timber on the other hand, works well in tension and compression if cross-laminated, and hence as a shell material does not require extra reinforcement. However, forming doubly curved timber surfaces becomes prohibitively expensive as each panel would have required a unique jig or be highly wasteful of material.

A suitable compromise therefore was to discretise the shell into flat panels of timber, whilst remaining close to the original surface so as not to introduce significant bending moments into the structure. This approach also allowed the structure to be demountable and flat packed for easy transportation.

3.1. Triangles and quads

The simplest planar discretisation possible is to form triangular panels from the initial surface mesh. Nodes are 6-valent, that is, 6 edges are incident per node. This was the first method attempted (Fig.4.). However, although the result follows the form closely, there were a number of structural concerns about adopting this solution.

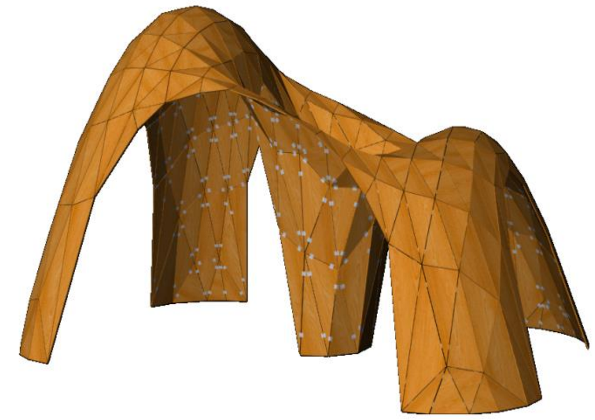

Fig. 4. The funicular surface discretised with triangular plates.

The triangulated mesh was found to have lines of edge continuity throughout the surface which allowed the shell to fold as it deforms under both dead and live load cases. It therefore required stiff connections to resist this bending action. Discretising the shell into planar quads with 4-valent nodes by aligning edges to the principal curvature of the surface [4] was also ruled out for a similar reason.

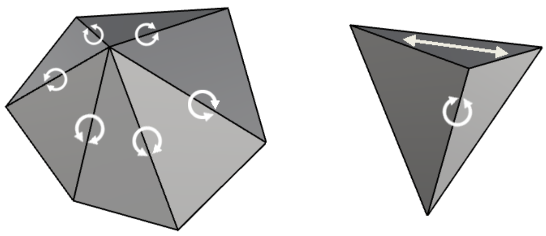

Fig. 5. In comparison to a 6-valent triangular mesh, a 3-valent planar mesh requires no edge restraint (bending stiffness) in order to remain locally stable

By using a 3-valent node however, local stability can be maintained even with an entirely hinged edge that offers no bending resistance, see Fig. 5. Any loads applied out of plane are taken via torsional restraint along each edge, i.e. where two plates meet. Ture Wester incorporated this property of 3-valent plate shells in his plate-lattice dualism approach [5]. Less edges incident per node also led to neater details over the whole structure and perhaps visually a more interesting result.

Hexagonal 3-valent plate structures that utilise this property can be found in nature, for example, the tessellation of plates on a sea urchin [6] and the formation of 'scutes' on turtle shells. Interestingly, although this approach also uses the underlying structural properties of a 3-valent system as with the form-finding stage, for the planar remeshing it does so in a completely different way.

The benefits of a 3-valent plate system have also been investigated extensively by Bagger et al. in relation to structural glass shells [7]. With triangular plates (6-valency), load concentrates in the edges of the elements whereas with a 3-valent system, load is transferred through the structure via in-plane stresses, thus acting similarly to a continuous shell. This better distribution of stress therefore allows for a thinner material to be used for the plates themselves.

3.2. 3-valent planar polygons

Discretising a doubly curved surface into 3-valent plates has only recently been achieved. Cutler and Whiting [8] were the first to adapt a technique developed in the computer graphics industry known as Variational Shape Approximation [9] for use in the architecture by integrating the approach with intersecting planes. Around the same time, Troche [10] independently developed a similar Tangent Plane Intersection (TPI) approach specifically for hexagons. More recently, Zimmer et al. have investigated generating dual supporting structures for flat plates using Variational Tangent Plane Intersection [11].

Using the same approach as Cutler and Whiting, the RCD team developed their own software in C# for use in Rhino Grasshopper. This meant that discretisations of varying densities could be quickly assessed in terms of assembly time, fabrication costs, overall appearance and structural behaviour, i.e. its deviation from the original smooth form.

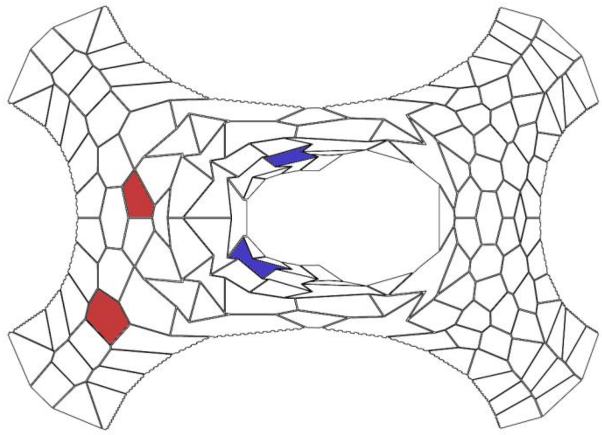

Fig. 6. Plan view of the final discretisation. Each panel's shape reflects the underlying curvature of the surface at that location.

The final discretised mesh consisted of 152 flat panels, each of which was unique. Although the appearance was irregular, each panel's shape was related to the curvature of the surface, see Fig.6. In areas of positive Gaussian curvature, such as the dome-like areas at the top of the structure, the panels are convex. In areas that are close to cylindrical or have approximated zero Gaussian curvature, such as the legs, the panels are generally rectangular. Finally, in areas of negative curvature such as the central funnel, interesting concave "bow-tie" shapes are present.

3.3. Free Edges

Although the three-valent mesh provided sufficient restraint for the internal shapes, the free edges however were not sufficiently restrained and hence vulnerable to buckling. Perpendicular edge stiffeners were therefore required to ensure stability, similar to the upturned edges used by Heinz Isler on his concrete shells [12].

Non-linear analysis of the structure was conducted to validate the approach and ensure that the same plate thickness could be used as per the main shell, see Fig.7. This analysis was combined with full-scale physical testing of a leg before committing to the design.

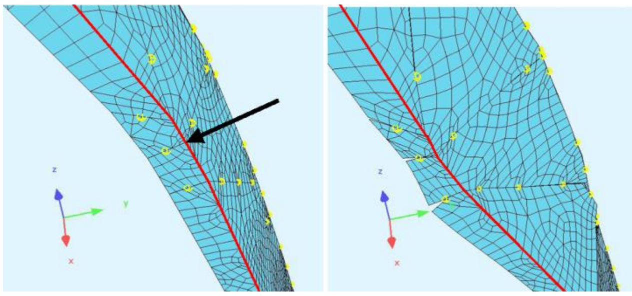

Fig. 7. Edge of the structure resists accidental point load (exaggerated deflection shown).

4. FABRICATION AND ASSEMBLY

By discretising the shell form into planar polygons the shape could then be realised with flat timber panels. 15mm thick birch plywood was chosen due to its strength and ease of use with a 3-axis CNC machine. The timber could be fire-treated before cutting commenced, greatly simplifying the process.

By designing with a 3-axis machine in mind (as opposed to a 5-axis), fabrication costs were significantly lower as well as reducing the amount of information required by the fabricator from the design team.

4.1. Connection detail

As already discussed, the nature of the 3-valent shell discretisation provides sufficient geometric restraint to allow a completely hinged connection to be used, thus reducing the costs required in fabricating bespoke connections. Adjacent timber plates were therefore joined using a standard stainless steel hinge connection along each edge (Fig.8), perhaps something of a first for this type of shell structure

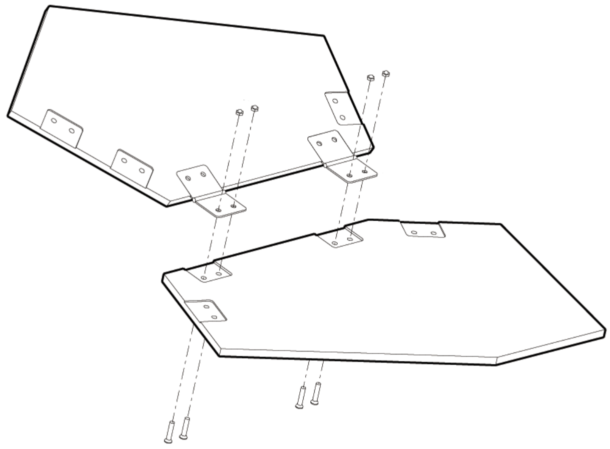

Fig. 8. Identical hinges were used to connect every panel.

Although the angle between every pair of plates is different throughout the entire structure, the hinge could easily adapt to suit both the positive and negatively curved areas. Recesses to locate the hinges were milled into each plate with each hinge then fixed to each by using a s/s M4 bolt countersunk on the outside face of the shell, see Fig.9.

Fig. 9. Assembled node detail.

4.2. Assembly

The final pavilion consisted of 152 panels, 900 hinges and 3600 bolts. The entire shell was flat packed and delivered to each site on two 2.4m x 1.2m x 0.9m palettes, and takes a single day to be assembled by 4 people. The speed of assembly is mainly due to the fact that no setting out information other than the support locations is required. Each panel contains a numerical reference, and so as each piece is connected the form begins to emerge as a natural consequence of the doubly curved shape and its discretisation.

Unlike concrete and masonry shells, no formwork was required. Instead, vertical props to support the structure were proposed, although at this scale it was found that the fixed base supports allowed the legs to simply cantilever before they were joined.

At the base supports, hinges were also used to provide a shadow gap of identical width to that between each panel in the main structure. These hinges were screwed into a plywood base in order to provide suitable horizontal restraint.

The final shell form (Fig.10 & Fig.11) covers 8m by 6m and is 4m tall at its highest point, governed by a planning requirement should the structure be used externally in the future.

Fig. 10. Completed Shell at the Surface Design Awards, 2013.

5. CONCULUSION

The design of the TRADA Pavilion highlights how a new combination of computational design techniques can be used to incorporate structural and fabrication logic into the design of shell structures and allow different materials to be considered in realising such forms. The recent rise in free-form surface geometry with little structural logic has given prominence to geometric post-rationalisation methods. However, when similar techniques are applied to structurally efficient shell forms, perhaps new and interesting ideas with regards to realising free-form funicular shells become possible.

Our long-term hope is to realise such shell structures at much larger scales, perhaps using cross laminated timber (CLT). Much like CLT offers a sustainable alternative to concrete for slabs, it may also have a future application in the construction of timber plate shells.

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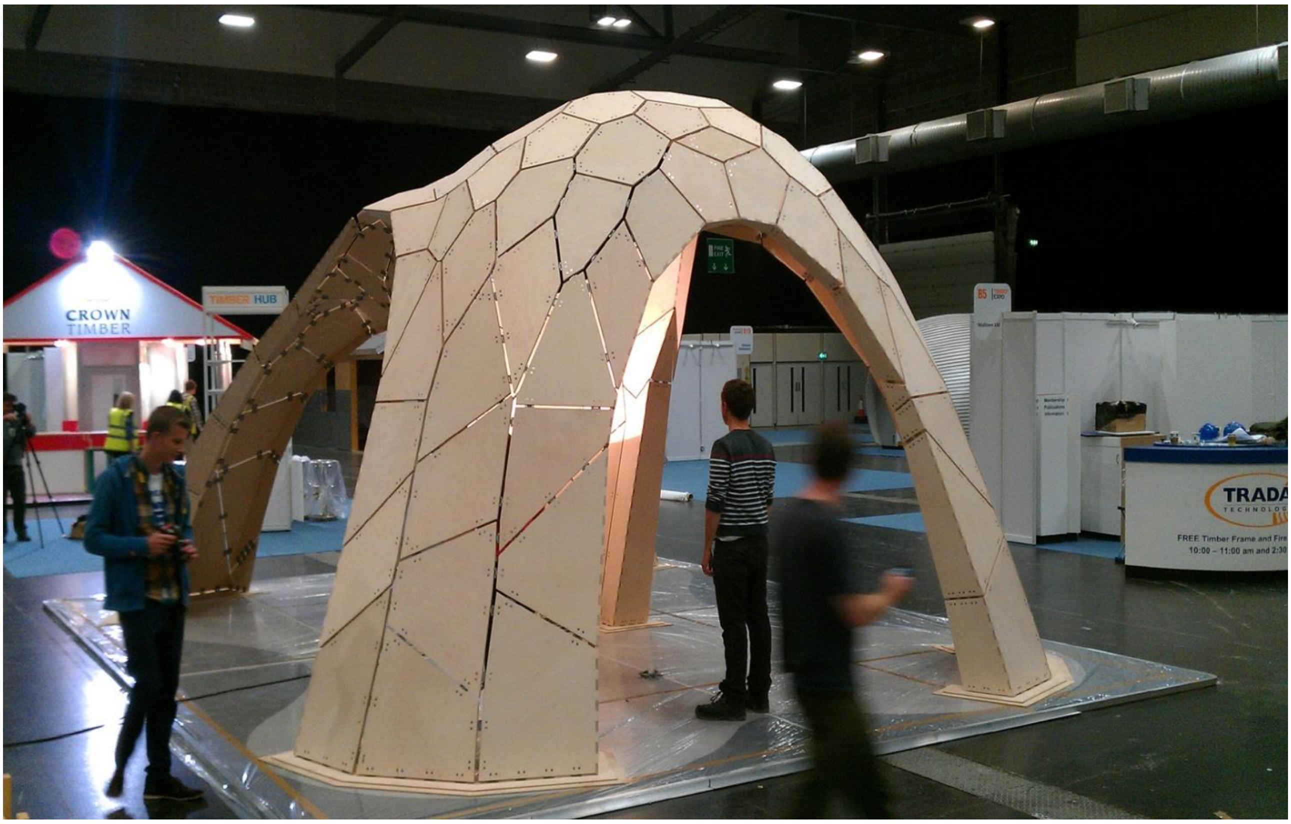

Fig. 11. Completed Shell at the UK Timber Expo, 2012.

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