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Design and analysis of moment-resisting nature-inspired-design structure using Graphic Statics methods

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Abstract

Based on Kiesler's perception of space and the idea of continuity, the design proposal from DARC (Digital Architecture Research Centre at Kent School of Architecture and Planning) follows a nature-inspired scheme discussing the notion of continuity of force through the study of combined loading. Geometric intuitive methods are used to examine and determine axial forces, bending moments, torsion values and deflections. These include the use of Kangaroo, mesh subdivision, and traditional and latest developments in Graphic Statics. The study originally explores the use of the Doo-Sabin subdivision method for determining force, and, through seeking parallelisms of structural design with biological systems, aims to detect the benefits and limitations of expanding the application of advanced Graphic Statics and Graphic Kinematics methods for moments and deflections in nature-inspired design vocabularies.

Keywords: Kiesler, nature-inspired design, moment-resisting, graphic statics, graphic kinematics, conjugate beam method, 3D Rankine, Doo-Sabin mesh subdivision.

1. Design concept and Research approach

1.1.Frederick Kiesler and continuity

The Digital Architecture Research Centre (DARC) at Kent School of Architecture & Planning (KSAP) explores the intersections between architecture and digital technologies to investigate the impact of digital cultures on architectural thinking and practice. Inspired by Frederick Kiesler's [1] idea of space, which he considered continuous or endless, the Centre's ethos is continuity, and that as designers we deal with forces, not objects. As Kiesler observed: "Nature builds by cell division towards continuity whilst man can only build by joining together into a unique structure without continuity"[2]. For Kiesler, the distinction is that architects make things through brute force (connecting parts together to form a whole) whereas nature produces through a process of continuous construction whereby parts merge, overlap and conjoin one another. As the study of natural systems has always been an inspiration for design and architectural research has adopted biomimetics as sound strategies [3] and given that human construction activities tend to have a negative impact on nature, we seek to learn from the natural world to enhance the built environment and build knowledge and understanding to promote a cleaner and positive entwined relation between the two. We see digital design methodologies and fabrication technologies as a route towards this aim.

Fig. 1: Rendering of the structure with the proposed interactive lighting. Sensors on the outer structure provide input for light colours.

1.2. Design principles-structure description

Instigated as a student design ideas competition DARC's structure is inspired by Kiesler's Endless House where he expresses concepts such as 'connectivity', 'co-reality', and 'biotechnique' and the notion of continuity - in a form of a line for which both ends meet. With its shape resembling roughly a flattened spheroid, the geometry can be also seen as an eggshell envelope with seamless curvature. Given that biological systems may suggest solutions for technical problems [4] and that a standard optimal solution can be achieved by using different strategies performing optimally under specific circumstances [5], the proposed design is an expression of natural continuity that blends with the architectural brute force and intentionally strain is explored sequentially in all of its forms (axial, shear, bending, torsion). This combined loading approach as a design decision is achieved through a nature-inspired scheme with imperfections and asymmetries resulting in a structure in state of self-stress.

The structure consists of an outer layer of birch plywood members pulled inwards with wire-ropes. Rope ends connect at a triangulated mesh of wires in tension. The internal mesh is being stressed at the end of the assembly by pulling its four ends (two continuous wire-rope windings) that then pulls the outer thirty-eight cables connecting to the beams. Force is carried through a combination of bending and torsion in the outer beams and through pure tension in the wires. This follows a nature-inspired philosophy of different types of properties in biological structures [6]. Ultimately the structure is in a state of self-stress manifesting the principle that the global behaviour of a structure can be seen as the product of local actions [7]. In Kiesler's terms, continuity is expressed as the strain is being carried along the structure in different forms. The connecting wires between the two main structural layers carry a series of waterproof fabric voronoi-like cell shapes. Each cell is individually lit with a set of six lights (one for each voronoi face) and proximity sensors provide input for color values.

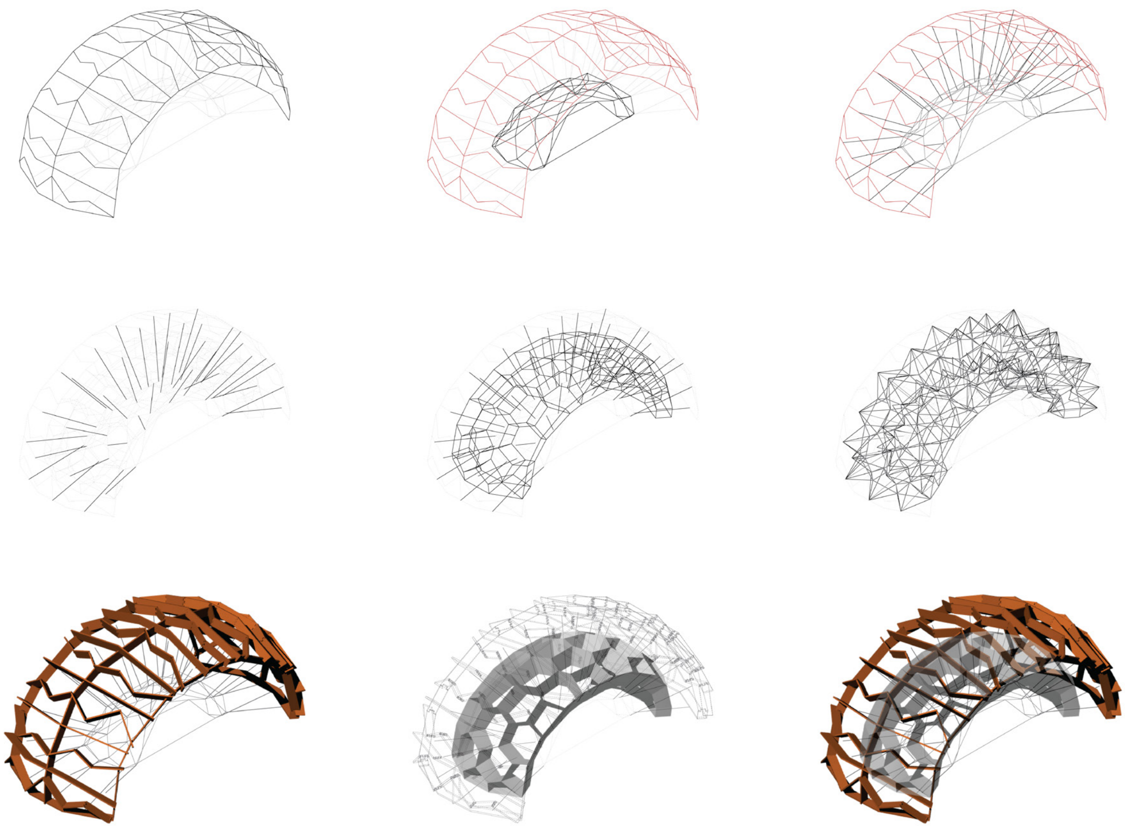

Fig.2: Diagrams showing member categories and assembling sequence (top row). Outer skeleton (birch plywood) connects with the internal wire mesh with additional wire ropes each one carrying a voronoi-cell waterproof fabric element. Bounding box dimensions: 5m, 2.5m, 2.2m (height).

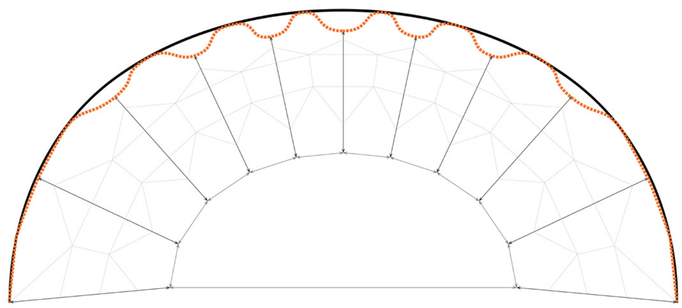

Fig.3: Outer structure members being pulled inwards with a set of wire-ropes ending to a wire mesh in tension.

2. Geometric method for determining force-moments-deflections

2.1. Research methods

Aiming to explore directions in pedagogical and intuitive approaches in structural design, original Graphic Statics methods are used to determine axial forces, bending moments and torsion, and also deflections. It is an objective of this project to explore the limitations and challenges of geometric and non-conventional solutions in structural analyses. Advanced methods were tested in Rhinoceros3D [8] environment with Grasshopper [9] and Kangaroo [10]. OasysGSA [11] was also used for cross-referencing with conventional methods for linear analysis.

2.2. Internal mesh geometry configuration

A first physical model (1:5 scale) was used to experiment with string on the internal mesh behaviour, shown in Fig.4. Strings were positioned to specific initial locations and were then pulled to examine the displacements of the mesh in tension. The first model with a full-envelope outer shell was followed by a second one resembling the designed structure to then notice the responses of both the wire-ropes and the exoskeleton. Fig.5 illustrates the kangaroo simulation mimicking the to-scale wire model behaviour. Kangaroo input parameters include anchor points at the outer skeleton and tension for all members while forcing length equalization of the outer thirty-eight long wires meeting the plywood members. Clearly, it is the intuitive aspect of the process that is of primary interest in an attempt to understand the force distribution and grasp a resulting wire geometry that can then be assumed to be in equilibrium. It is this geometry that then provides the basis for determining the force distribution on the outer thirty-eight wire ropes.

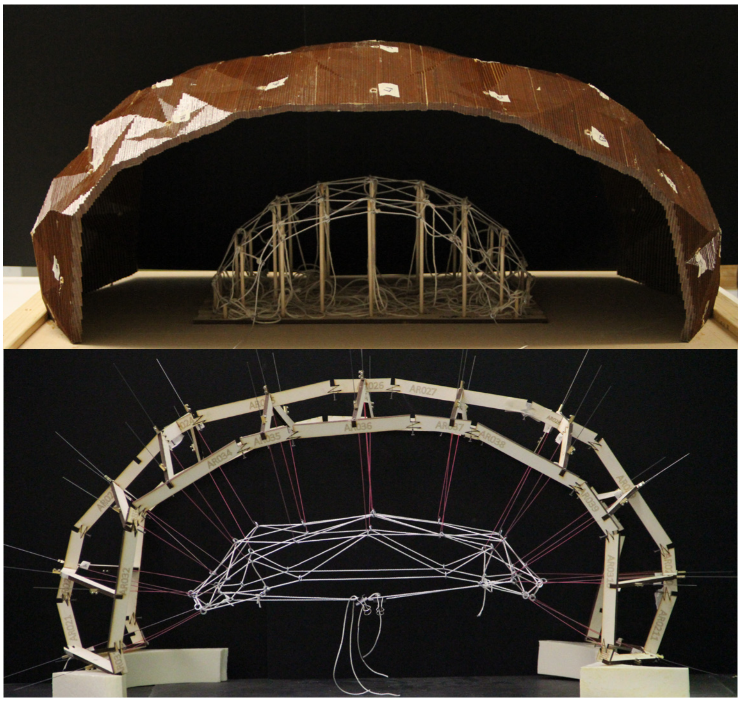

Fig. 4: Physical models were used for observing the internal wire mesh behaviour and provide input for determining the resulting geometry.

2.3. Outer wire-ropes force distribution

The output geometry from Kangaroo -based on the physical model behaviour- is now the input for an OasysGSA model and is also used to apply Graphic Statics methods. This initial geometry hypothesis allows for simplifying the problem to a linear analysis. The first OasysGSA model is a reverse configuration where the thirty-eight outer wires are designed as struts with fixed ends at the points where they meet the mesh; the outer skeleton is a set of lines hanging from the struts. Weights on either side of the structure define the loading case. The resulting axial force along the struts can be considered to be the amount of force (pure tension) in the thirty-eight wires of the original reversed model. These values are the ones to be compared with the first Graphic Statics approach following.

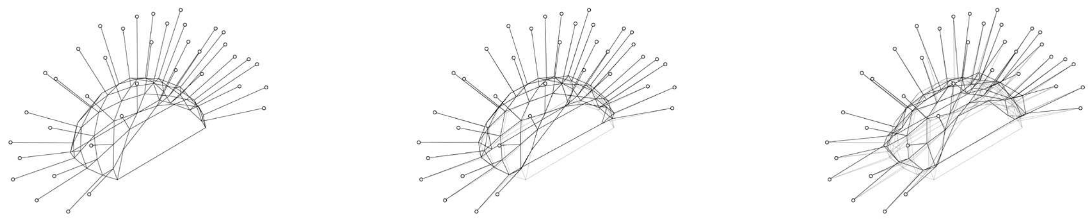

Fig.5: Diagrams grasping the Kangaroo simulation sequence, input parameters were adjusted to reflect the physical model behaviour.

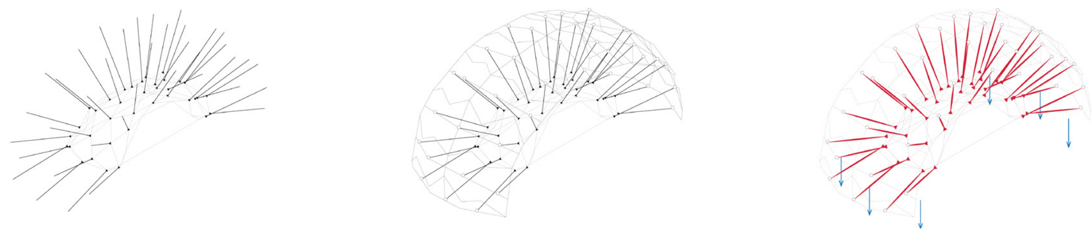

Fig.6: Sequence of the setup of the OasysGSA model, a reverse logic was followed, the set of the outer wires is considered a series of bars fixed on one end where the outer structure is considered to be hanging.

Construction of reciprocal form and force diagrams is a standard geometric method in Graphic Statics. Key founders include Maxwell [12] and Rankine [13] who both treated form and force diagrams as two-dimensional projections of three-dimensional polyhedral faces. Expanding this geometric principle to three-dimensional structures remains a non-trivial task continuously under investigation by many researchers [14] [15] aiming at generalising force-equilibrium-based form-finding methodologies or at overcoming Rankine's construction methods restrictions [16] [17]. Following the latter, advancements on gridshell geometries are shown in Athanasopoulos and McRobie[18] and McRobie et al.[19] Based on the same principles, the exercise presented here aims at testing the construction of a force and form diagram sum with the novel introduction of a particular mesh subdivision method, the Doo-Sabin subdivision [20]. A thorough analysis of this is beyond the purposes of this paper and only an initial, though original, investigation is shown.

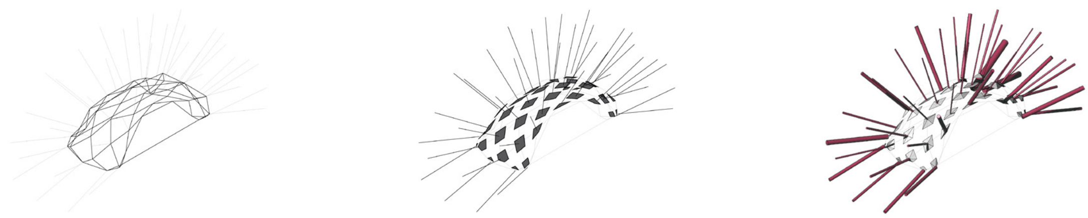

Fig.7: Introducing the Doo-Sabin mesh subdivision for determining force, the areas of the polygonal geometries created are assumed to provide the amount of force for each wire in tension; pipe diameters graphically show the deviation from OasysGSA values.

As shown in Fig.7, the internal mesh of the wires in tension is subdivided using the Doo-Sabin method. The subdivision creates a series of non-planar polygons on the mesh vertices. The intent is to examine if the area of each non-planar polygon is equal to the tension force of its corresponding wire-rope connecting to the exoskeleton. Each polygon is to be seen as a series of triangles by linking the polygon's vertices to the equivalent mesh vertex. The sum of the areas of the triangles is then the assumed amount of the pulling force carried by each wire. The results of this hypothesis are shown graphically in Fig.7 where the pipe geometry diameters resemble the variation from the values obtained from OasysGSA. Interestingly, the differentiation is relative to the angles formed between each polygon's triangles and the wire-rope connecting to them. Thus, the area values from the Doo-Sabin triangulation method can be further adjusted based on the geometry of the internal mesh, future examination of the approach should be focusing on this relationship. Clearly, for the purposes of further analysing the structure, the correct force proportions are selected with a maximum force set to 0,15kN as an average value of human pulling strength in different positions [21]. Concludingly, a Doo-Sabin subdivision prior to the Kangaroo simulation results in a resultant force with horizontal force, whereas the post-Kangaroo force resultant is a vector on the z axis pulling the exoskeleton downwards which will be equilibrated by the support reactions.

2.4. Graphical input on bending moments, torsion, and deflections

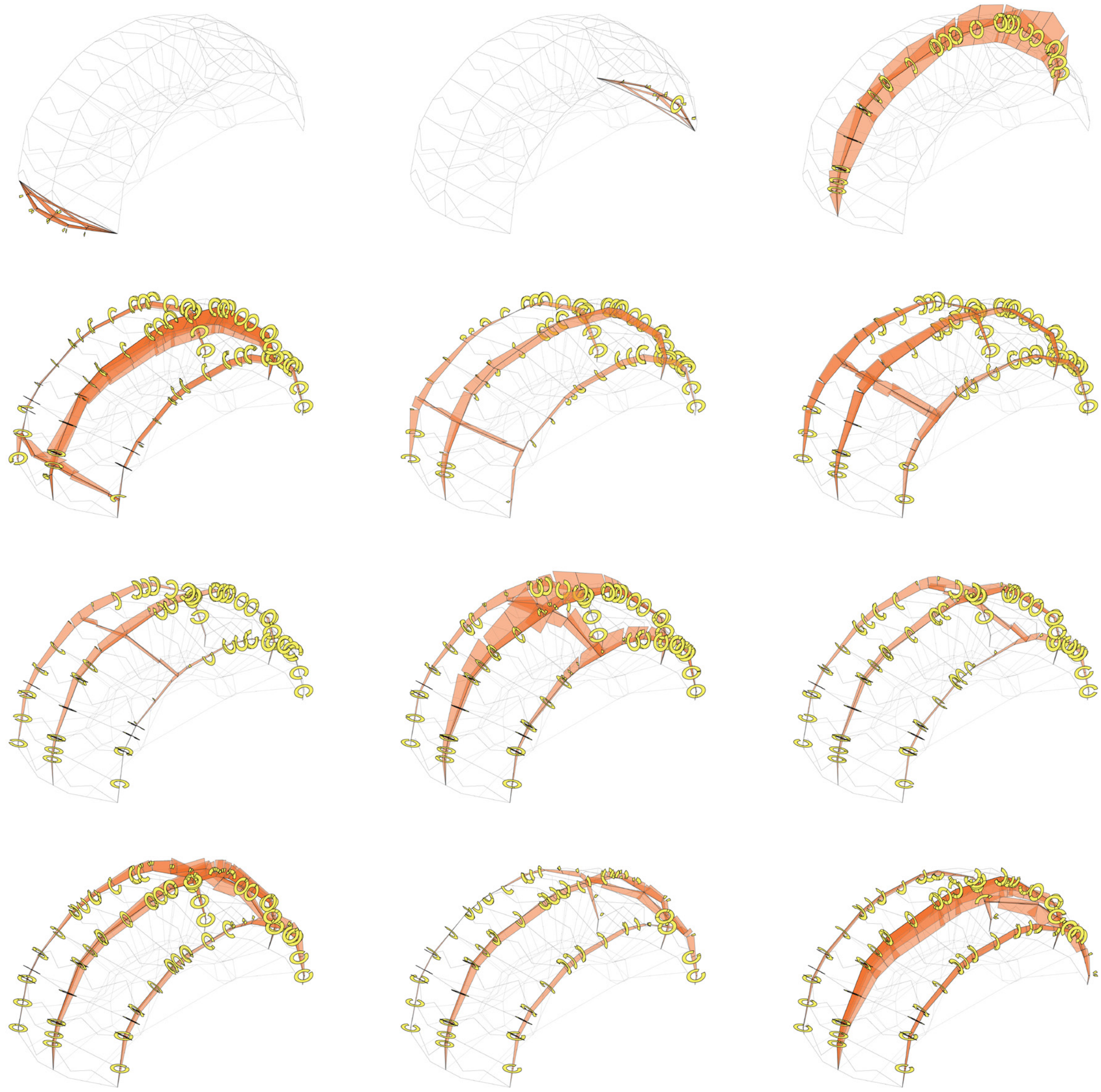

Fig.8: Display of the geometric loop-based method for distributing force and for visualising bending moments and torsion. The superimposition of the diagrams provides the total bending and torsion applied.

Following advancements in Graphic Statics based on the implementation of Clifford Algebra [22], and with the introduction of architectural hypotheses for frame design, more recent developments [23] focus on geometric methods for constructing bending moment and torsion diagrams on designated load paths. This approach, based on a loop element that can be orchestrated for composing both the form and the force-and-moments diagram is applied here and a series of such loops are constructed to visualise bending and torsion. Back to the discussion on Kiesler's continuity, each loop expresses the main design concept of combined loading being carried along its curvature. Fig.8 shows different sets of loops carrying the force of their connecting wires with their corresponding diagramming of bending and torsion. Superimposing those provides the total bending and torsion values that are used for checks on the structure's cross sections. Since torsion maximises shear stresses on the members [24], birch plywood properties provide the maximum allowable shear stress parallel-to-the-grain value for the check. Interestingly, the calculated shear stress approaches the material limit (11 MPA compared to 12 MPA), a fact that highlights the overall delicacy due to the small cross section (21mmx96mm) and also the significance of having the ability to examine torsion effortlessly with this graphical method. This extreme case of approaching the limit only applies to very few spots along the outer exoskeleton and, certainly, the additional nodal treatment (finger joints with dowels) provides additional strength.

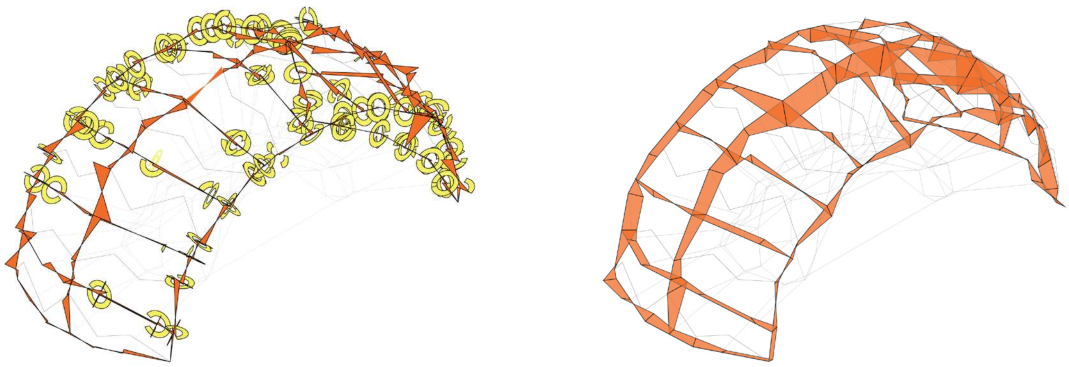

Fig.9: Resulting final diagrams of bending moments and torsion (left) and of deflections (right) following the geometric methods applied.

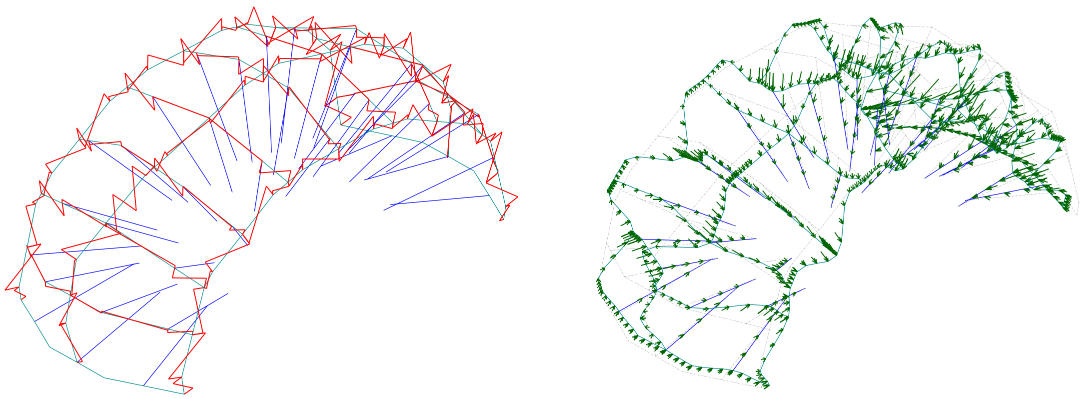

Fig.10: OasysGSA analysis results.

Building upon traditional geometric methods for linear deformations, advancements [25] have introduced solutions for studying kinematics on trusses. Following a similar approach, further developments [26] have introduced the use of the conjugated beam method [27] [28] for graphically determining deflections for cantilever beams. The original application of the same method is shown in Fig.9 where the initial loops are used as input for implementing the conjugated beam method. The resulting deflection diagram provides an intuitive reading of the structure's behaviour and can then be juxtaposed to an OasysGSA analysis. Notably, the latter lacks the multi-directional aspect of bending diagramming that the graphic method offers, and it is the conventional analysis that does include rotations to its calculations, rotations however, are more intuitively shown in the geometric method describing torsion. Furthermore, since force distribution is decided simultaneously with the construction of the initial loops, their redesign can allow for more precise solutions.

3. Assembling and materials

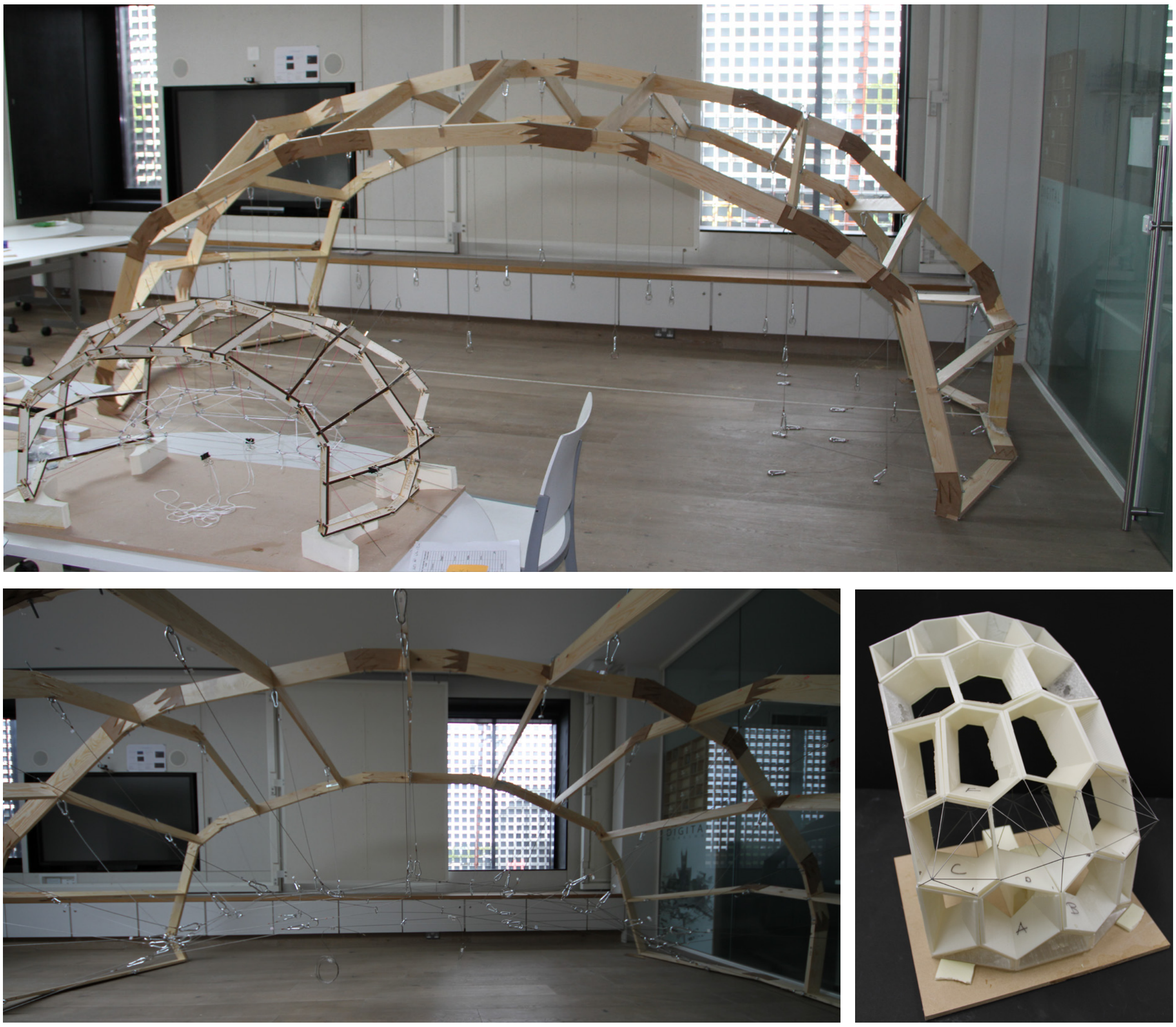

Fig.11: Structure and prototypes.

After the assembly of the outer exoskeleton, the outer wires are hanged to lift the internal mesh. The latter is then pulled at its four ends to provide the tension. At the same time each outer wire carries a corresponding voronoi cell with the lighting(not shown). Following the competition brief, material sizes were selected based on weight limitations. Same applies to the overall size of the structure since the decomposition of all members has to address the transportation requirements. Furthermore, the 3D-printer was used for prototyping the voronoi geometry that works as scaffolding for understanding the fabric behaviour.

Materials weights: Birch plywood members: 0.16 cubic metres* 510 kg/cubic metre =~ 77kg, Wire rope 2mm - 1.52kg/100metres *250m =~ 4kg, , Waterproof fabric: 0.2kg/sqm *20sqm =~ 4kg, Connectors (dowels and metal) =~ 5 kg.

4. Conclusion

Following Kiesler's ideas on the notion of 'natural continuity' and its negotiation with the architectural 'brute force' this competition entry proposed a nature-inspired scheme exploring a combined loading approach to structural design and the potential of this loading scenario to be apprehended through intuitive geometric methods. Tools used and geometric constructions developed included the Kangaroo plugin for Grasshopper, the Doo-Sabin mesh subdivision method, and latest advancements in Graphic Statics for visualising bending moment and torsion together with deflection studies based on traditional techniques. Conventional methods were used to compare results intuitively. It was shown that notably, the Doo-Sabin mesh subdivision provides a fertile ground for exploring a novel way of further revisiting the construction of a Rankine three-dimensional force diagram. It was also shown that the benefit of trivially constructing torsion diagrams allows for instantly locating the spots of maximum shear stress of the material (parallel to grain) without tedious calculations. Furthermore, it was shown that as conventional tools by default discuss bending only along a global z-axis, the developed geometric method for constructing bending moment diagrams offers a specificity of the input geometry that is of value. Also, the limitation of omitting the twisting in the conjugated beam method is an area for future investigation. Concludingly, expanding the application of Graphic Statics methods in architectural morphologies beyond their mere relevant vocabulary provides insights on the geometric techniques themselves and, certainly, nature-inspired designs and biological structures offer a rich framework for such an experimentation.

Acknowledgements

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