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The Geldeford Riband Pavillion

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Abstract

Since 2012, our team of an artist, computational designers, and engineers (Godfrey, D. and AKT II P.art, Dudley, J. et al) have collaborated in the development of new digital design methods, modelling, simulation, and fabrication tools, to expand the material and structural complexity of Godfrey's sculptural systems. Godfrey's earliest sculptures were informal and improvisational arrangements of steel cylinders where the shape of the individual elements resulted from and were determined by gravity, adjacency, size, scale, and material behaviour (*Codaworks, n.d.)*

Over the course of our collaboration, we have completed nearly a dozen permanent and temporary sculptural installations, many in the context of public art. Working in the public realm requires meeting or exceeding rigorous building codes around life safety and use, and would be challenging for even the most straightforward forms, but is especially difficult given the inherent characteristics of Godfrey's works: responsive structures, minimal material thicknesses, dynamic behaviour, and so on. To counter this, we employ computational tools at each step of the design process, enabling us to construct simulations of these unique systems that provide the necessary predictability of their behaviour, coupled with innovations in structure: for example, by employing varying thicknesses of steel and adjusting the size and depth of individual conical elements we can control performance locally or globally across these structures.

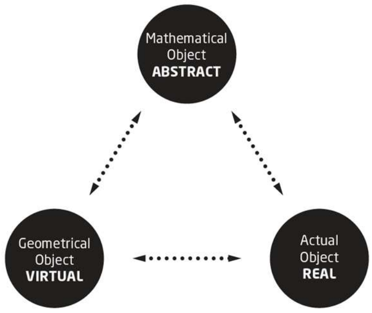
What further distinguishes this work from those created through more fully automated processes is that the digital invention and precision is coupled with personal material imagination and expressiveness; both areas of expertise meeting in a space of semi-predictability, where cutting-edge digital forms are resolutely hand-made.

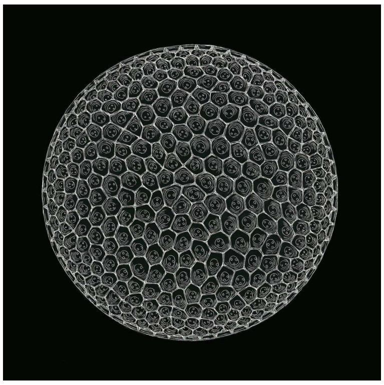
Our submission for IASS further expands the capacities of these systems: rather than relying on discrete conical elements, we propose to create an extruded ribbon-esque structure that loops on itself, creating organic truss-like elements running across the pavilion's surface. In addition to development of the ribbon concept, other innovations explored through this pavilion focus on analysis of the structural stressing of the dome (with its multiple openings) to influence and optimise the density and packing of the hoops themselves, thus explicitly linking behaviour and form through digital feedback. The challenges inherent in the IASS brief - pavilion scale, weight limits, shipping requirements - have led us to use lightweight, flexible, and resilient polypropylene and nylon fasteners for the first time in a Godfrey sculpture. This will create a structurally sound yet environmentally responsive structure full of light and space.

Keywords: *Parametric Modelling, Digital Workflows, Structural Optimization, Spatial Packing, Circle Packing.*

1. Recollection – Previous Work (2000 – 2020)

1.1 Origins – Initial Research





Our proposal for IASS 2021 has its origins in Godfrey's earliest sculptural works: a series of manually designed and assembled structures composed of both flexible materials and connections that allowed these dynamic structures to exhibit a range of behaviours. These new structures performed, in a crude way, like natural, living organisms – they were only semi-predictable and (much like a plant) would vary in form depending on the environment in which they were sited. As in nature, these variations were not indiscriminate, and could only take on forms proscribed by the genetic (structural) code inherent in their material and construction.

1.2 Evolution; history of built and unbuilt projects

1.2.1 Background

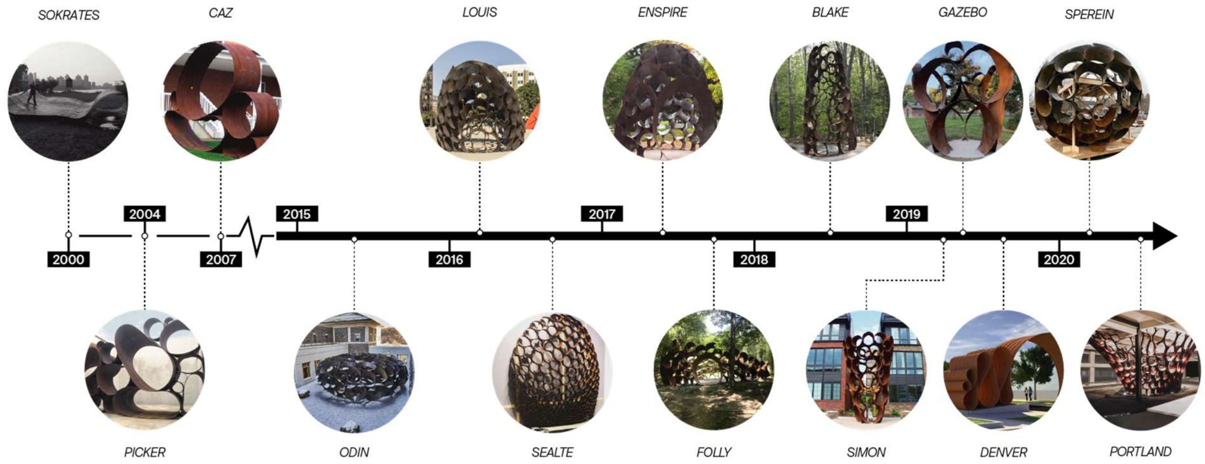
As the scale and complexity of the earlier works grew, it became clear that there was a need for more control and understanding to undertake these installations safely and to discover the next step in the evolution of the work. In the early 2000's during several of the presentations of this body of work in public venues, Godfrey was asked to consult with engineers by the presenting institutions. In most cases, when confronted with these unusual forms and materials, the engineers just threw up their hands and said it was impossible to provide any reliable structural analysis of these complex systems.

1.2.2 Evolution / Timeline

In the earlier sculptures the shape of the individual elements was determined by the combination of gravity, adjacency, size, scale, and material behaviour. Making these sculptures was intuitive and improvisational, with little formal engineering and were limited to linear, fence or wall-like arrangements. The methods created during our initial research project (Picker Interdisciplinary Science Institute, Colgate University, 2012 – 15) built on the physical ways form emerged in the earlier work. These newly developed digital tools made it possible to break away from linear arrangements, allowing us to pack conical sections on complex surfaces. We can also simulate the compressive forces where the sections collide and rapidly test a range of potential configurations on these virtual surfaces. Our most recent working methods take advantage of both the digital strategies of the bespoke, the design and execution of otherwise impossible structures, and of optimization, using and analysing the data that undergirds these designs in different ways and forms. What distinguishes our work from that created through more fully automated processes, is digital invention and precision coupled with material imagination and expressiveness; both areas of expertise meeting in a space of semi-predictability, where cutting-edge digital forms are resolutely hand-made.

One critical aspect of computational design is the ways that the underlying data can be employed in structural analysis and optimization. Working in the public realm requires meeting or exceeding rigorous building codes around life safety and use, we have successfully constructed simulations of these unique and dynamic systems that provide the necessary predictability of their behaviour, coupled with innovations in structure -- for example by employing varying thicknesses of steel and controlling for the size and depth of individual conical elements to increase performance across the structures.

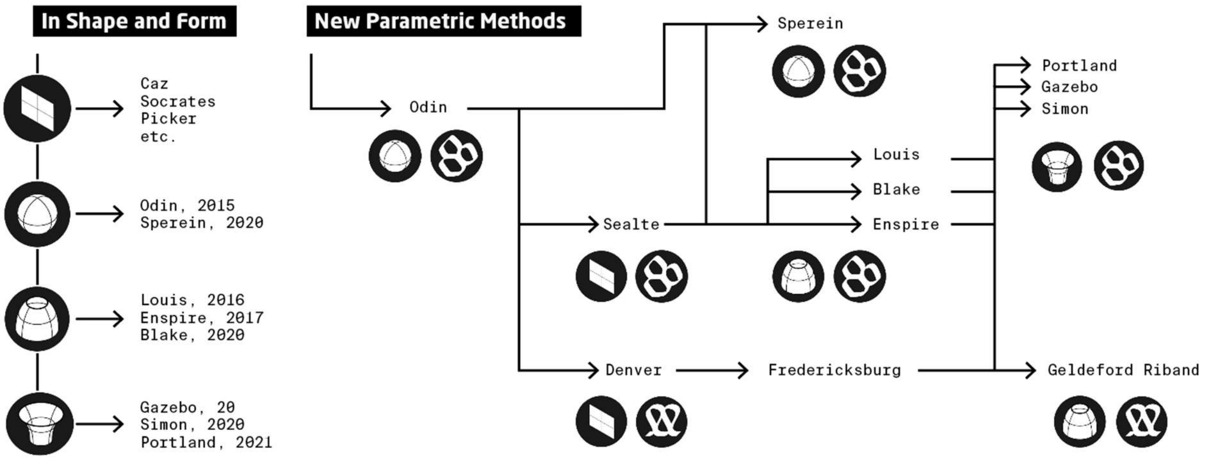
The tools and relationships formed during the Picker ISI research project set the stage for a remarkably productive period in Godfrey's career. Since *Odin* we (including our core IASS Pavilion Competition team) have completed ten public and private commissions across the US.



Timeline over previous collaborations

Over the course of these many projects, in collaboration with an evolving group of design and engineering partners at AKT II (Tibuzzi, E., Pedersen, J., Dudley, J., et al) we have continued to refine and augment these digital design and fabrication tools, guided by the same iterative process that informed the earlier work: exploring ways to preserve or alter the systems behaviour through simple changes.

Across all of these projects, a series of themes have been explored - such as material behaviour, spatial connectivity and packing, and the relationship between component and assembly. As our understanding of the structural behaviours that govern these systems has grown, the complexity and scale of subsequent sculptures has been able to increase, and new ideas have been introduced that morph and reformulate these relationships.

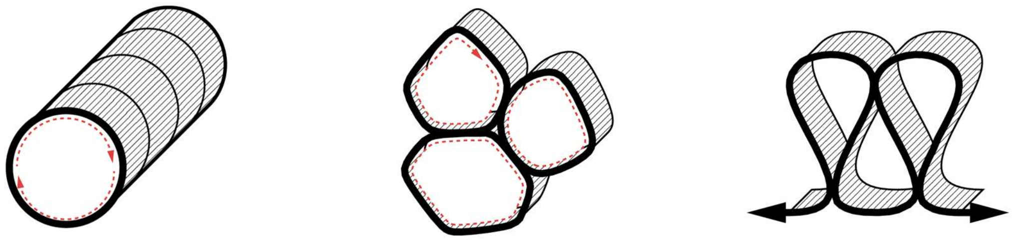


Typological evolution of sculptures.

Presently, we are engaged with projects in Denver, CO, Alameda, CA, Portland, OR and a commission for *Time Space Existence* organized by the European Cultural Centre that will run concurrently with the 2021 Venice Architecture Biennale (postponed from 2020).

1.3. Exploration of Typologies

All of these projects can, on a component level, be divided into three distinct typologies. These are the early cylindrical compositions, then the 3-dimensional hoop packings, and finally the more recent introduction of continuous ribbons.

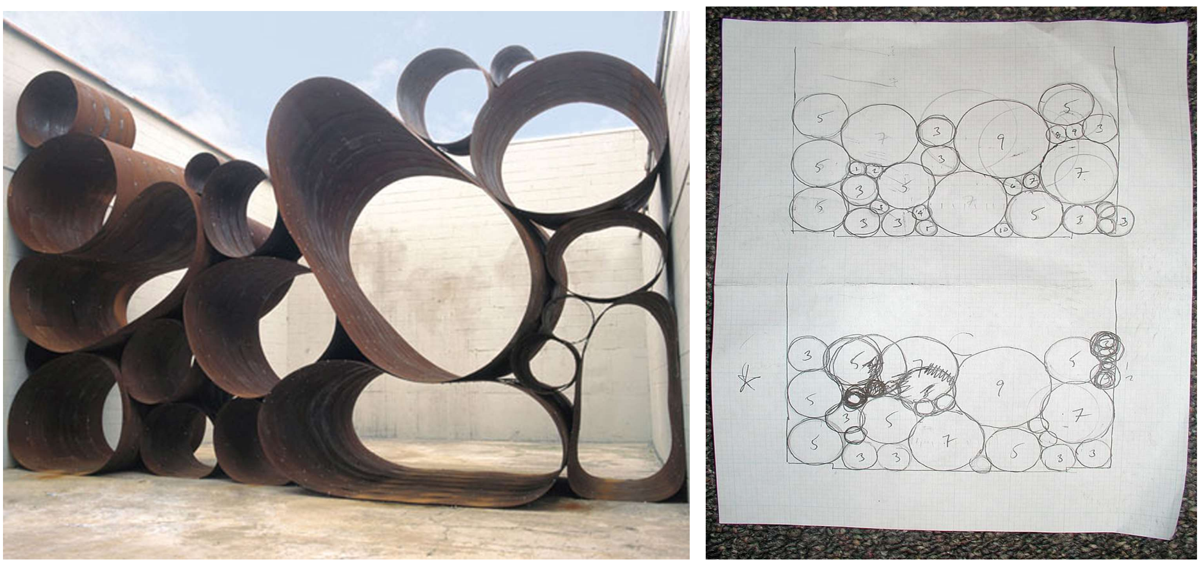


Local typologies: Cylinders, Hoops and Ribbons.

Although these three typologies share a common language and foundation in their material processes, there are also key aspects which distinguish them from one another.

1.3.1 Cylinders

The earliest forms in this series were cylindrical structures built from concentric Corten steel strips. Groups of these singular tubes – as long as 44’, and with diameters up to 16’’ – were informally rested against architectural elements within exhibiting gallery spaces. These architectural elements – columns, staircases, walls – shored up the thin steel tubes, preventing complete collapse and giving them shape. Later this process evolved into cylinders of varying diameters and lengths positioned in more complex arrangements, sited in various architectural and landscape locations, a set of elements that could be reused and remixed in both indoor and outdoor venues.



Cylinder examples: all from Picker (2004).

Engaged by gravity, position and orientation the cylinders settled into their own structural logic and had an active role in their own making – their strength and physical integrity rely upon a capacity to absorb and distribute stresses throughout the network of components that made up the whole. Each installation built on the performance of previous experiments: exploring ways to preserve or alter the behaviour of the system through simple modifications to form, materials, and process.

1.3.2 Hoops

The cylindrical typology relied solely on intuition and physical experimentation, and thus only allowed simple uni-directional groupings, by applying digital tools and processes it was possible to break away from those linear arrangements and instead pack conical extrusions across complex surfaces.

The first of these hoop-based structures was *Odin* (2015) built on the campus of Colgate University. With *Odin*, the decision was made not to use mathematics and computer science to instrumentally demonstrate mathematical forms, and instead work to develop methods to generate ideas and forms, embedding then within a set of digital tools and form-finding processes.

Hoop examples: first two are Odin (2015), then Enspire (2017) and Sperein (2020).

These packed hoops generated global forms that were more determinate and static, in comparison to the previous cylindrical structures, whose final forms were dictated by the interplay of gravity and the freely stacked elements within a fixed architectural boundary. However, in the process of geometrically defining these hoop forms, features mimicking the ad-hoc settling and bulging of the cylinders could still be introduced and controlled. The agency in these systems therefore transferred away from the process of manual positioning, and into the geometric algorithm that defined each hoop's individual behaviour, and the whole sculpture's global performance. Once again, the degree of control one has over the design is only implicit though: the designer dictates the input parameters and principles of the system, but not the final geometry or equilibrium state.

Some examples of this typology - of which many have been constructed - are the aforementioned *Odin* sculpture, as well as *Enspire* (2017), *Blake* (2018), and most recently *Sperein* (2020).

1.3.3 Ribbons

In recent years a third typology has emerged – of continuous ribbons that cellulate space in a manner similar to the hoop sculptures, but which also reconnects to the expression of continuous surfaces present in Godfrey's earliest pieces like *Socrates* (2000) and *Picker* (2004). These ribbon projects have explored both straight extruded forms - such as *Denver Gateway* (2020-ongoing) and *Brunswick* (unrealised) - and also variable-direction extrusions - such as *North Boulder Competition* (2019-unrealised) and *IASS Pavilion* (2021).

Ribbon examples: Denver Gateway (2020-in construction), Brunswick (unrealised).

These projects have focused primarily on different aspects to the past cellular sculptures: looking at the ability to locally reinforce and adjust structural behaviour through different layering and lapping techniques in the strips, as well as beginning to develop an expression of freeform structural trusses within the global ribbon shape.

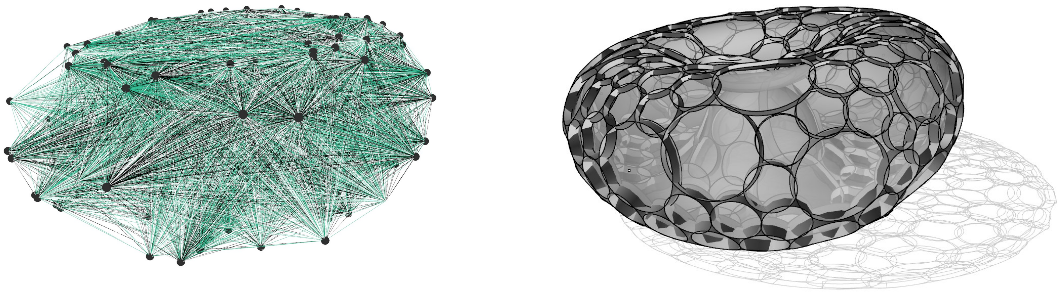
1.4. Exploration of Computational Processes

In parallel with the typological progression described above, each project has also afforded the opportunity to refine (or challenge) our set of computational design processes. Lessons learnt from previous built works are used to refine these digital form-finding methods and modelling tools, while each new commission inevitably generates new constraints, features or artistic ambitions. The end result is an ever-evolving digital toolkit that in many ways has the artist's sensibilities and interests 'embedded' within it.

1.4.1 Spatial Packing

The project that started this toolkit was *Odin* (2015), for which our first parametric circle packing was developed. Like the earlier works, this sculpture shares a material and formal vocabulary of packed or aligned circles, and like them the final outcome here was also not predetermined but instead emerged organically through the process of problem solving and form finding.

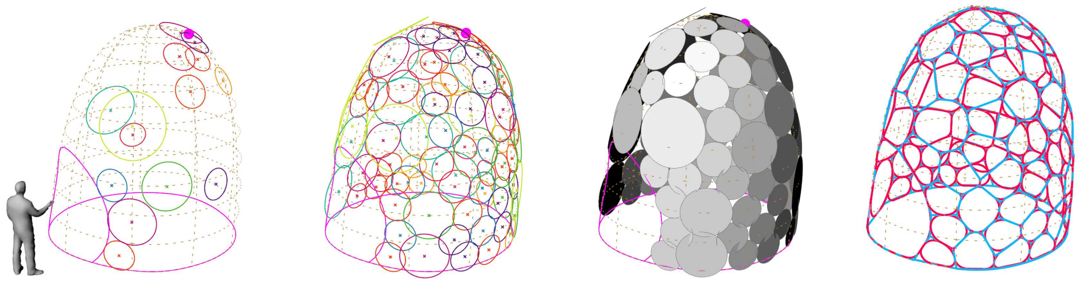
With the help of AKT II, Tucker, and Pisanski, Godfrey worked to create a series of digital definitions that tested various patterns and forms, eventually leading to a first physical model about one-sixth the size of the final piece. The virtual computer models of the designs took a year or more to develop and refine into a form which was satisfactory.



Initial circle packing: Odin (2015).

The digital packing process utilised the spring solver system in the Grasshopper plugin Kangaroo by Daniel Piker [1]. Each node in the system, representing a hoop, was placed on the 'control surface' (in this case an irregular indented ellipsoid defined by Godfrey) and given a desired radius, and allowed to attract and repel nearby nodes until the system found a state of equilibrium acceptable to all nodes. These points and their associated radii then served as the base for the generation of the hoops.

In a final set of steps, the ground fixings and bolt holes and connections between adjacent hoops were automatically generated, and the entire 3D arrangement of hoops was automatically exploded, unrolled, labelled and nested for fabrication. The labelling generated at each pair of bolt holes clearly defined the adjacent hoop that must be connected to, thus obviating the need for further assembly information.



Refined circle packing: Enspire (2017).

Although the packing algorithm used for *Odin* had proven largely successful, in later projects it lacked flexibility and the artist desired finer control over certain aspects of the process. Therefore during the *Enspire* (2017) project, the Kangaroo implementation was substituted with a custom circle-packing process coded by AKT II.

This process has been slowly expanded over each subsequent project and now allows, among other things, for the circles to dynamically adjust their radius during the packing process in response to various factors (custom colour gradients applied to the underlying mesh control surface, graph-based size distributions, input control curves, etc.), and also gives the artist the ability to intuitively interact with the process while it is running: adding or removing circles, overriding the default radius definition controls, and so on.

1.4.2 Voronoi Cellulation and Density.

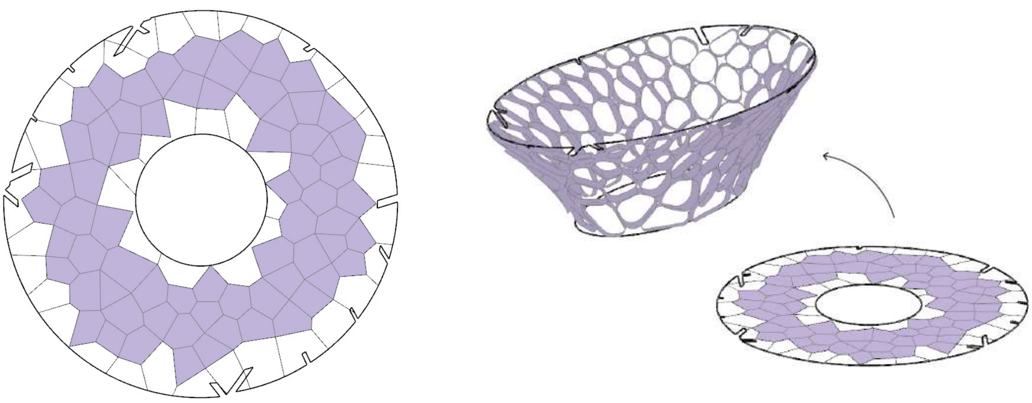
Another problem that presented itself during the design of *Odin* was that the circles in the packing were not perfectly cotangent, with small discrepancies and overlaps between adjacent circles due to the comparatively tight curvatures of the underlying form (in comparison to the desired circle size). To resolve this, two intermediate steps were introduced during the *Sealte* (2016) project: a voronoi cell division process and a smoothing process that both occurred after the step of circle packing and before extruding the hoops. In this new method, each circle is mapped to a closed cell representation, which ensures that a clean geometric condition is achieved at the locations where pairs of hoops connect. From these cells, the final physical hoops were then generated by smoothing and relaxing their polygonal outlines, creating perfect co-planar connection zones between hoops.

Voronoi cellulation and density: Sealte (2016).

These extra steps begun with *Sealte* have been refined and improved since – for example, the traditional unweighted Voronoi algorithm averages out any adjacent cells with differing input radii, and so various Voronoi re-weighting options have been added to the toolkit to preserve that radius contrast desired by the artist.

1.4.3 3D Packing vs. 2D Packing and Mapping

Across all of the previous examples, the circle packing was carried out on a 3D control surface. For many of these projects this was the most intuitive approach, as each packed circle directly corresponds to a final hoop position and scale. However, in cases like the *Portland Sculpture* (2020-ongoing), which have which have a complex set of edge conditions and boundaries on the surface where it meets other elements such as roof beams, this 3D process can be problematic. The algorithm can struggle to adapt to short edges and tight direction changes along these surface boundaries. To resolve these constraints, a different approach was implemented: the domain of the control surface was mapped into 2D space, and this planar form was packed with an initial circle distribution. This arrangement was then cellulated using the weighted Voronoi processes and remapped back into 3D space on the original 3D control surface. By utilising this approach the design team found each new packing conformed far more closely to the physical site constraints – however further work is needed in this step of the process, as some manual remodelling and adjustment was necessary to avoid small clashes between the upper row of hoops and structural beams.



3D packing versus 2D packing and mapping: Portland (2020).

2. New Research Directions – The Geldeford Riband

The IASS pavilion brief provides an interesting framework for a set of new directions in which to take this continuously evolving set of work. Given the scale and format for the pavilion some topics have been explored to further extend both the geometric typologies and the digital form-finding processes.

2.1.1 New *typologies and their modelling a*pproaches

In terms of typologies and modelling, two specific new strands have formed the base of the research behind this pavilion design. The first is how to link the form and behaviour on a global scale in terms of structural performance. As the form has a stress distribution which is largely influenced by properties in the base geometry such as edges, apertures and curvature, how do we engage a conversation between the component packing and the features of the underlying base geometry? Here the power of computational design enables the designers to use the underlying analysis data both as design features and as a form of optimisation by selectively distributing material where it's needed.

The second strand of progress looked at a new form of local typology, a merging of the hoop and ribbon concepts presented earlier. This new typology took the form of an elastic continuous ribbon wrapping around itself and forming long, truss-like components which run across a three dimensional surface. These ribbons were given their own structural agency as an actively bent and elastic element.

2.1.2 New material opportunities

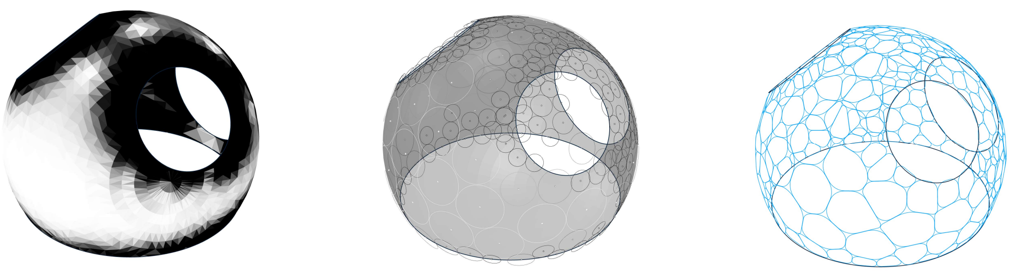
When working with steel, the hoops were rolled into an explicit form, but as can be seen in the earliest works, there is an inescapable elastic nature to the components, and they morphed and deformed with time due to gravity or other external factors. Instead of counteracting this, we can think of the components as elastic and active, as opposed to having an explicit form imposed on them.

With the brief of the IASS pavilion being a lightweight pavilion, and with the desire for the components to be active, polypropylene was selected as it's an ideal material that exhibits the desired structural properties and weight. This change in material from the earlier rolled-steel forms necessitated some adjustments in how the structure is modelled, analysed and fabricated - while also keeping some shared, fundamental properties, such as the sheet-like nature.

Density	Strength	Young's modulus	Thermal Exp
0.946 g/cm^3	40 Mpa	1325 Mpa	104E-6 1/K

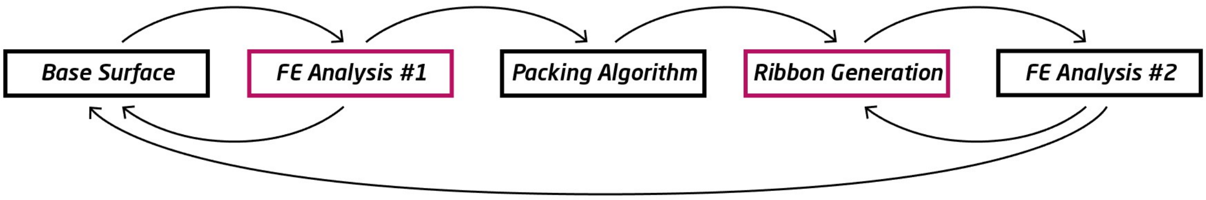
Material properties Table (Polypropylene Material, n.d.)

2.2 Pavilion - Design Exploration



Different stages in the global form finding.

Left shows the stress map, Centre the packed circles and right the resulting cells.



Steps for the pavilion design process. Red steps are new additions compared to the previous projects.

2.2.1 Form Finding (Global structural system)

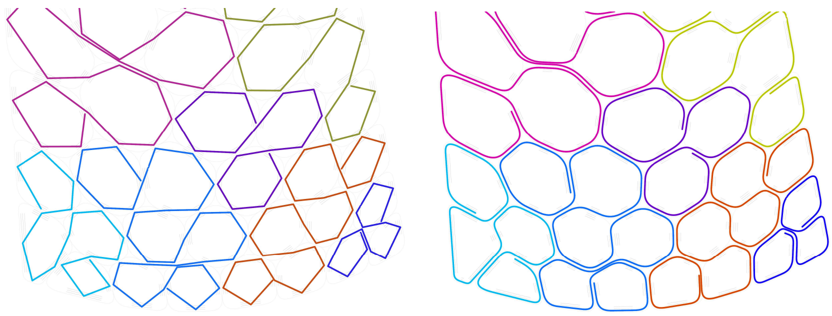
The new process established for the design of the pavilion was largely based on the previous packing logic. Generation of the pavilion started from a sculpted control surface, which in this case was a truncated sphere cut with a series of planes to create apertures.

From the control surface an initial structural analysis was carried out based on the global form as a continuous shell, which returns a map of the stress distribution in the idealised form. The distribution is closely linked to the underlying properties and features of the control surface, such as apertures or curvatures. Loading for this analysis was a simple combination of both vertical and horizontal loads, in-order to capture a general state of stress. Based on this a gradient was generated by interpolating from white (least stress) to black (most stress).

With the stress pattern represented as a grayscale gradient, this data was then used with the streamlined process to alter the packing density, becoming denser in regions of higher stress. The circle packing used the same process that has been explained earlier, with the addition that the stress pattern formed the base for the circle radii. Regions with higher stress were given a higher density of material, as the circles in these areas reduced their radius and packed tighter.

2.2.3 Form Finding (Local material systems)

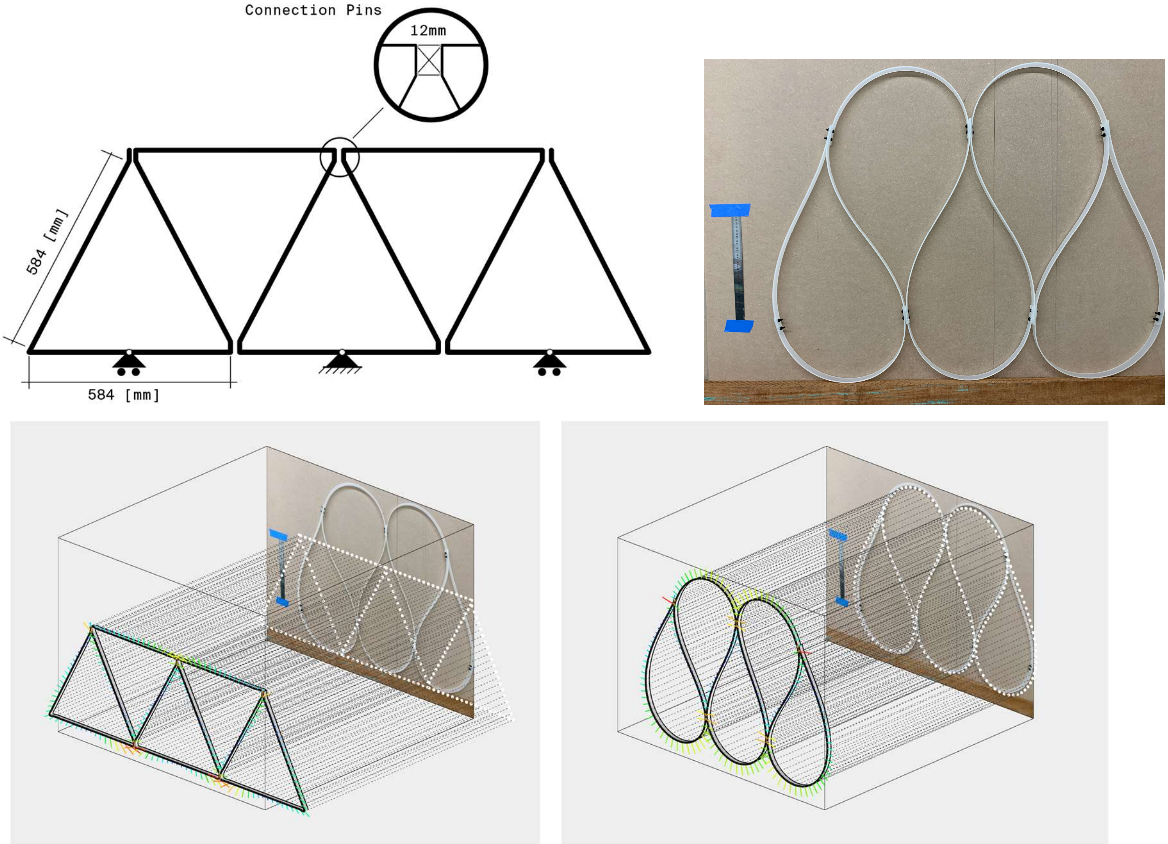
On the local component level two new aspects were explored, both being extensions of the old hoop definition. Firstly, the ribbon geometries were generated from the cell division by clustering together sets of hoops into topologies that described how the ribbon moves across the surface, and which were then used to generate a continuous ribbon geometry. To create these topologies an incremental breath first search (BFS) was used to find cell clusters based on a 'parent' node and generalised connectivity diagram. Underneath, this was driven by a half-edge mesh structure (Plankton Mesh Library, n.d.) created from the Voronoi cells. Still, some need for manual interaction was needed to achieve a saturated packing, as some cells ended up isolated and did not merge into the clusters.



Ribbon examples. Left shows the ribbon topology from the cluster of cells. Right shows the physical ribbons

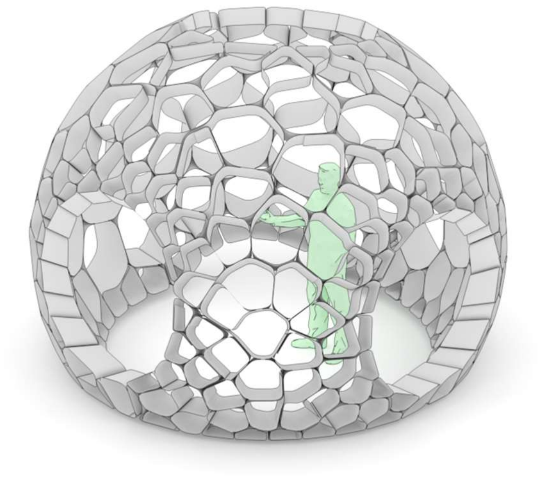
Further, these elastic components must be understood in relation to their self-forming nature. Each component was prescribed a set of connections at certain lengths. To achieve this a physical mock-up was made, to calibrate the digital material simulation with their real-world phenomena. To capture this behaviour, simulation models using the engineering extension for the previously mentioned Kangaroo plugin were set up (Kangaroo 2 Engineering Extension, n.d.). Using a rod with an equivalent bending stiffness to the strips, the initial configuration based on the connection positions at the specific lengths could be modelled. This corresponded to the ribbon topologies shown above. The bolted connections were modelled as two bolts with the spacing set at a fixed length, which is the centre-to-centre distance of the connected strips. Abstract braces were added to lock the shear.

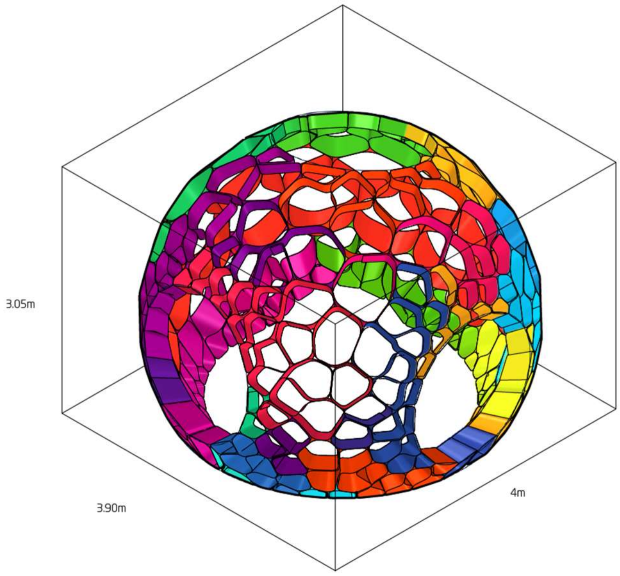
As the initial configuration was not in equilibrium, the strip sprung into its desired shape and the curvatures smoothing out. The outcome of this simple model corresponded well to the physical prototype, as seen in the images below.



Left shows initial configuration projected onto the physical prototype. Second shows the digitally deformed strip.

2.3 Proposed Pavilion Design





Weight [kg]	Number of Ribbons	Surface Area [m^2]	Dimensions [m]
170kg	42	63	3.9 x 4 x 3.05

The final pavilion design proposal can be seen in the images above. It features a total of 42 ribbons forming the structural envelope, weighing a total of 170kg.

3. Conclusions

The design of this pavilion allowed this series of works to progress into new and exciting territories – by both extending the current library of component typologies and with new computational design processes. These design explorations have continued the current trajectories while also reconnecting with principles present in the earliest work of Godfrey and embraced the elastic nature of these compositions and material.

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