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Magnolia: a glass-fibre reinforced polymer gridshell with a novel pattern and deployment concept

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Abstract

This paper presents the design, structural concept and construction process of the Magnolia gridshell, a temporary structure built as part of a larger exhibition on timber gridshells, which itself was part of Sheffield's "Year of Making 2016" festival. This deployable, lightweight structure in composite materials was built by staff and students of Sheffield Hallam University during a workshop which took place from Tuesday November 1st to Friday November 4th 2016. The gridshell features a central funnel with a pattern of varying density and a unique deployment concept. A two-stage form-finding process was required in which the pattern was determined first, before arriving at the final shape.

Keywords: Gridshell, elastic, deployable, form finding, glass-fibre reinforced polymer, GFRP.

1. Introduction

This paper details the design, engineering and construction of the "Magnolia" gridshell. The system is constructed from a flat mat that is then deployed, i.e. bent into shape. For more information, the reader is referred to Hennicke and Schaur [3] on traditional gridshells, and to Chilton and Tang [2] and Schober [8] on general gridshells in timber and steel respectively.

1.2. Context

The gridshell (Figure 1) was constructed from Tuesday November 1st to Friday November 4th 2016 at Sheffield Hallam University (SHU), in Sheffield, UK, as part of "Catalyst: Festival of Creativity" which was SHU's offering to the city's "2016 Year of Making" event. The structure was built as part of a larger event on gridshells, which included lectures, an exhibition and the UK book release of Chilton and Tang [2].

1.3. Description

The design of the gridshell was initially inspired by strong double curvatures of the magnolia flower. In nature, naturally existing curvatures produce efficient and strong structural forms. The final design was 9.5 by 9.5 m in plan, and 2.8 m high. It was constructed using: glass-fibre reinforced polymer (GFRP), 8 mm diameter, 1.5 mm thick rods; steel, 2 mm diameter cables; plastic cable-ties; gaffer tape and heavy duty tape; MDF compression rings; and, plywood abutments filled with sand. The grid spacing varied and was either 45 by 45 cm or 90 by 90 cm. The total length of GFRP rods was about 740 m. The gridshell itself weighed 112 kg and was secured to five plywood abutments. The material cost of the gridshell, excluding timber, was estimated to be GBP 2.113 or 24 GBP/m^2 including tax.

Figure 1: Final structure erected in November 2016 at Hallam Square, Sheffield, UK (© Matt Bell for SHU)

1.4. Contributions

Two novel concepts for deployable gridshells emerged from the design process:

- the flat mat was constructed to wrap in on itself, forming an upright cylinder, then pulling its upper edge to the centre;
- the gridshell has a pattern that varies in spacing.

The deployment concept using a cylindrical, intermediate step differs from existing gridshells. In those instances, the shell starts from a planar mat where either the exterior is eased down or the interior is pushed or pulled up mechanically or pushed up using air pressure (Quinn & Gengnagel [6]).

The varying spacing was necessary to keep the grid density at the funnel manageable. This spacing and the central funnel support were also a product of the initial design intent, which was to refer to the magnolia flower, through the shape and pattern of its leaves. The idea of the funnel itself, though not previously executed to our knowledge, does already appear in designs presented by Hennicke and Schaur [3].

2. Design and engineering

The design was generated and structurally optimized using parametric modelling in Grasshopper (Rutten [7]). The design process consisted of two stages: pattern finding of the flat mat based on a parametric input surface; and final shape finding based on that pattern. This final model also included structural analysis of the gridshell and production of labelled fabrication plans for the flat mat. Several plug-ins for Grasshopper were used: Toolbox elastic gridshell (Bagnéris et al. [1]), Kangaroo 2 (Piker [4]) and Karamba3D (Preisinger et al. [5]).

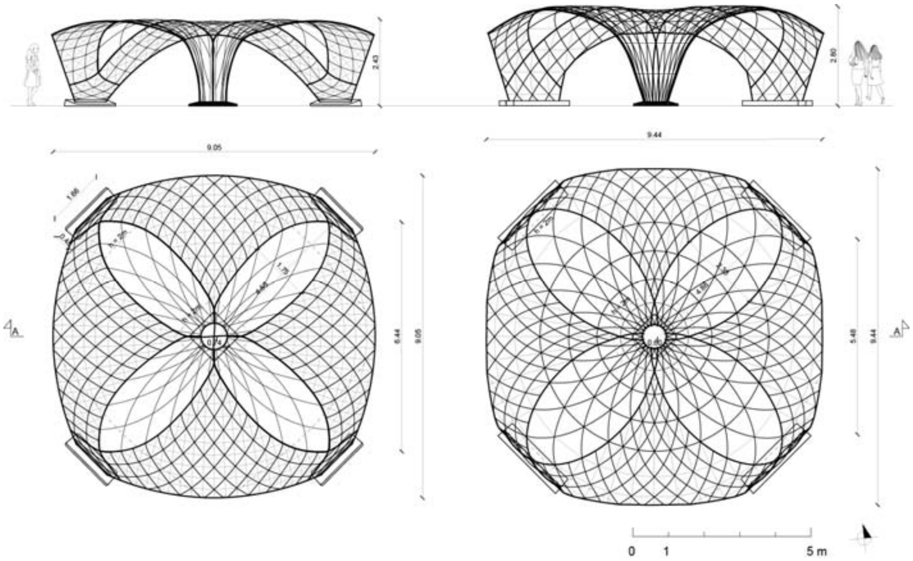

Figure 2: Sections and plans for the preliminary (left) and final (right) design.

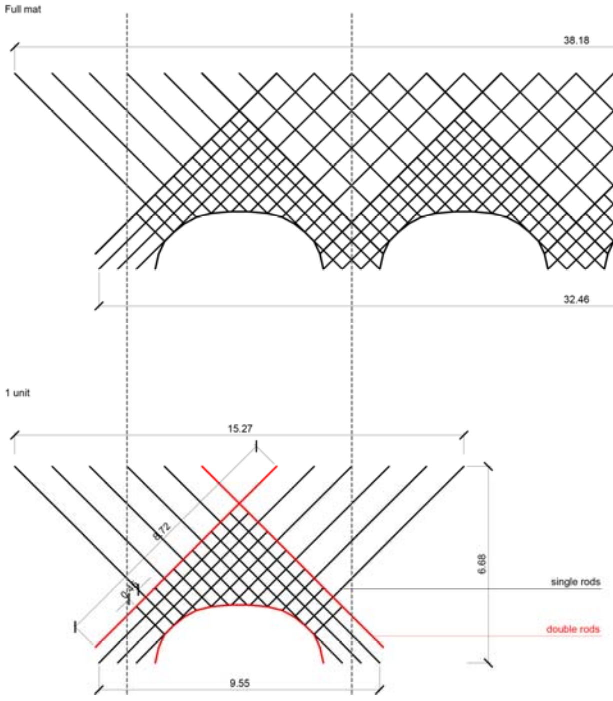

Figure 3: Flat mat (above) consisting of repeating unit (below).

2.2. Pattern finding

Initially, a symmetrical shape was parametrically generated using three guide curves to define a NURBS surface. The shape was refined until it reached the desired architectural form. Then, the edges of the leaf-like openings were defined on the resulting surface as guidelines for generation of the grid and as borders between two pattern densities. A grid was mapped onto the surface with the compass method (Hennicke and Schaur [3]) using Toolbox elastic gridshell. The compass method turned out to be unable to define a reasonable grid for a given, strongly curved surface with an internal funnel, producing irregularities at the centre and corners (Figure 2, left). These were difficult to manage while maintaining the desired shape and sufficient head clearance below the structure. Additionally, the defined NURBS surface had no reason to lead directly to a structural shape. A second stage to redefine the shape became necessary, relying on the roughly defined geometry and topology for the flat mat, that had now been established with the compass method.

2.3. Shape finding

The flat mat produced by the compass method in the previous step was used as a starting point for a new, manually drawn mat (Figure 3). The pattern consisted of eight repetitive rod sequences that form four identical lattice mats. The resulting mat was then mapped onto a cylinder which was sized to maintain the prescribed pattern spacing. The cylinder was then bent into doubly curved form (Figure 2) using Kangaroo 2.0, while ensuring that rods did not curve more than 1.2 m. Realistic values (Table 1) were used in a final check on equilibrium in which the bracing cables were added as well.

2.4 Structural analysis

The final braced structure was checked using Karamba3D, which assumes linear elasticity and small displacements. Factored load combinations consisted of self-weight, internal strain generated by the active bending, and wind or vandalism loads.

Table 1: Material properties used for the final design analysis based on literature and supplier specifications. Plexiglass was replaced by plywood during construction.

	E-modulus [GPa]	Yield strength [MPa]	Poisson's ratio	Density [kg/m^3]
GFRP	30	433	0.28	1800
Steel (cables)	210	1080	0.30	7850
Plexiglass (rings)	3.21	77	0.38	1190

Karamba3D is incapable of handling prescribed, or saving intermediate, internal stress states, meaning it is not ideally suited to analyze actively bent gridshells. As an approximation, the active bending was modelled by applying prestress (internal strain) and assuming pure bending. In pure bending, the internal strain ε is equal to the negative ratio of the distance ɣ above the neutral surface over the radius of curvature R. The distance ɣ was 4 mm for the rods, and the radius varied locally.

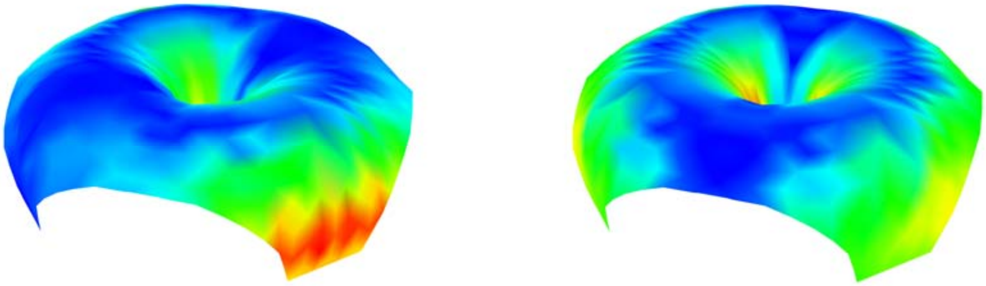

Figure 4: Wind pressure coefficients between 0.7 and 11, for NW and W wind orientation.

Horizontal wind loads were defined with a pressure of 0.217 kN/m^2 for a 10 year return period and wind coefficients depending on the angle to the shell surface, based on "plane lattice structures" in Eurocode

(Figure 4). The resulting critical buckling load factor was 1.6 with displacement in the range of 17 mm (Figure 5) and stresses in the range of 5% of the strength.

Vandalism was modelled by four point loads of 67.2 N based on two people hanging from the shell from both arms. Stresses locally reached 95% of the factored flexural strength, while the shell deformed by 17cm (Figure 5). This reveals that the shell gives ample warning for such local failure, but that determined vandalism cannot be designed against. However, the structure is very redundant, and global failure will not occur as a result. Regular inspection was recommended to assess whether local damage had been incurred.

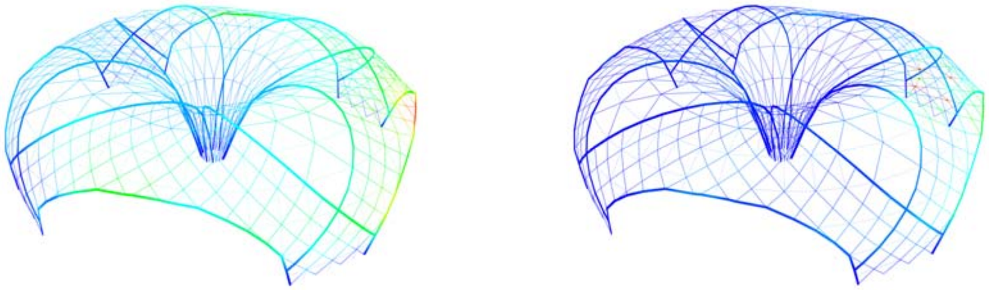

Figure 5: Deformations for W wind orientation (0 to 17 mm) and vandalism (0 to 17 cm).

The reaction forces were used to dimension the plywood abutments and the additional amount of sand needed to weigh them down: 300 and 178 kg for the centre and corners.

2.5 Fabrication drawings

Fabrication drawings were generated to facilitate construction (Figure 6). The location of the splices between two segments was optimized in two ways: their location was between nodes, to avoid complicating those nodes further; and material waste due to cutting losses had to be minimized as rods came in fixed lengths (3 and 5 m rods). A total number of 157 rods was used with less than 6% of waste.

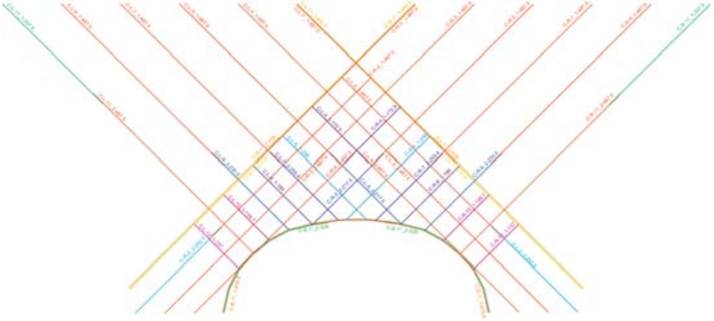

Figure 6: Example of labelling system for fabrication.

3. Construction and disassembly

Preparation for construction involved cutting and labelling rods according to their length and position. Five abutments were fabricated by hand tooling 18mm plywood. Two compression rings were made by laminating laser cut MDF arcs. Structural assembly began on a flat grass area which provided sufficient working space and to avoid obstructing traffic at Hallam Square, the final position of the pavilion.

Four flat lattice mats were constructed by joining the GFRP rods, wrapped with gaffer tape, using cable ties (Figure 7). Longer rods were formed from two segments, connected by a lap splice of gaffer tape and cable ties. The mat had to be assembled from two parts due to lack of space (Figure 3). The edges of the latticed mat were secured to the five abutments by hammering steel staples to create the arched forms. Once the structure took an approximate shape, it was manually carried to Hallam Square and positioned centrally (Figure 8). The bases were weighed down with sandbags placed inside, before completing their assembly and screwing on the lids. It was subsequently stiffened and braced with the steel cables, compression rings made from rods or MDF, and double rods along the four opening arches (Figure 9).

Figure 7 Flat mat assembly at flat grass area and cable ties at intersections (© Edyta Augustynowicz)

Figure 8 Relocation possible due to low weight. Screwing of bases. (© Matt Bell for SHU)

Figure 9 Rods to rings, and rods to cable connection details using gaffer tape and cable ties (© Matt Bell for SHU).

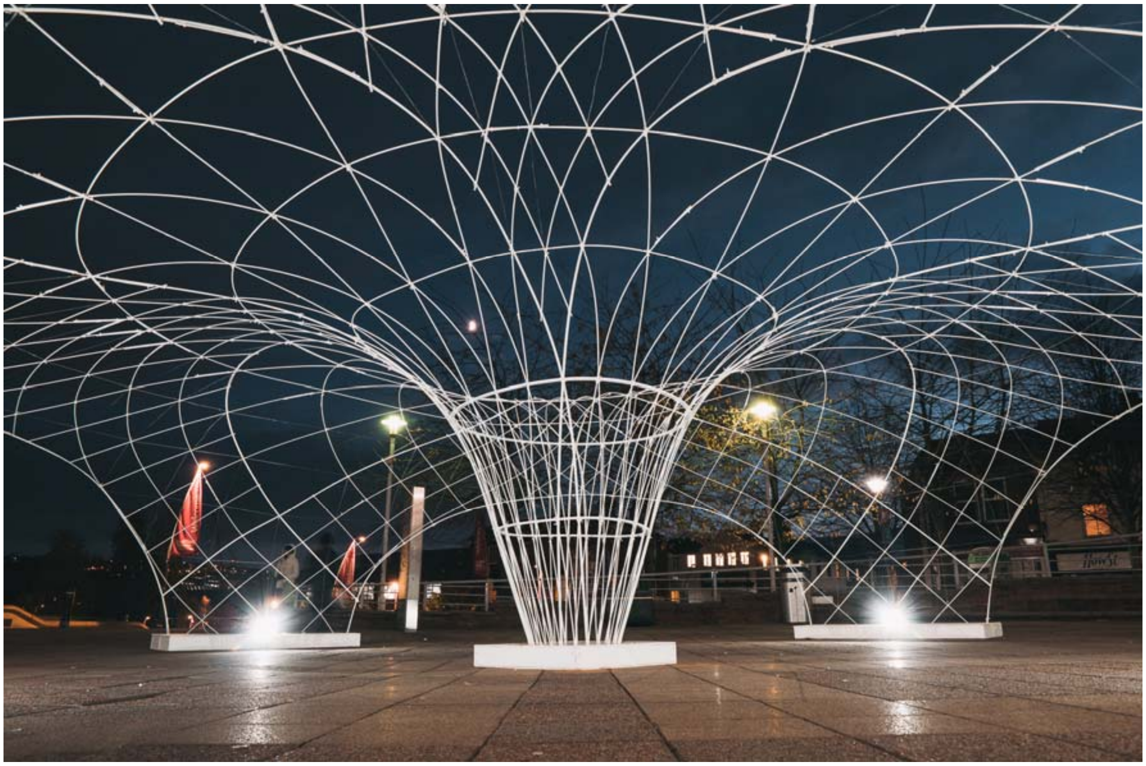

Figure 10: Final result at Hallam Square, Sheffield, UK (© Matt Bell for SHU).

Following a successful six week outdoor display (Figure 10), the structure was taken down. The steel cable bracing was removed first, before removing the grid from the abutments. Afterwards it was allowed to flatten out before being folded and closed up similar to an umbrella. (Figure 11).

Figure 11 Disassembly benefits from deployability (© Gabriel Tang).

5. Structural testing

During the six weeks the structure stood outside, it was subjected to nocturnal, alcohol-induced, non-destructive testing on three occasions (Figure 12). The structure underwent large deflections, potentially finding stable buckling modes, but would always be able to return to its original state. This return took the form of damped, oscillating motion over the course of several seconds, and had the ability to surprise and even hit the test subject that applied the original load.

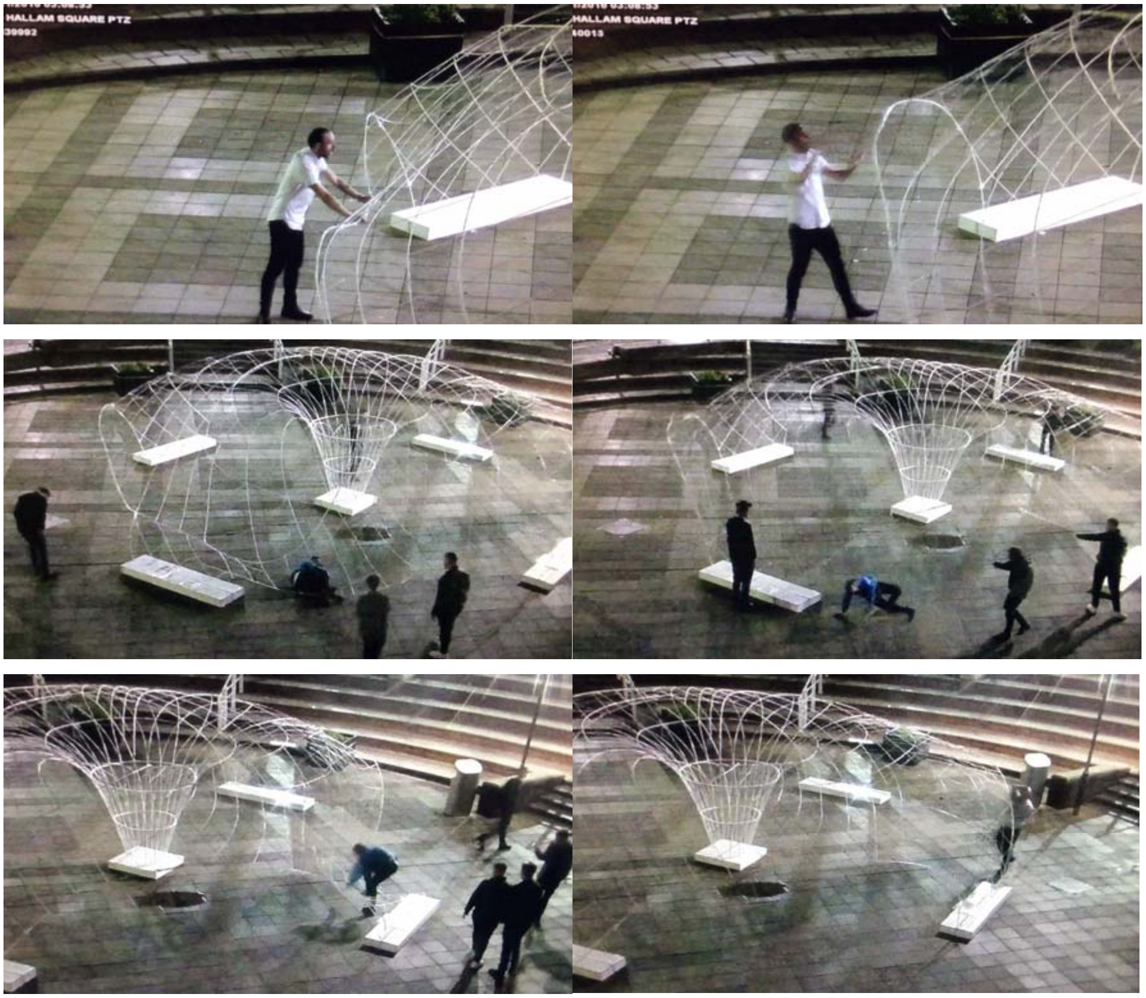

Figure 12 Three unintended tests, captured on CCTV: (above) mid-edge point loading, with test subject hit in the face due to springback; (middle) near-corner point loading, with structure partially invisible on camera due to damped, oscillating springback: and, (below) corner point loading, resulting in a stable buckling mode, with security guard later pushed back due to springback.

6. Conclusions

The Magnolia gridshell features a novel deployment concept and grid with varying pattern density. Material efficiency resulted in low material cost and weight. Its deployability and portability resulted in simple disassembly and storage for future reuse.

A two-stage form-finding process was required to arrive at its final form; first finding the pattern using the compass method, then form finding using constrained physical simulation. Future design methods should be able to mediate between the grid pattern and form, instead of taking either as fixed input.

Unintended structural testing revealed the enormous capacity of the structure to undergo large deflections before returning to its original form. This redundancy cannot be fully appreciated during structural analysis without including higher order geometric as well as dynamic effects.

To be involved in building an innovative structure, the construction exercise was a refreshing learning experience for students. Standing at a prominent position in Sheffield city centre, it was estimated that the Magnolia gridshell has been viewed by in excess of 20,000 visitors to the university and to Sheffield. It stood testimony to the effective collaboration between academics, practitioners and constructors at an international level.

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