IN(FLATABLE) MOD(ULI)

Air-buoyant, form-resistant, temporary structures

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Abstract. Conventional inflatable material systems offer a quick and reversible means of construction, however presenting limitations in terms of adaptability. Conventional, discrete, form-resistant structures feature stability through the complex organisation of discrete elements, however featuring inertias in terms of flexibility and diseconomies if applied to projects with a short lifespan. This paper discusses an alternative application of inflatable buoyant moduli to a discrete form-resistant structure in order to provide an adaptive installation for temporary events. Numerical and physical models are developed through a series of benchmarks, first, and a design project application eventually. The inherent predictability of this complex system is studied in terms of constructability, costs, flexibility and spatial quality.

Keywords. Inflatable; buoyant; form-finding; modular; structure.

1. Introduction

Conventional material systems for inflatables and discrete form-resistant structures are described in separate literatures and provide suitable design means for permanent structures, in the first case, and temporary structures in the second. A critical review of these two separate categories inspires the futuring (Fry, 2009) over a hybrid application that draws, on the one hand, from the structural principles of form-resistant structures and, on the other, from the temporary features of inflatables. Following Dunne and Raby (2013), this aims to envision an alternative design and construction approach which allows users to become makers in assembling temporary structures.

Digital computation links form-finding with inflatable modular technology through an adaptive system (Hensel, 2006); the inherent predictability of such a complex system is implemented, with numerical models, in the
Grasshopper parametric environment. Physical models are developed in order to, first, validate the numerical ones and, second, test the constructability, costs, flexibility and spatial quality of the built system. A series of benchmarks and a site-application show how different factors affect the relationship between structure, materiality and space generation.

1.1. INFLATABLES IN ARCHITECTURE

The first theoretical application of inflatable technology in architecture comes from the 1917 patent by Frederick W. Lanchester (1917) “An improved Construction of Tent for Field Hospitals, Depots and like purposes”. Only after the 1930’s however, with the introduction of PVC, PE and PTFE, applications became more consistent.

In 1946, Walter Bird prototyped and built, for the US Air Force, the “Radome”: a sphere radar cover and also the world’s first example of inflatable architecture. The economic appeal of this technology allowed Bird to successfully commercialise inflatable cover structures – mainly generated through analytical surfaces, such as spheres and cylinders, in order to carry out both representation and fabrication through well-known shapes.

With form-finding physical models Frei Otto (1962), Heinz Isler (1961) and Dante Bini (2014) pioneered more complex geometry-generation methods, inspiring the 1967 “First International Colloquium on Pneumatic Structures” in Stuttgart. Inflatable technology also inspired the 1968 exhibition “Structures Gonflables” held in Paris. Such an exhibition showcased, as part of the “Utopie” movement, the exploration of the ephemeral and changeable features of inflatable architecture which was in ideological contrast to the inertia and repression of traditional post-war architecture (Dessauce and York, 1999).

Inflatable architecture reached an apogee in the 1970’s with Buckminster Fuller’s utopian architectures and the Osaka Expo pneumatic pavilions – among which the Fuji Pavilion by Kawaguchi and Murata is worthy of mention. The design of this air-inflated ribbed structure came from bending a square surface onto a 50m-diameter circle. By creating an anticlastic geometry, gravity and wind loads were successfully counterbalanced by tension forces (Adrover, 2015). Inflated ribs and anticlastic surfaces also drove the design of the 2013 Peace Pavilion by Atelier Zündel Cristea. Compared to the Fuji pavilion, this project brought innovation to the design process through the blending of inflatable technology with parametric modelling and digital fabrication (www.zundelcristea.com: Nov 2015). Both projects featured a quick erection / dismantling process – hence offering the possibility of them being reused. However, no actual shape reconfiguration was possi-
ble due to the fact that membranes were pre-formed. This reveals an intrinsic limit of pre-formed inflatable membranes in adapting to different site conditions.

A more adaptive system was explored through generative modelling by the Aerial Assemblies test performed by the MIT’s Self-Assembly Lab. Each modulus of a buoyant particle system is made of a helium-inflated weather balloon encased in a frame with a positive or a negative magnet located at each tip of the frame. With the magnets attracting and repelling one another, the moduli eventually aggregate into a flying spatial structure. As the helium dissipates and the balloons deflate, this self-assembled aggregate touches the ground (www.selfassemblylab.net/AerialAssemblies.php: Nov 2015).

Such a self-organising structure is generated through the balancing of emergent systemic forces (Ahlquist and Menges, 2012), showing an application of digital design that surpasses, in terms of flexibility, the framework of discrete rules such as the ones used in the Peace Pavilion. This system can provide a more flexible, automated response to multiple boundary conditions, overcoming imprecisions and diseconomies related to analogic man-made construction. Nevertheless, applications and literature on adaptive inflatable structures remains scarce, suggesting, on the one hand, more focused efforts on the development and role of digital tools and, on the other hand, the development and application of suitable construction technologies. These explorations can offer relevant outcomes especially to the rising category of users/makers and the field of temporary installations.

1.2. DISCRETE FORM-RESISTANT STRUCTURES

Physical form-finding bases geometry generation on systemic acting forces and material properties. After setting parameters such as model topology, supports and acting forces, the system reaches a "form-resistant" static equilibrium, where shape resists loads through membrane behaviour – a state in which mainly in-plane stress and reduced or no bending stress act (Burkhardt and Otto, 1978).

Tile/vousoir vaults are a sub-category of form-resistant structures. These vaults allow covering large areas without intermediate supports by aggregating discrete small elements. Despite a low resistance to traction, such structures achieve cohesion and bearing capacity by assuming a funicular-like shape; this allows compression forces to be transmitted throughout the structure through the reverse catenary principle (Block and Ochsendorf, 2014). The Church of Colònia Güell and the Sagrada Familia by Antoni Gaudí are two examples of this tectonic system (Tomlow, 1989).
The design of discrete form-resistant structures is a fairly consolidated field. Shape is generally generated by means of either analytical surfaces or physical form finding; however, examples of freeform shapes are scarce. The lack of well-established, flexible, industrialised methods for processing voussoirs are among the reasons why the use of complex, freeform geometries can be justified primarily for high-budget, long-lifespan projects.

Technologies such as stereotomy or the “Tile Arch System” provide viable means of construction for vaults (Ochsendorf and Freeman, 2010). However, these require a high degree of precision for both design and preparation. Because such technologies require high inertias and low flexibility, adopting a different, more adaptive, technology would allow delivering a more flexible design-to-construction framework.

Inertias and inflexibility also contribute to the discontinuities that can often arise in form generation, materialisation and construction. Philippe Block’s MLK Jr Park Stone Vault project (Block et al, 2013) addresses the issue by developing a seamless, digital design-to-construction process. Digital tools are used to inform the system’s complexity, from form generation to custom elements preparation. Such a digital framework can be applied to the field of temporary / reconfigurable structures and be simplified through the use of standard / modular elements rather than custom ones.

2. In(flatable) Mod(uli)

Inflatable Moduli (InMod) addresses the aforementioned gaps in the field of inflatables and discrete form-resistant structures. The driving criteria of the design processes are: to create reconfigurable complexity through low-tech / low-cost construction technology; to provide the makers/users with a simple design-to-construction/dismantling process; to provide a self-supporting structure; to deliver a temporary stage for small/medium, open-air, seasonal events such as White Night Melbourne and the Moomba Festival that are often hosted along the Yarra River. Tools and strategies from computational design are applied and tested for the purpose.

Similar to traditional discrete form-resistant structures, InMod is made of mutually-supporting small discrete elements that resist loads mainly through compression. However, where traditional elements are often hard and gain cohesion primarily because of gravity, InMod’s moduli are buoyant, soft and gain cohesion through two combined actions: the action of (compressed) helium lifting the balloons and the action of a (tensioned) mesh wire sack pressing against them. Referring to Motro (2003), this resembles the features of a self-equilibrating tensegrity system. The sack’s upper and lower faces are pinned together, where necessary, to prevent the balloons from piling.
Whereas traditional voussoir structures require a precise, a-priori, form-generation/elements preparation, InMod works more interactively: the overall shape is governed, first, by the mesh sack’s footprint and, secondly, from the arrangement of the inflatable moduli.

The mesh sack initially acts as a dynamic formwork during erection, and then as a structural element during the operational life of the structure. This technological solution reduces the time/cost/waste that the conventional use of timber formworks and scaffolds often involve. The systemic adaptive behaviour also avoids the risk of imprecisions often related to discrepancies between form-generation and materialization/construction. This way, every systemic configuration is form-resistant, and can be flexibly controlled by changing the mesh extension or moving/changing the ground-restrained control points. The overall system is simulated and tested through benchmarking and prototyping first, and then applied to a design phase.

2.1. BENCHMARKS

Benchmark models aim to tune the systemic settings of the initial concept – such as moduli arrangement, sizes and quantity.

![Figure 1. Benchmark steps; step1: planar approximation $S \rightarrow S'$; step2: CP (attractor point in red); step3: trapezoid control space and mesh; step4: DR (anchor points and applied loads in red); step5: post-forming process (control points in red); step6: final outcome](image)

A primary assumption is that, since balloons are restrained between two mesh layers, the whole canopy can be approximated as the ideal surface that cuts each balloon in half – hence allowing representing the $\mathbb{R}^3$ system as a $\mathbb{R}^2$ surface $S$ with a 3D-to-2.5D approximation. A further assumption is that
collision among moduli happens as a result of the combined action of a centripetal force, by the mesh, and a vertical push, by helium. The overall system can thus be simulated as the sum of two separate sub-systems: a Circle Packing (CP) planar collision and a Dynamic Relaxation (DR).

CP is implemented in the 2-D ground projections of the moduli (Figure 1, step 1). CP creates a combinatoric pattern of tangencies among the circles.
and satisfies the geometric condition of contact with no overlapping (Collins and Stephenson, 2003). Figure 1, step 2 shows the CP implementation, in Grasshopper’s plugin Kangaroo Physics, with a many-to-many collision; the collision attractor point is located at the centre of the system (Piker, 2013).

Once the circles are clustered, a 20m x 10m trapezoid control space is introduced. The circles within the control space only are picked and a virtual mesh is created by connecting their centres (Figure 1, step 3). Such a mesh is therefore transformed into an inextensible particle spring system in Kangaroo Physics. Figure 1, step 4 illustrates the preliminary settings for the Dynamic Relaxation algorithm (DR): setting the spring system’s anchor points along the shorter base and the two sides; applying unary vertical loads at the springs’ ends. DR is performed in Kangaroo (Kilian and Ochsendorf, 2005). Since springs are modelled as inextensible elements, the funicular outcome can be post-formed again to a desired height by moving the control points inwards or outwards (Figure 1, step 5).

Figure 2 shows some of the benchmarks developed from different boundary conditions such as: hexagonal / random starting grid; striped / patterned / random distribution; use of 1 / 2 / 3 / 4 moduli. Although a wide range of compelling solutions arise, benchmark r3 only is picked for further developments since: first, fabrication is quicker when no specific pattern needs to be precisely followed – suggesting adopting a random initial distribution. Second, according to Majkut (2014), using similar-sized helium balloons can generate problems related to vibration/resonance – suggesting adopting two or more sizes of moduli in order to provide a good acoustical performance. The choice is further narrowed down by the range of latex balloons available on the market and by aesthetic considerations.

2.2. PROTOTYPING

After a preliminary series of draft models (Figure 3, top), a 1:5 prototype is developed on benchmark r3 to prefigure its constructability and adaptability.

First, a 4m x 2m mesh sack is laid on the ground and restrained along the shorter base and the two sides. 40 latex balloons per each size are taken – respectively 10cm, 25cm and 40cm (Figure 3, top); a helium tank is used to inflate each balloon before placing it inside the mesh sack. According to the initial concept, a random scattering allows speedier construction while still providing visual complexity to the final outcome.

After filling the mesh, the upper and lower faces of it are pinched every 40-50cm; this keeps the centre of each modulus on the ideal surface used in the Grasshopper algorithm, preventing the balloons from piling up during DR and fostering an overall membrane behaviour (Figure 3, top).
Once the flat canopy is prepared, 9 anchor control points are set to control the post-forming process (Figure 3). By changing their position, multiple configurations are generated after the numerical simulations. Thanks to the
irregular distribution of different-sized balloons, both daytime and nighttime light modulation is rather evocative (Figure 3, bottom).

Prototyping required two hours of unskilled labour and a budget under 200AU$, showing good replicability-adaptability to different site conditions while providing adequate structural and aesthetic performances.

The canopy’s foldability and buoyancy allowed, on the one hand, easily and quickly relocating the structure around the site and, on the other hand, flattening / securing it to the ground to contrast severe weather conditions. Balloons preserved buoyancy for 3 days, proving InMod to be a viable solution for a temporary installation / a weekend event.

2.3. DESIGN

Design aims to further explore the extension and range of shapes InMod benchmark \( r_2 \) can achieve according to different site topographies (Figure 4). Form-finding is determined in each case according to the control points’ position and the mesh shape; on the side of CP and DR, form generation is informed via the acoustic performance, analysed through a ray tracing simulation implemented in Grasshopper following Reinhardt (2012). Sound propagation is taken as a qualitative feedback from the structure, along with aesthetic and programmatic features.

Multiple design outcomes are achieved starting from a standard set of elements, showing how InMod can provide a flexible and elegant material system for temporary installation – especially if compared to other inflatable commercial products such as inflatable tents or bouncing castles, which need to be univocally, a-priori shaped and often appear massive.

3. Future developments

Future developments shall focus on implementing an aggregative system integrated directly in the moduli; this is likely to increase cost while, however, allowing transcending the fixed canopy configuration and enhancing the adaptive features of the system. A 1:1 model shall help to test further installation mechanism and construction details.

*Figure 4.* Design-applications on a flat site (left), a gentle hill (centre), a steep slope (left). The sections show how the acoustic performance responds to the site topography.
4. Conclusions

The work explores an integration of inflatable modular technology and form-resistant structures through the design and construction of a temporary stage. By focusing on the framework development rather than on the outcome, systemic variations are showcased and tested through numerical and physical models. InMod integrates adaptive principles in a modular system by combining digital computation and material; this offers an easy-to-construct, flexible, low-cost alternative to existing commercial inflatable products.

Acknowledgements

Thanks are due to Stanislav Roudavski for having provided key-feedbacks and ideas to this work, both within and outside Studio AIR.

References

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