Pneumatic Hybrid Structure

A prototypical, quick deployable, temporary event structure

A Master's Thesis submitted for the degree of
"Master of Engineering"

supervised by
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Affidavit

I, **Clive Edward Kirsten**, hereby declare

1. that I am the sole author of the present Master's Thesis, "Pneumatic Hybrid Structure", 79 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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Vienna, 10.11.2015

Signature

ACKNOWLEDGEMENTS

To my beautiful family, Gina, Liam and Mila who had the patience and understanding to allow me the many hours, days and weeks. Focussing on this task has been important to me and you gave me that. Thank you.

To the office of Event Canopies Asia, thank you for support in allowing me to walk out of the office early to work on thesis. You all gave me space to get there.

The Vienna University of Technology, thank you for the program and all the incredible knowledge and people that I have been introduced too.

ABSTRACT

Inflatable structures are used as quick deployable structures for many different commercial and military purposes. The advantage of small packing volumes and quick installation are extremely attractive to the event industry, internationally. The commercial agenda driving the industry demands flexibility, mobility, short installations and reduced deployment costs.

There are inflatable solutions currently deployed and working within the industry. Safety of the structures are the most questionable with many products claiming resistance to high wind speed pressure. Most not supported by structural engineering documentation and most even without proper testing been undertaken.

The point of failure in pneumatic structures follows the development of compression zones in the membrane that eventually leads to collapse. This translates quickly to buckling deformation due to external load application. Most solutions simply increase internal pressure to achieve a stiffer inflated structure. And this leads to practical complications and costs that are not sustainable in a commercial environment.

This thesis begins the exploration of a solution that will comply with UK event industry safety standards that are prescribed under publication. The deployment of a bending active element integrated and working with the pneumatic structure is proposed as a hybrid solution. The aim is to achieve greater advantages than the standard inflatable approach currently offers.

TABLE OF CONTENTS

1

INTRODUCTION

Outdoor events are an important part of all societies need to gather and celebrate for many different reasons. This takes the form of both public and private events during all times of the year.

As these events take place outdoors they are subject to the risk of inclement weather conditions that could potentially prevent the activity or procession from taking place. Temporary structures have played an important role in responding to the need for protected space that reduces the risk of uncertain weather conditions that are located at preferred venues. These structures take on many different forms and protect against sun, wind and rain and in addition, sometimes fully enclosed with climatic control when outside conditions are simply not favourable at all.

Temporary structures need to satisfy many conditions and requirements to make them suitable, practical, safe and commercially viable. Traditionally steel framed structures enclosed in PVC Pes membranes have provided the majority of temporary event structure solutions. They are transportable, robust, safe and of low maintenance. At the same time they can be considered to be utilitarian in visual appearance that is not always in contribution to the nature of the event gathering. Further the steel framing requires time, labour and machinery to install properly. Those are costly requirements that are commercially favourable to reduce from all users perspectives.

Pneumatically pressurised beam structures, as opposed to air supported structures, have many characteristics that favour temporary installation requirements. One of the main advantages being that the usable interior space is not pressurised, with pressurised beams structures allowing flexibility to create easily accessible space that can be partially enclosed or completely enclosed. In a deflated state, they are relatively small in packing, light in weight and therefore easy and cost effective to transport. The installation is fast by temporary structure standards and once anchored securely against lateral and upward movement, make for the creation of space to gather that is not only protected against the elements, but can also be visually manipulated or designed to achieve outcomes that are in alignment with the event outcomes. Provided that the pneumatic structure conforms to the principles of pneu, then almost any shape or form can be built. This includes structures that reinforce commercial branding and brand activation awareness. These benefits make the pneumatic temporary structure ideal for the event industry.

"All structures must be designed to safely resist the loading forces applied to them" (IStructE 2007: 50). The disadvantage of the pneumatic structure or "*pneumatically stabilised membrane structures" (Herzog 1976: 15)* is how the structure deals with external loads being applied and mostly, as a result from climatic conditions such as wind and snow. It is well researched and documented that the structures have low resistance to externally applied loads. *The applied loads change the state of the membrane in tension to that of compression causing wrinkle and crimp and reducing the ability of the beam element or structure to take load. (Bechthold 2008: 61).* Failure follows rapidly, making the structure unsafe for its intended purpose.

Solutions to negate the one primary disadvantage have been extensively researched and built and include many different strategies such as the use of internal & external rigid framing systems, guy cabling, cable mesh, negative pressure components, lightweight infill materials and most simply, by increasing the internal pressure. All have implications that complicate the advantages of the overall system. Hence the simple use of increasing internal pressure has been explored the most. Air halls are pressurised to manage wind and snow loads however kept at approximately 2.5kPa to keep the occupants within, safe. In comparison, air beams must be pressurised sufficiently to become a structural safe element and the pressure is highly dependent on their position in the overall system. It then becomes necessary to adopt strategies to achieve the desired outcome. Examples include increasing pressure or increasing tube diameter or creating a hybrid solution by adding other elements. Increasing pressure takes the system into a high pressure condition as defined by T. Herzog in the influential book Pneumatic Structures that stresses the membrane dramatically and has led to failures of the weakest components in the system. There have also been examples of explosive disruption and therefore considered not safe for general public use.

In this thesis, the author will study past precedent and proposes the application of a new additional element to the pneumatically stabilised membrane structure that will reduce or negate the membrane changing into a state of compression when an external load is applied. And keeping it in a low internal pressure condition that will be safe for use without the failure risk of explosive rupture. This element, unlike previously explored in the past, needs to in addition, contribute toward the advantageous properties of the pneumatically stabilised structure. Lightweight, mobile, quick deployable, robust, flexible and cost effective. The criteria for the overall structure will be clarified later in the thesis.

To satisfy these conditions the author proposes the structural inclusion of a bending-active element to the pneumatically stabilised membrane structure. The research and implementation of bending-active elements in architecture and engineering is currently being re-evaluated and implemented into a few recent building projects. Intentional elastic deformation of select material elements brings about a load bearing capacity that when stabilized or kept in equilibrium, achieves a lightweight structural framework. The system lends itself to temporary or mobile shelter systems such as those employed successfully by nomadic tribes in the Middle East for thousands of years. The correct material behaviour is the basis of bending-active elements that have sufficient flexural strength. This includes natural materials like certain timbers and particularly bamboo. Made-made materials include Fibre Reinforced Polymers (FRP) and that includes Glass Fibre Reinforced Polymers (GFRP) and Carbon Fibre Reinforced Polymers (CFRP). Inducing bending and holding the element in that form state lends itself to use with materials that will hold it in a deformed state. Tensile membranes are ideally suited to this application and has already been implemented in the camping tent industry for a few years. The lightweight rods are bent into position and held with the tent membrane in a deformed state. The elements are single rods in an arched form. This principle has been explored, researched and implemented in projects like the membrane Restrained Arch at the University of Dundee, the Bat-Wing-Sail Research Project by IMS and the Hybrid Textile Umbrella Project in Marrakesh by students of ITKE & HFT Stuttgart. These structures are not of a typical structural typology however rather should be considered as hybrid structures. Bending-active membrane hybrids have great potential as the addition of the bending-active component not only brings in certain structural advantage, it also brings in the potential to explore new forms that pure membrane structures are not part of. This is well demonstrated in projects completed by students at ITKE Stuttgart and include the Temporary Textile Hybrid Structure: M1.

For this thesis, the author proposes to explore the mutual benefits of pneumatics and bending-active as a new hybrid

2

OBJECTIVE & METHODOLOGY

For the purpose of clarity this thesis is focussed on the structural typology of membrane structures and particularly within that framework, on pneumatically stabilized membrane structures (Herzog 1976: 16). Reference is made to the table below that indicates the specific area of focus.

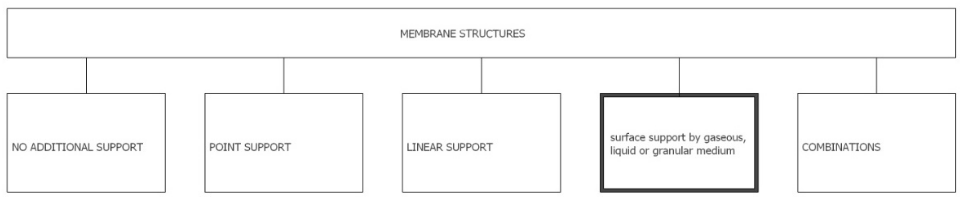


Figure 1. Classification of Membrane Structures. (Herzog 1976: 16)

2.1 OBJECTIVE

Proposing a possible and new solution to the condition that progresses structural failure of pneumatically stabilized structures and translating that strategy as a key benefit, into a structure fit for purpose as a temporary, robust event structure.

As a proof of concept, the key structural component of the system will be fabricated as a scaled down test model. The initial test as part of the thesis, will be to explore how the hybrid arch behaves under loading as a typical pneumatic element or as a stiff arch. This step is important as it will determine if the solution is acting as a hybrid or as two independent elements without mutual benefit.

2.2 METHODOLOGY

A multi-pronged approach has been adopted for this thesis to reach the objective. Firstly, researching through literature, publications and other thesis papers previously written to understand why pneumatically stabilized structures fail once sufficient external loads are applied. To review previously built structures and understand the principles and strategies adopted and how that knowledge can be used to inform the proposed new structure. In parallel, to build a scaled down test model of the primary structural element and through an actual load simulation, observe and record the behaviour. The outcome has the potential to prove or dis-prove the concept of the prototypical hybrid.

3

INVESTIGATION OF PNEUMATIC STRUCTURES

> *"Inflatable structures are part of a characteristic group called tensile structures. A tensile structure is a membrane-like structure that requires tensile pre-stresses in order to bear externally applied compressive loads. An inflatable structure creates these pre-stresses by means of a pressure differential over the skin. Inflatable structures offer advantages such as being lightweight, being easy to erect and having a low storage volume."(Veldman 2005: 1)*

Pneumatically stabilised membrane structures (Herzog 1976: 15) is a descriptive term that accurately describes the structural nature of inflated structures.

They have been researched thoroughly over the past 60-years and enjoyed periods of great popularity. Used successfully by the military and emergency relief agencies as quick deployable structures and by the community in sports and commercial facilities. Inevitably also explored as dynamic art, event installations and prototypical research structures. The Institute of Lightweight Stuttgart Germany in particular, researched and published a vast amount of work on minimal structures, pneu, bone, air halls and convertible pneu. The latter explored thoroughly the possibility of exciting pneu-form and its use as a convertible structure. The 1970 Expo in Osaka, Japan demonstrated a high point of exploration with the pavilions designed by Yutaka Murata and Tanero Oki & Associates. These are explored in more detail as case studies.

As a typology, pneumatics have developed broadly into two types, the air-supported pneumatic membrane and the inflated pressurized beam pneumatic membrane. (Herzog 1976: 15)

The air-supported pneumatics are used commercially, creating large area coverage with relative ease. The large, pneumatic air hall industry has been successfully operating for many years and used for covering space, column-free and suitable for activities like sports and conference/ expo halls etc. The technical aspect of that is researched and documented in the IL15, Air Hall Handbook publication and confirmed technically with many successful installations. Their popularity has however dwindled due to reasons that are beyond this thesis scope.

As opposed to the air-supported membrane structure, the air-inflated pressurized membrane beam system is more structurally suitable to create smaller coverage structures and that have a distinct advantage of shape, cost, packing dimension, weight, installation ease and install plus dismantle time. Making them ideal for temporary structure use.

The simplest form of pressurized system is a single tube or beam. Completely enclosed, applied internal air pressure induces tension force into the membrane material and providing the externally applied load does not exceed the membranes tension force, a load bearing capacity is possible of the extremely lightweight element. "The relationship between surface curvature radii R, internal pressure P, and the membrane tension T is quantified by a simple equation that is valid for any curved pressurized membrane.” (See Figure 2) (Bechthold 2008: 57)

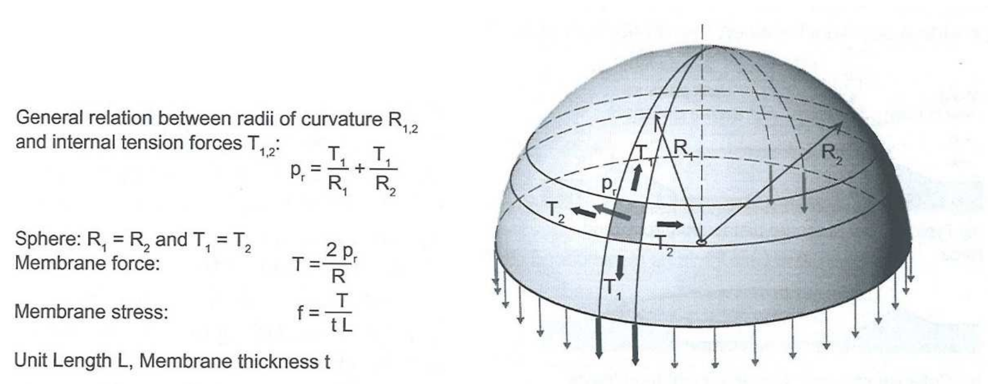


Figure 2. Membrane stresses of air-inflated spherical pneu. (Bechthold 2008: 57)

From the above it is clear to see that there is a direct relationship between Geometry, Material and Pressure for pneumatically stabilized membrane structures (Herzog 1976: 15). Pressure is the differential between the internal pressure (Turgor), and the external pressure that includes applied loads.

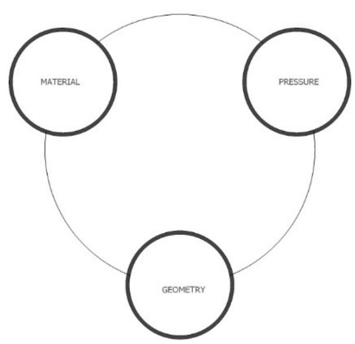


Figure 3. Trinity between Material, Geometry and Pressure. (Veldman 2005: 2)

In order to create self-supporting structures the single air-inflated tube or beams are used in multiples. This can be considered a sub-category divided into tubular frame structure or dual wall cushion structures. The dual wall cushion can be separated by internal lamella or by cord drop threads. Using these methods many forms can be created. (Veldman 2005: 9, 10) The precedent study later in this chapter will identify the sub-categories used by previous designers.

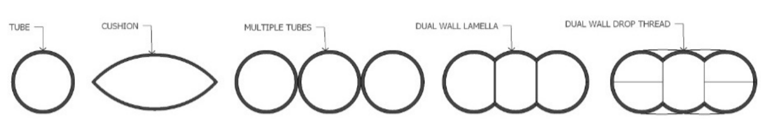


Figure 4. Typical cross sections of air inflated structures. (By author)

3.1 GEOMETRY

Pneumatically stabilised membrane structures resist the inevitable compression forces incurred through inducing greater tensile forces in the membrane. To fulfil this condition, the geometry must be pneumatically formed. (Herzog 1976: 164) The form or geometry of the pneu must be employed. Without this the membrane will create wrinkle zones as the tensile forces reach zero or go into compression. The geometry for a wrinkle free pneumatic structure has been explored and described by Frei Otto in a 1967 publication:

"A geometry can be formed pneumatically when spheres with a steady changing radius can be included, the centre points of which lie on a curve and when at least one parallel of latitude of the generator sphere rests on the whole length of the membrane." (Otto 1967)

Steady changing radius manages the distribution of membrane stresses. The more uniform this curve of curvature ratios, the more uniform is the stress distribution, creating a harmonic form or surface. (IL15 1983: 42) This is a desirable outcome to use the membrane material in the most optimal manner. Unlike rigid structures, the pneumatically stabilised membrane structure must be restrained to ensure the optimum geometric form is maintained. Most notably the plan layout, if restrained against lateral movement will together with internal pressure, keep the geometry optimal. This will be reviewed in the case studies of this section.

Well documented is the relationship of the radius of surface curvature, of the pneu form, to the tensile forces induced in the membrane. Summarized in the Figure 5.

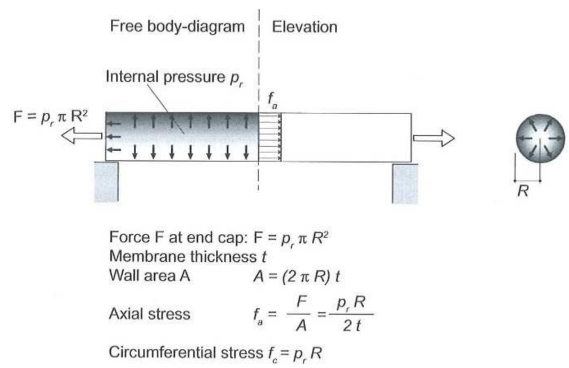


Figure 5. Membrane stresses in an air inflated pneu. (Bechthold 2008: 57)

When considering the implementation of material to describe the geometric form, its constraints are brought into play. The geometric form for air inflated or pressurised membranes reduces into a basic language that originates in a simple sphere. From that it can be extended to a tube with rounded ends or flattened into a cushion shape form. Manipulation of the basic pneu form through deployment of cutting patterns is what has been used to create many of the pneumatically stabilised structures, some of those reviewed in the case studies that follow. All of the translated form to create the structures use clear geometry that is pneumatically formed as described by Herzog.

3.2 MATERIAL

In the pneumatic structure, material defines geometry, air creates pressure within an enclosure that material withstands. An optimum relationship of all three creates equilibrium that is a stabilised pneumatic structure.

The material used plays an important mechanical behaviour of an inflated beam or structure. Properties deployed optimally can have significant impact to the designed performance and longevity of the structure. Early structures explored many materials to find the best solution to that particular project requirement. As the case study that follows indicates early structures explored extensively both isotropic materials such as plastic films, fabrics, rubber membranes, metal foils and orthotropic materials such as woven fabrics and gridded fabrics. (Herzog 1976: 138) Contemporary commercial structures today adopt the use of Pes PVC or lightweight 'rip-stop' as a single membrane approach or a double membrane approach of a PU internal bladder with a high tensile strength, woven or braided nylon with optimization of the fibre orientation.

However all the materials are still impacted by geometry and pressure. This means the inherent properties need to contribute to the lightweight pneumatic structures. Lightweight, tensile strength, tear strength, elongation, UV resistance, ability to fold and pack are some of the required characteristic.

In addition, along with form, the selected material is part of the architectural language. How it contributes to the users understanding of the building and the space within is important and has sometimes been neglected in past and present solutions. The Fuji Pavilion (see Figure 10) example is arguably more of an engineering solution language that creates a resulting space as opposed to The Modern Teahouse (see Figure 22) example where the internal space is considered as a priority of the pneumatic solution.

Consideration of the overall safety of the structure includes selection of the correct membrane material specification. It does encompass the entire envelope and with this component working properly, the relationship of the trinity breaks down and can lead to failure.

Maintenance and longevity needs again to be considered in the very outset of design. Understanding what is required of the structure and how it will be used will inform material selection. Example being The Modern Teahouse, Case Study 3.59. Here Kuma selected Tenara as it folds and packs well without any mechanical wear of the membrane, perfectly ready of multiple use moving from one location to another. Harmonic geometry will add to the longevity. (IL15 1976)

In summary the material is the visual evidence of the success or failure of the structure.

3.3 PRESSURE

Highlighted previously, pressure is part of the trinity relationship including geometry and material. It is also the only item of the three that can be changed relatively easily after completion of the fabrication of the structure and has a great degree of impact on stabilisation.

In his book, Pneumatic Structures, Herzog defines low and high pressure systems. The range is not clearly set out apart from where low pressure starts at 10mmH2O/ 0.098kPa and high pressure starts at 2,000mmH2O/ 19.6kPa. Table 1, below lists some well-known structures as well as some well-known every day products that are inflated as a comparison.

Noting the extreme example of the bicycle road tyre, what is also known is that these systems have been known to fail despite the technology and research that goes into the product. High pressure systems place maximum stress on the material of the compartment and maximum stress on the workmanship where junctions need to be made to fabricate a complete product. It also further increases the risk of air leakage through the smallest apertures and even through the thickness of the material itself.

Early military quick deployable structures explore the use of high pressure systems as it provided the necessary outcome of stabilisation against dynamic external loading. These structures however have been known to fail with an explosive nature and makes it then unsafe and unfit for purpose. In response, most new structures explore the use of low pressure systems and have to support the lower performance with active management systems. It also helps keep costs lower especially for commercially available structures.

Comparative table of well-known inflated structures and everyday inflated products.

LOW PRESSURE SYSTEMS

- 0.98mBar/ 0.098kPa low pressure systems, start at (Herzog 1976: 17)
- 2.2mBar/ 0.22kPa ETFE cushion (Architen Landrell : 2)
- 7.5mBar/ 0.75kPa Solar Impulse Hanger (Pauli interview)
- 3.0mBar/ 0.3kPa Typical Air Hall minimum (IL15 1976: 90)
- 4.0mBar/ 0.4kPa Atoms for Peace Pavilion (Herzog 1976: 134)
- 14mBar/ 1.4kPa Trident Dome (Inflate 2011: 10)
- 15mBar/ 1.5kPa The Modern Teahouse (Schmit 2011: 122)
- 20mBar/ 2kPa Pneumocell event structure (Herzig interview)
- 20mBar/ 2kPa Thesis Proof of Concept
- 50mBar/ 5kPa Tensairity® beam min. p. (Maffei lecture)
- 98mBar/ 9.8kPa Fuji Pavilion Expo 70, min. p. (Herzog 1976: 76)
- 147mBar/ 14.7kPa Floating Theatre Expo 70, min. p. (Herzog 1976: 88)

HIGH PRESSURE SYSTEMS

- 196mBar/ 19.6kPa HIGH PRESSURE SYSTEM start (Herzog 1976: 28)
- 245mBar/ 24.5kPa Fuji Pavilion Expo 70, max. p. (Herzog 1976: 76)
- 250mBar/ 25kPa Rubber rib boat, side tube (website Aquamarine)
- 294mBar/ 29.4kPa Floating Theatre Expo 70, max. p. (Herzog 1976: 88)
- 300mBar/ 30kPa Tensairity® beam max. p. (Maffei lecture)
- 2,500mBar/ 250kPa Passenger vehicle tire typical (Ask.cars.com)
- 2,750mBar/ 275kPa Small Tactical Air beam Tent (Verge (): 14)
- 8,960mBar/ 896kPa Road bicycle tire max. p. (Bicycling website)

Table 1: Comparison of Pressure systems. (By author)

Structures like the Trident Dome, the Pneumocell and the Solar Impulse Hanger all have an optimum working pressure that is not changed when the structures are installed. The Trident Dome in fact works on a continual supply of air to create pressure within the wall compartments however, as the membrane material is only stitched together, the air escapes creating a continual air flow system. An aspect that requires continual management to ensure the structure remains in an inflated state that is stable.

Interesting to note that the structures at the Expo 70, Osaka all had an optimum working pressure that was increased for storm conditions to ensure the stability of the structure and reduce flutter on the membranes. That increase was dramatic and in the case of the Floating Theatre, the principle beams for example, the range as defined by Herzog made it both a low pressure and high pressure system. Alternatively viewed, it was a high pressure system used for the majority of the time in a low pressure state. This was potentially in response to building code requirements, the risk of severe weather conditions and the vertical height of the structures.

In respect of the Tensairity® beams, the pressure range is dependent on the span of the beam as it is used in a true hybrid configuration. It can be detailed and used in both a low pressure state and a high pressure state. It is not only a low pressure system and as a high pressure system that negates one of its claimed advantages.

What it clearly demonstrates is that the use of increasing pressure is the simplest way of managing active external loading on the membrane. Pneumatic stabilisation. The increase in material and equipment performance however attracts costs that are unfortunately not known on these previously built structures but must be noted.

3.4 EXTERNAL LOAD APPLICATION

The pneumatically stabilized membrane structure has all the advantages of being a quick deployable structure. Suitable especially for temporary installation and most notably used in the industry of events. Its low value of permanence defines the value of its functionality. Inherent temporary quality equates to a low stiffness of structure. Therefore knowing its behaviour under dynamic loading of wind, rain and snow is most critical in understanding how to make it safe for its intended purpose, even if temporary.

There has been a large amount of research on this particular subject from the 1950's onwards. Both for air supported structures and pressurized beams as summarized by Carradine (Carradine 1998) and Veldman (Veldman 2005) in their thesis papers. The studies have covered wind tunnel testing to understand deflection and deformation behaviour especially for air supported structures. Analytical methods explored and tested against wind tunnel tests to be in a position to predict behaviour reliably.

Steeves, in his publications that were used specifically for military application, focussed on the pressurized tube and arch rather than the air-supported structure. The quick deployable structure was seen to be in the pressurised tube and arch combination. Understanding of the structural behaviour of pressurized stabilized arches and the load capacities were studied in the 70's and this placed Steeves in a key position to write a book entitled, “Optimum Design of Pressurized Stabilized Beams’.

Brazier, Baruch et al, Wood, Stein et al, Zender, Seide et al, Veldman, Wielgosz et al and others have studied analytical methods to determine the behaviour and prediction of the point of collapse. Several different expressions for the collapse moment can be found and this difference is due to the manner in which the material is regarded as a shell or as a membrane, or whether they concern isotropic or orthotropic material. Other differences include whether they deal with pressurized beams or not, whether it’s an analytical or empirical expression, or whether the beam is of finite length or not. (Veldman 2005: 27)

3.5 PRECEDENT STUDY

The following structures designed and built or some only designed and never built are selected from a vast array of previous work done by Architects and Engineers. The intent is to understand how the principles of pneumatic stabilized membrane structures have been explored, fabricated and installed. Particularly how the trinity of Geometry, Material and Pressure are employed to achieve slightly different outcomes dependent on the desirable outcome of the structure.

3.51 CASE STUDY

Beach pavilion

Design: - Frei Otto

Year designed: - before 1962

Type: - Tubular frame structure

Material: - unknown as never built

Pressure: - unknown as never built

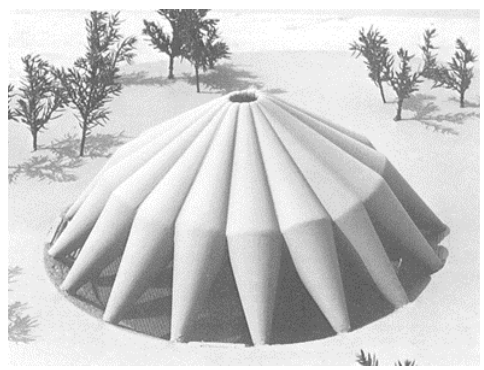


Figure 6. Beach pavilion model. (Herzog 1976: 74)

This is a very early explorative model and design by Frei Otto into the advantages of lightweight, pressure stabilised structures. A multiple tubular system arranged radially creates the structure and economy of scale. Tubes adjacent creates linking of volumes for easy inflation. The advantages of the tubular frame is acknowledged in many structures and even more so in the modern contemporary fabrication 50 years later.

3.52 Case Study

Travelling Theatre

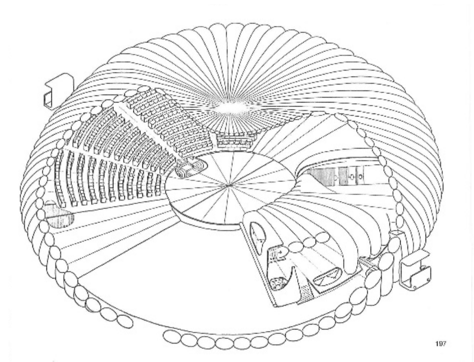
Design: - Willi Ramstein

Year designed: - 1961

Type: - Tubular frame structure

Material: unknown as never built

Pressure: - unknown as never built



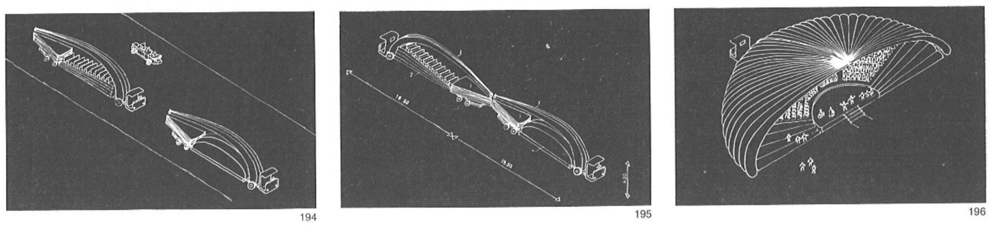


Figure 7. Travelling Theatre, deployment diagrams. (Herzog 1976: 81)

This project by Willi Ramstein shows how he saw the advantages in 1961 of using compressed air as a stabilizing medium for membrane structures. Further that the structures could be extremely lightweight, transportable and short installation times for a travelling and re-usable theatre. (Herzog: 1976: 81)

3.53 Case Study

“Atoms for Peace” Pavilion

Design: - Victor Lundy

Year built: - 1960

Type: - Dual wall cushion structure

Material: - two membranes of vinyl coated polymide fabric, 1.2m airspace divided into compartments

Pressure: - dual wall membrane with internal pressure of 0.4kPa

The structure covered 2,000m², weight of the inflatable membrane less is than 6,000kg and it took 12 men 3 to 4 days to install. To achieve such impressive statistics, the structure employed manipulation of form, pressure and material very well. (Herzog 1976: 134)

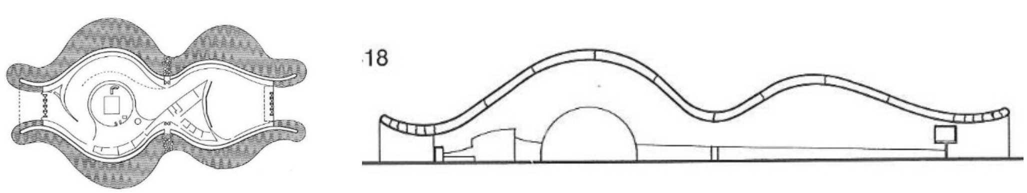


Figure 8. Layout plan and section. (Herzog 1976: 135)

The form as evident in the layout and photos explores the organic opportunities and strengths of pneumatic structures. At no section is the structure a straight line. The geometry of convex and concave form in both section and plan contributes to its stability.

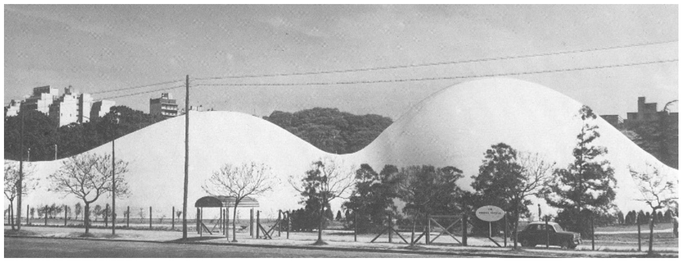


Figure 9. Pavilion installed complete showing its geometric organic form. (Herzog 1976: 135)

The low pressure system is possible due to the geometry as well as the dual wall cushion that has been compartmentalized. At 0.4kPa this is a safe working pressure given that the structure was visited by a large number of the general public. The lightweight membrane of vinyl coated polymide supports the possibility of the geometry and low pressure achieved. It is a very good resolution of the trinity of geometry, material and pressure given the function.

3.54 CASE STUDY

Fuji Pavilion, Expo 70, Osaka

Design: - Yutaka Murata

Year built: - 1970

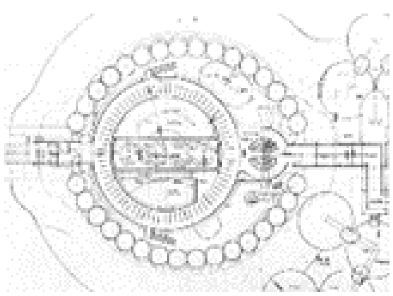
Type: - Tubular frame structure

Material: - PVA

Pressure: - 9.8kPa to 24.5kPa

Figure 10. Fuji Pavilion side view. (Wikimedia website)

This pavilion is a clever use of a single length tube that is arched and each tube end located on a circular plan. The end results is a dynamic form, that when strapped together achieves a stabilised structure. The individual tube ends are fixed into steel cylinders for anchorage as well as ensuring the form is achieved and maintained.



The pressure was controlled through a central management system with quick response to dynamic wind load and increasing pressure to stabilise the structure. Working pressure was 9.8kPa however it could be increased quickly to as high as 24.5kPa. All detailing, specification and management was for a high pressure structure as defined by Herzog. (Herzog 1976: 28)

Figure 11. Fuji Pavilion layout plan. (Herzog 1976: 76)

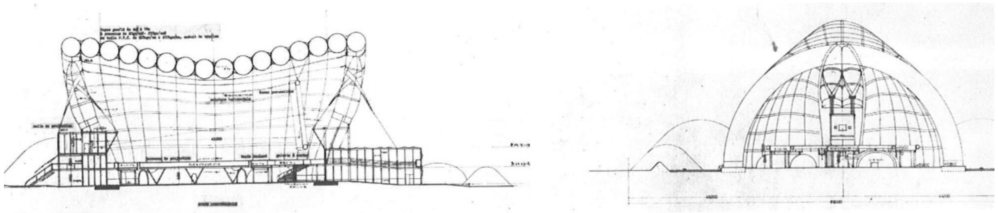


Figure 12. Fuji Pavilion longitudinal & cross section. (Herzog 1976: 77)

3.55 CASE STUDY

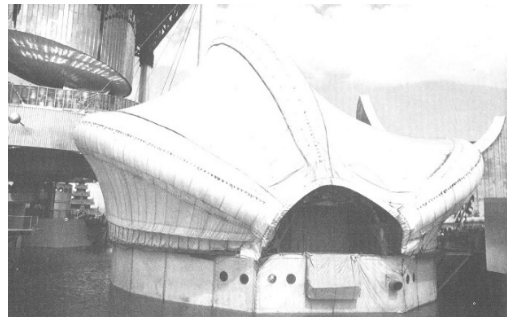


Figure 13. Floating Theatre. (Herzog 1976: 88)

Floating Theatre, Expo 70, Osaka

Design: - Yutaka Murata

Year built: - 1970

Type: - Tubular frame structure

Material: - Pes PVC

Pressure: - 14.7kPa to 29.4kPa

This structure uses the principles of positive and negative internal pressure compartments to stabilise the structure that is anchored to a floating structural platform in water. Three primary tubes arch across a circular plan. Between are two membranes, an upper and lower that is kept in negative pressure. Acting together the arch tubes and web membranes keep in equilibrium.

Internal pressure is further managed actively to counter act the dynamic wind load and like the Fuji Pavilion this structure is a high pressure system with a low working pressure.

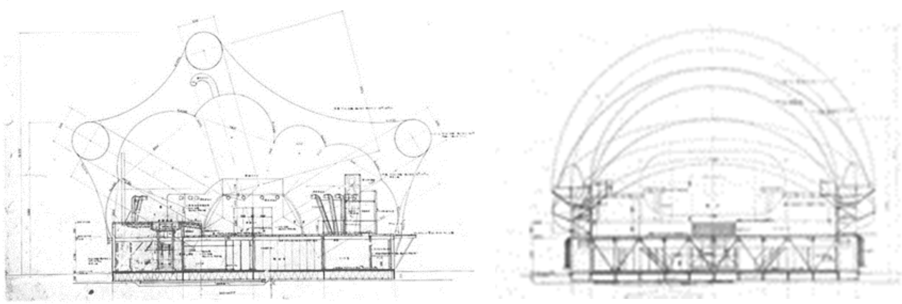


Figure 14. Cross & long section showing primary tubes in elevation. (Herzog 1976: 89)

The circular floating platform creates the dimensional constraint of the plan that optimises form.

3.56 CASE STUDY

Trident Dome event pavilion

Design: - Inflate London

Year built: - unknown

Type: - Dual wall cushion structure

Material: - Rip-stop lightweight fabric + Pes PVC

Pressure: - 1.4kPa

Figure 15. Trident Dome. (Inflate 2011)

Figure 16. Inside view & fan detail. (Photo by author)

The Trident design optimises lightweight perhaps more than any other of the structures in this case study series. The rip-stop fabric that it is largely fabricated from, is extremely lightweight and packs small for transport and moving around as required for events. The material is stitched together and inflation for stabilisation uses a continuous air flow to achieve a working internal pressure of 1.4kPa. The air leaks through the stitching and is continually replenished at a pre-determined rate. Continuous power supply and backup power source is imperative to keep this structure stable.

An independent, "trident" configuration Pes PVC rib is used to support the rip stop compartments for additional stabilisation. The user manual for this system indicates the structure should be abandoned at a wind speed of 12.5 meters per second. (Inflate 2011: 10) This makes the structure very susceptible to dynamic wind loading at a low speed. The implication being that events within have to be actively managed to ensure safety. The window of safe operation is therefore narrow.

The author has also observed installation of this structure. There is no mechanism to control the geometry of the plan required to keep the shape or form optimal. This has another impact on the stability of the inflated form and the internal planning of the event.

3.57 CASE STUDY

Pneumocell event pavilion

Design: - Thomas Herzig

Year built: - unknown

Type: - Dual wall cushion structure

Material:- TPU

Pressure:- 2kPa

Figure 17. Pneumocell Dome. (Pneumocell)

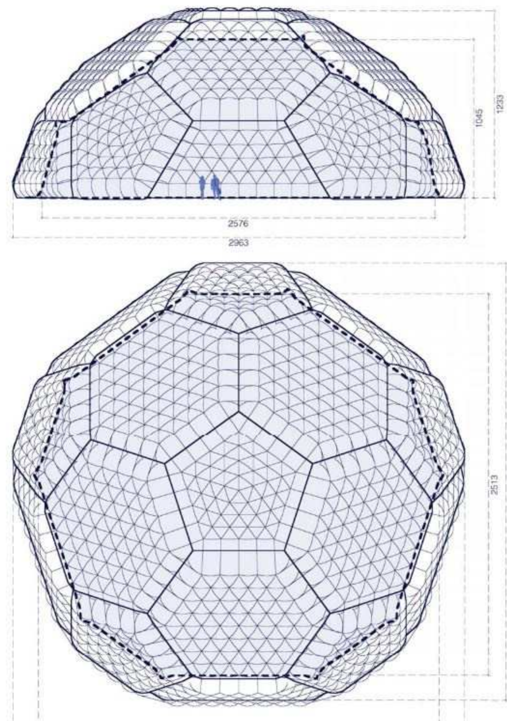


Figure 18. Top view & section. (Pneumocell)

This structure like the Trident Dome, is built specifically for temporary event installation. The dome structure is achieved completely differently. The strategy is to create inflated module units, small enough for one or two persons to work with and joined together with a waterproof zip system. The structures modules are assembled together in a deflated state and then inflated and pushed up into the designed dome configuration.

The modules are pressurised to approximately 2kPa, the double membrane held together with internal cords in tension. Additional cords on the exterior create a mesh support that helps the membrane manage the induced stress.

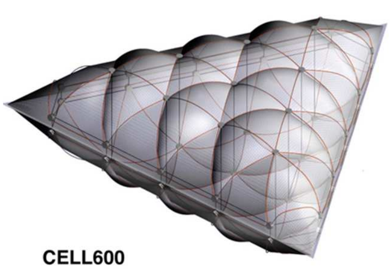


Figure 19. Pressurised Cell Unit. (Pneumocell)

Also with reference to the Trident Dome, the Pneumocell Dome has no mechanism to control the plan dimension required to keep the overall shape optimal.

3.58 CASE STUDY

Solar Impulse Temporary Hanger

Design: - Nicola Pauli

Year Built: - 2014

Type: - tubular frame structure

Material: - unknown

Pressure:- 0.75kPa (Pauli interview)

Figure 20. Hanger installed complete. (www.gizmag.com)

Figure 21. Internal views of hanger. (www.gizmag.com)

The temporary hanger structure, for the aircraft, adopts a simple half circle, inflated arch that is repeated in detail as a linear extrusion. The installations are managed by transporting modular lengths of the inflated vault and fixed once pushed together as a simple butt joint. Exposed belt devices are fixed at the termination end of the arch, regularly along the length, to prevent the lateral flattening of the arch. External guy ropes and anchor devices are utilized to prevent uplift and lateral movement of the structure. The inflation pressure is low for such a large structure, for safety purposes. The multiple tube configuration prevents a total failure situation when a single individual tube pressure fails.

3.59 CASE STUDY

The Modern Teahouse

Design: - Keno Kuma & Associates

Year Built: - 2007

Type: - Dual wall cushion structure

Material: - Sefar Tenara Type 1

Pressure: - 1,5kPa

Figure 22. Teahouse structure installed & illuminated (Tensinet)

This is a temporary structure for internal and external installation and used for the practise of Japanese tea preparation and consumption. The walls are a single pressure compartment connected internally with tension belts creating the visual “pin-cushion” effect.

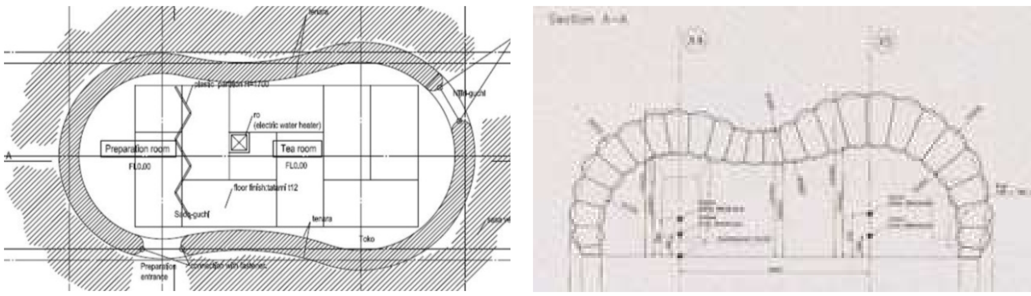


Figure 23. Teahouse, layout plan and section. (Tensinet)

Layout plan and section shows the form that takes on a very similar shape to that of natural forms of the peanut shell. This shape is not coincidental as the pneu form gives it much greater stability in the inflated mode. It is part of the pneu family of form that is important in the integrity of the structure. The internal wall pressure at 1.5kPa provides sufficient stability of the structure in winds as high as 100km/h or 27m/s. (Schmit 2011: 122)

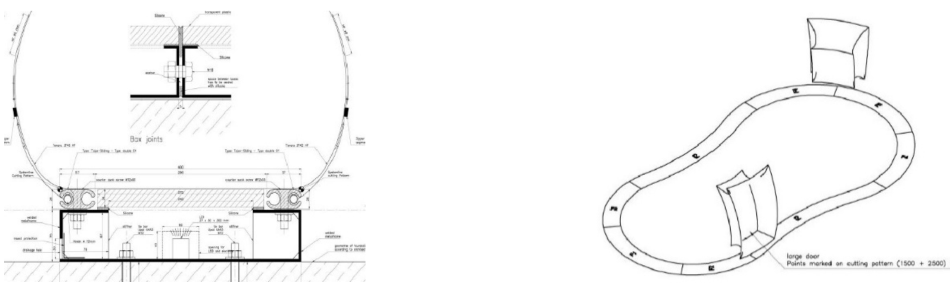


Figure 24. Teahouse, perimeter wall anchor detail. (Schmit 2011: 125)

With reference to the two drawings above, there is a steel channel located under the pressurised wall that anchors the structure against uplift. Importantly it also locates the inflatable wall in plan to ensure the form as designed and fabricated is achieved for optimum performance in stability.

4

HYBRID PNEUMATIC STRUCTURES

Many of the well-known pressure stabilised structures are not pure pneumatic structures. The utilization of a combination of systems has many precedents. The results are successful however not always fully appreciated as hybrid systems. Others like the Tensairity® principle define a hybrid system entirely and cannot be classified as one particular system.

Hybrids have advantages greater that a pure pneumatic system. In review of precedent it becomes evident the resolution of how the pneumatic structure manages dynamic external loading is one of the key considerations to achieve a safe structure and has been the generator of research into a pneumatic systems with all the typical advantages plus an integration, with a beneficial system, that brings stiffness and lightweight at the same time.

Bechthold (2007: 61) summarised hybrid systems as, *“Mixed approaches have been developed and implemented that combine the advantages of distinct systems. One design objective that has driven the development of combination systems is the need for deployment and mobility.”*

That is partially accurate in that any pneumatic structure is challenged by external loading from the environment it is located in. Mobility is the benefit of lightweight and pneumatic. Hybrid brings the advantages of distinct systems to the structure managing a minimum external load capacity criteria and retaining the distinct advantages of lightweight and mobility. This succinctly describes the case study projects that follow.

The US Army have seen the advantages of lightweight hybrid pneumatic structures from as early as the 1960’s. Research has been strategically organised around the reduction of weight as a key criteria to bring about greater deployability. The work by Steeves resulted in the conclusion that less weight is achieved by simply using less material. That translates to reducing the number of tubes and smaller diameter inflated tubes. To resist the minimum wind and snow load as a strictly set criteria, high pressure was the result. The small tubes have developed into a frame with a similar geometric configuration of a steel frame structure. The containment and enclose achieved with a lightweight membrane. (Steeves 1979) In the authors opinion it is a hybrid system however not a good example.

Very few are true hybrid systems with the exception of the Tensairity® system by Airlight. The beam designed and engineered is a combination of three elements working together in perfect balance to create a spanning element that is stiff, lightweight, mobile and transportable. This system is a true hybrid as described by Bechthold (2007: 61), all the elements, the membrane, the steel beam and the steel cable, are intrinsically connected, each depends on each and every element for stiffness and strength. As a good example, the Tensairity® beams used in combination with infill membranes has created a roof assembly for a vehicle parking garage in Montreux, Switzerland. (See case study 4.14) Permanently installed it takes wind and snow load however does not utilise its characteristic of mobility. The application of the hybrid in this example is therefore questionable.

4.1 PRECEDENT STUDY

4.11 CASE STUDY

Floating Theatre, Expo 70, Osaka

Design: - Yutaka Murata

Year built: - 1970

Material: - Pes PVC

Pressure: - 14.7kPa to 29.4kPa

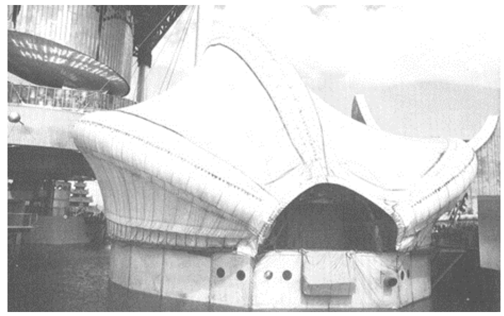


Figure 25. Floating Theatre. (Herzog 1976: 88)

This structure uses the principles of positive and negative internal pressure compartments to stabilise the structure that is anchored to a floating structural platform in water.

Three primary tubes arch across a circular plan. Between are two membranes, an upper and lower that is kept in negative pressure. Acting together the arch tubes and web membranes keep in equilibrium.

Internal pressure is further managed actively to counter act the dynamic wind load and like the Fuji Pavilion this structure is a high pressure system with a low working pressure.

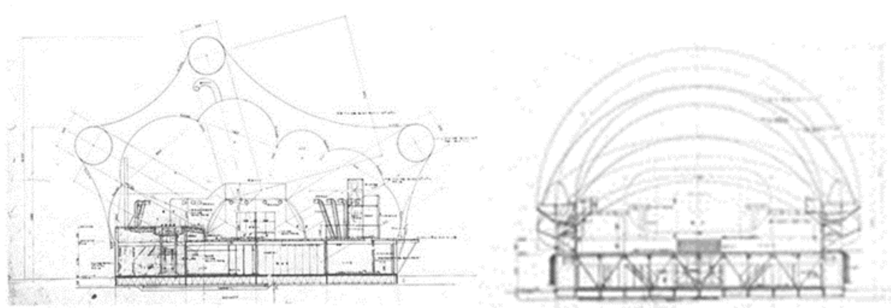


Figure 26. Cross and long sections showing primary tubes and infill membranes. (Herzog 1976: 89)

The circular floating platform creates the dimensional constraint of the plan that optimises form.

4.12 CASE STUDY

Demountable exhibition pavilion

Design:- Seminar Pneumatische Konstruktionen, Institut für Umweltplanung, Ulm, Germany

Year designed: - 1971

Material: - Unknown material specification.

Pressure: - negative pressure system of unknown value as never built

The membrane is a dual wall system with the internal volume under negative pressure. The outer membrane held in position with multiple point fixings to a lightweight steel frame in a radial array. The inner membrane held up in position through negative pressure application. The result is a large obstruction free space for exhibition.

The steel frame is of slim proportion and the author assumes that this is possible due to the negative pressure dual wall system preventing the frame from lateral movement and buckling.

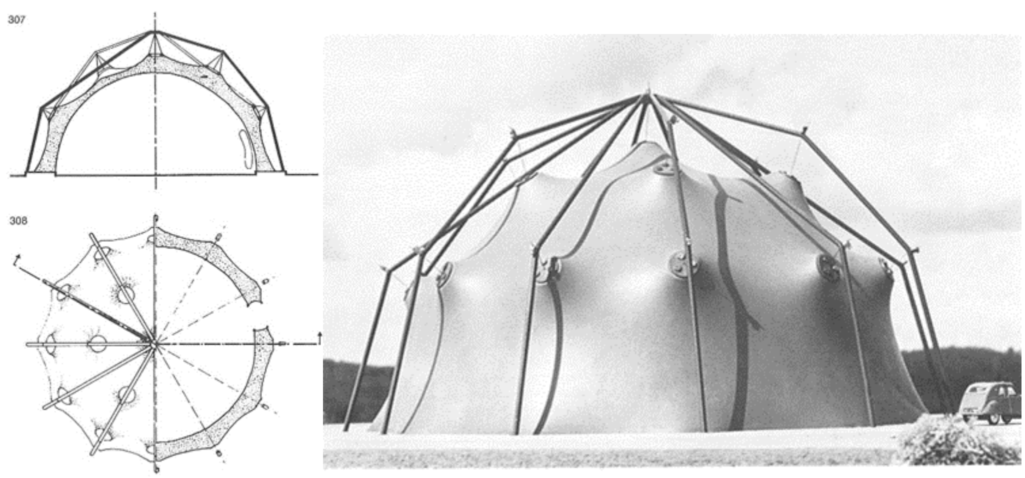


Figure 27. Section, plan & model view. (Herzog 1976: 109)

Multiple systems, the structural steel frame and the dual negative pressure membrane enclosure work in mutual reliance to achieve a unique structure with distinct advantages. (Herzog 1976: 109)

4.13 CASE STUDY

Small Tactical Airbeam Tent

Design: - Natick Soldier Center, US Army

Year designed: - not published

Pressure: - 275kPa (Airbeam)

Material: - This is a dual containment system. The external membrane to take the extremely high tension forces is made from braided Vectran® material. The internal bladder is a urethane material providing exceptional air containment qualities.

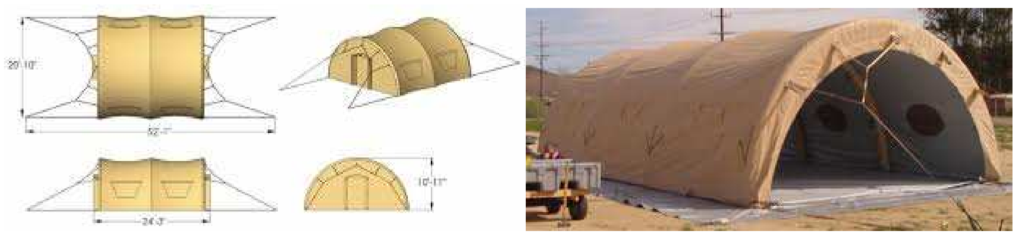


Figure 28. Diagram of two bay unit plus photo of three bay unit (Verge (): 15)

This structure currently used by the US Army is a small span unit. There is also a large span unit however important to note that both types utilise high pressure arch tubes with an attached enclosure membrane. The development of this started in the early 1970's with research by Johnson and Steeves concluded that a reduction of weight was the priority in achieving quick deploy ability. The resulting research and prototyping developed into a solution of very high pressure beams being used in a simple arch repeated to create structural bays that can extend for additional coverage. Guy ropes are required to stabilise the system and resist the environmental external load application.

The entire structural system revolves around the performance of a high pressure air beam frame. Reduction of weight requires the least amount of material application, a small diameter tube and high pressure to manage span and external load factors and a high performance material to take the pressure. The air beam frame uses a small diameter tube of 255mm, in a semi cylindrical arch geometry spanning 6m. The span to diameter ratio is 1:23.5. Compared to other pneumatic structures that use tube arches to span, this ratio is very efficient.

The tubes are strapped to the enclosure membrane with belts. The enclosure membrane is a single piece unit that remains attached to the beams even in the deflated packed state. This allows for very quick deployment with minimal manpower. (Verge (): 14)

The external membrane is only tensioned through the guy rope system. The hybrid is the assembly of the air beam, membrane enclosure and guy rope system.

4.14 CASE STUDY

Tensairity® garage roof, Montreux, Switzerland

Design: - Architect Luscher in cooperation with engineer Pedretti

Year built: - 2004

Pressure: - (unknown)

Material: - silicone coated fibreglass membrane

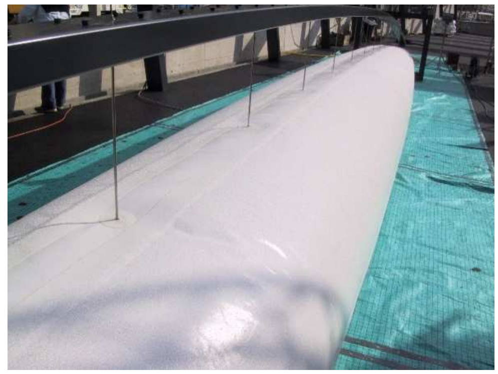


Figure 29. Internal view and assembly view of Tensairity beam. (Tensinet)

The roof for this vehicle parking garage was constructed with 12 units of lightweight beams using the Tensairity ® principle. The span achieved is an impressive 27m and infill panels of a single saddle shape membrane create the waterproof roof enclosure. The beams are an assembly of a pressure stabilised tube with a top & bottom steel section of small dimension connected with vertical steel rods through the tube. The pressure of the tube is constantly monitored and managed to ensure optimum load bearing capacity through the changing conditions of the seasons. It also counteracts loss of pressure through unavoidable leakage. The steel components manage the compression and tension forces, the inflated tube stabilises against torsional buckling. Working in mutual reliance to create an exceptionally lightweight beam with a large span. (Tensinet)

Figure 30. Photos of beams craned into position (Tensinet)

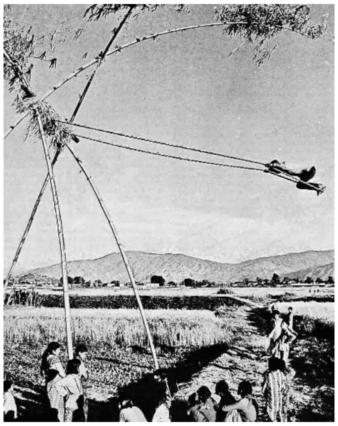
Whilst the beam and entire roof assembly can be considered lightweight, it was demonstrated not to be easily deployable in construction. The 12 beams were assembled in the factory, transported by train to the adjoining site and craned into position.

5

INVESTIGATION ON BENDING-ACTIVE PRINCIPLES

Pursuant to the thesis topic leads to the exploration of a hybrid solution. A system or approach that integrates with the pneumatically stabilized membrane structure resulting in a greater load bearing outcome than the single, original structure.

5.1 DEFINITION



The term “bending-active” is introduced by Lienhard (2014) in his doctoral dissertation to describe curved beams and surface structures that base their geometry on the elastic deformation of initially straight or planar elements. The motivation for deploying bending-active systems lies in the simplicity of producing complex curved elements with load bearing capacity. (Lienhard 2014: 13) By comparison to traditional building elements, the system deploys quickly, is light in weight and transportable. It is however not a complete structural type, bending-active is described rather as an approach. Both traditional and modern techniques of employment use the approach in combination with other components and structural systems. Lightweight hybrid structures are typical of this type of approach and examples are discussed further in this chapter.

Figure 31. Intuitive deployment of bending natural active elements. (IL31, 1985: 9)

5.2 MECHANICAL BEHAVIOUR

The elastic behaviour of particular materials has been identified from very early times and the advantages exploited to the benefit of intuitive builders seeking particular performance advantages. Lightweight building elements that have sufficient flexural strength in deformation to withstand the loading induced by natural environmental forces. The problem of understanding the geometry of deflection mathematically was first put forward by James Bernoulli and he published after many years of attempts, the Curvatura Laminae Elasticae in 1694.

Daniel Bernoulli first suggested in a letter to Euler the idea of stored and minimized energy in the bending action. In 1744, Euler building on the work of the Bernoulli’s publishes the Additamentum, a definitive works that characterize the family of curves known as the elastica.

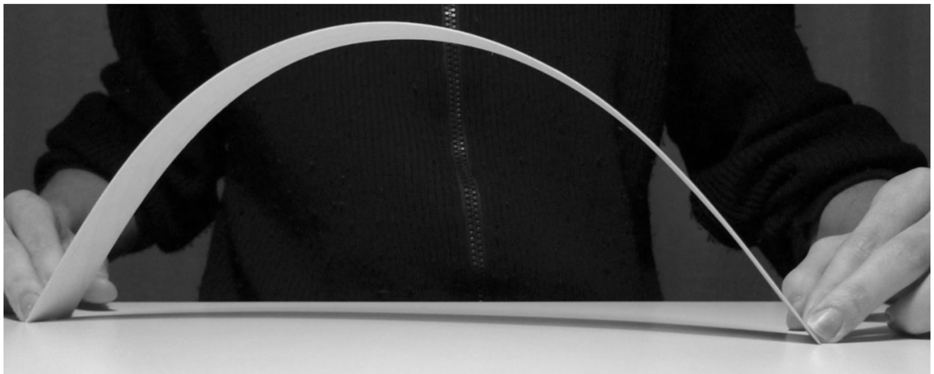


Figure 32. Plywood strip in bending. (Nettelbladt 2013: 29)

With reference to the photo, bending a thin strip of timber and assuming that bending takes place along its central axis with no twisting, stretching or compression, induces potential energy. Much like a spring. According to the theory of elasticity, the bending energy is proportional to the square of the curvature. When completely unconstrained, the elastic will assume the shape of a straight line, in which the curvature is everywhere zero and thus the total bending energy is also zero. When constrained the bending energy will tend to be the minimum possible under the given constraints. (Levien 2009: 17)

5.3 PRECEDENT STUDY

The technique of bending slender proportioned materials in a particular manner to gain structural load bearing capacity has a history of thousands of years. Some traditional cultures saw the benefit of locally available and abundant materials that were easy to harvest, easy to transport and integrate as a primary structural element in the construction of shelters and buildings. Materials that were suitable to this adoption are always slender long elements with a certain bending capacity and high breaking strain. This included certain green-cut, thin, long wooden poles, reeds found in wet march areas and bamboo. The adoption of the material into the structural system was always due to the materials natural properties. The forms generated were therefore unique to the material and the culture of building. However the technique of extracting load bearing capacity from these slender building materials was constant.

Due to the efficiencies of the technique and the potential of lightweight principles, the Institute of Lightweight Structures (IL) under Frei Otto researched and developed a greater understanding to the potential exploited instinctively by traditional cultures. The lightweight principle is described by the IL as the structures ability to transmit forces over prescribed distances using a minimum of material. IL25 (1990). The research included a wide range of elements, principles and applications. From some as simple as a mast for membrane structures integrated in a deformed state of equilibrium to the application of complex grid shell structures. IL10 (1974) this work has generated huge interest and adopted in many applications and generating further research. Lienhard in his doctoral thesis specifically took on and defines the approach as a term Bending-Active structures. Understanding form-finding strategies using elastic deformation and the structural potentials. Lienhard (2014)

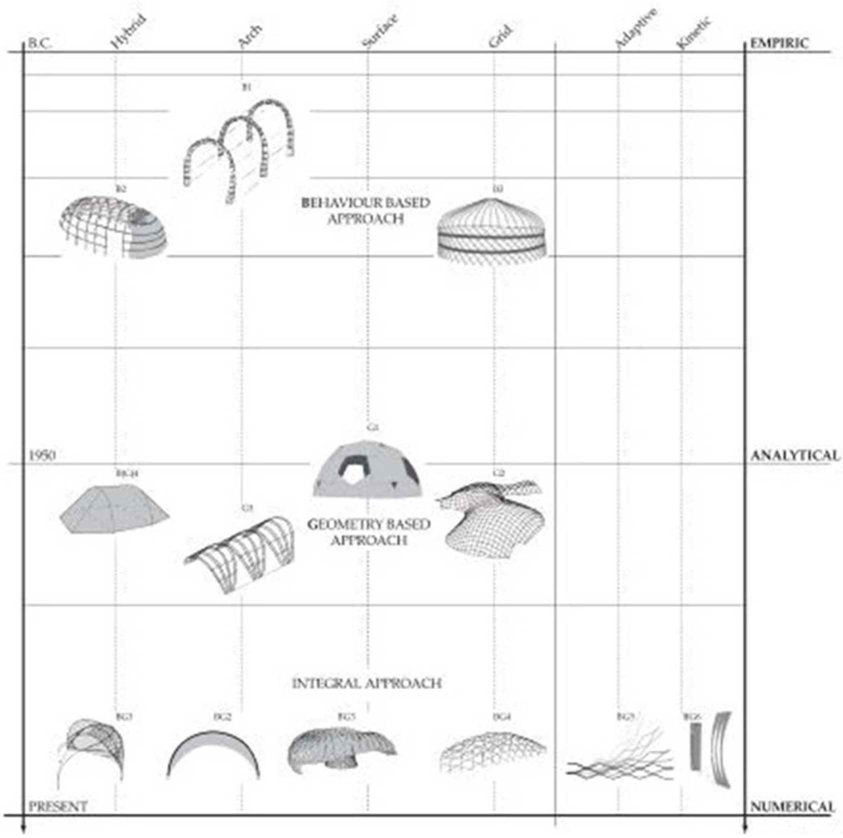


Figure 33. Development of bending-active structures. (Lienhard et al 2013: 190)

The following are case studies documenting a selection of applications that covers the spectrum of design approaches as defined by Lienhard et al (2013). The three design approaches are shown in the adjacent diagram.

The behaviour based approach where the material is used intuitively and tested physically in the process of building. Examples include the Mudhif house and the Yamut house construction.

The geometry based approach where the structures geometry is pre-defined on analytical or experimental form-finding methods. Material limitations are considered analytically. Example includes the grid shell of the Hooke Park Forest School.

The third design approach is the integration of both approaches and termed the integral approach. Elastic bending is analysed through numerical form-finding and enables full control of material behaviour based geometry.

5.31 CASE STUDY

Mudhif house construction

Approach: - Behaviour based

Design: - Madan people of Southern Iraq

Year built: - ancient building technique still used today

Material: - giant reed, Phragmite Communis (Learning-from-vernacular.epfl.ch)

The marsh reed found in abundance has the property, once it has reached a certain maturity to be deformed or bent into an arch shape and combined with many to form bundles, each bundle an arched rib and then repeated in parallel. The spaces in between are filled in with lightweight woven mats that manipulate functionality for waterproofness or light.

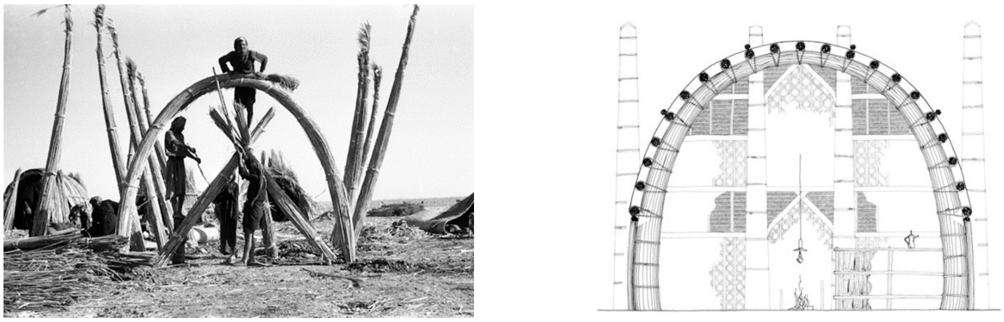


Figure 34. Bundles of marsh reed deformed into a structural arch. (Learning-from-vernacular.epfl.ch)

5.32 Case Study

Yamut house construction

Approach: - Behaviour based

Design: - Nomadic Turkmen

Year built: - ancient building technique still used

Material: - long, wood poles of small diameter

Figure 35. Complete structural frame of Yamut house (Islamic Republic of Iran Broadcasting website)

5.33 Case Study

Weald and Downland Grid shell

Approach: - Geometry based

Design: - Edward Cullinan Architects

Year built: - 2002

Material: - oak timber

Figure 36. Grid shell partially clad during construction. (StudyBlue website)

5.34 CASE STUDY

Umbrella for Marrakesh

Approach: - Integral based

Design: - Institute of Building Structures and Structural Design in collaboration with HFT Stuttgart

Year built: - 2012

Material: - Pes PVC membrane with integrated GFRP tubes as bending-active elements

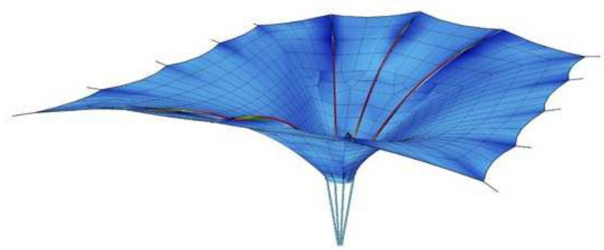


Figure 37. Marrakesh, umbrella computer simulation visual. (Str.ucture website)

5.4 MATERIALS

Actively bending and stabilising structural elements for increased load bearing requires materials of suitable elasticity. Low density and high strength combined with low bending stiffness is found within a small range of materials. Traditional builders found that in certain green timbers, reeds and bamboo.

The most important variables, in bending-active elements or components, to set into relation are Young's Modulus E and permissible bending stress. The diagram, figure 34, adopts the Ashby methodology of mapping out design guidelines and search regions that identify design spaces for certain applications. (Ashby 2005)

Bending-active that is statically employed is where the pressure stabilised membrane hybrid is located. Plotting within the diagram the three materials available are certain timbers, certain metals and fibre reinforced polymers. Noting that Bamboo is located not within the timber design space but rather demonstrating equally with glass fibre reinforced polymers.

The FRP's demonstrate a ratio of flexural strength (MPA) to flexural Young's Modulus (GPa) of between 4.5 and 16.97. With carbon based FRP's at the high end of the ratio. Only Bamboo with a ratio of 11.13 is comparative.

Glass fibre reinforced polymers offer advantage over the carbon based product in that is it commercially widely available and of a more cost effective range. The process of pultrusion has made possible long continuous units to specification. As a fibre reinforced polymer, the properties of the fibres are used to resist tensile and compressive loads and the polymer matrix transfers shear. (Fibreline 2003: 12) The GFRP as a composite can be engineered to fulfil a specific purpose. By adapting the ratio of material composition the composite product can be dedicated to purpose of specific application.

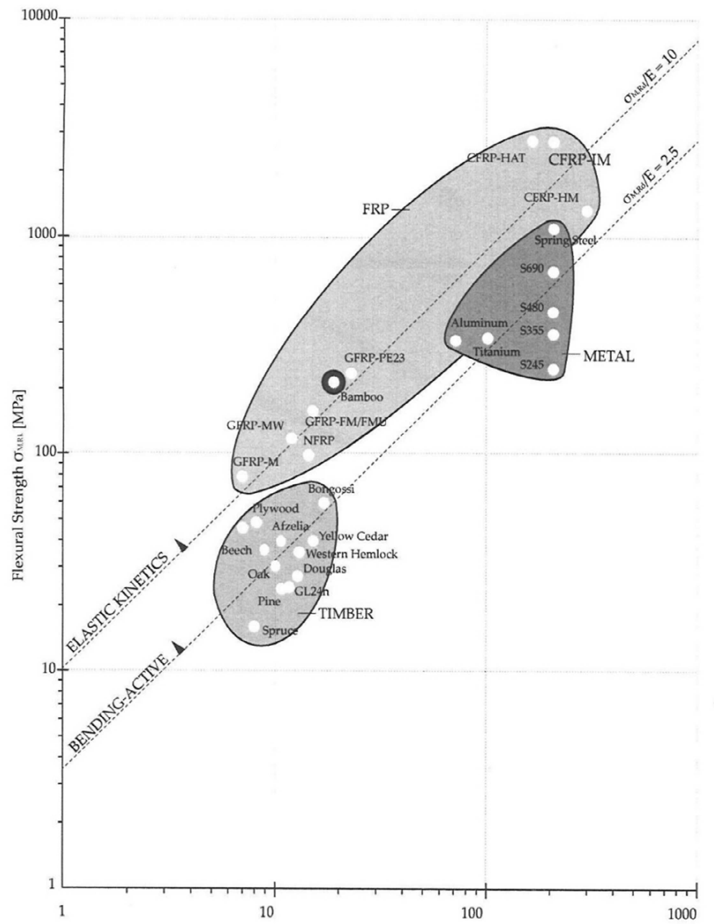


Figure 38. Diagram of bending-active materials strength to stiffness ratio. (Lienhard et al 2013)

5.5 BENEFITS & HYBRIDS

A key feature of bending-active structures is their potential for structural integration and heterogeneity, leaving the limits of strictly categorised building structures by accumulating different load bearing strategies in hybrids. (Lienhard 2014: 13)

For this thesis, the central argument adopted and explored is that the principle of elastic deformation can be actively deployed to a pressure stabilised membrane arch to prevent compression zones, due to external loading, developing into a folding point of failure, a behaviour typical of pressure stabilised membrane structures. The proof of concept is to test and observe the behaviour of the two components and the interaction as a hybrid structure when external load is applied.

The motivation is to develop a safe structure for event purposes with all the benefits of a low pressure, stabilised membrane structure plus through hybridization, create a structure that can withstand higher gust wind speeds without attracting the penalties that other systems have adopted. Reference is made directly to the very high pressure systems deployed by the US Army. Reference is also made directly to the steel component integration of the Tensairity® beam principle. Here deployability is questionable, the benefit lost.

6

PROTOTYPICAL STRUCTURE CRITERIA

What the structure and its function needs to be as an event structure is important to define in the development process. As it will provide the basis for the application of the hybrid structure and give it meaning for occupation. Further the basic criteria if defined properly from the outset, will direct development beyond this thesis into a commercial reality.

To gain insight into what the industry of event production requires of a temporary structure, two independent experts have been consulted and requested to complete a questionnaire. The questionnaire assumes a pneumatic structure and the intent is to explore what are the important requirement expected from using a structure of this type and what benefits it is seen to bring to the event production.

The interview questionnaire was filled out by the following two senior, experienced employees, at two separate international production agencies. Copies included in the Appendix for reference.

› Chris MacDonald, VP Executive Producer, JACK MORTON WORLDWIDE
› Faresh Jowharsha, Head of Production, IMAGINATION (HK, Macau)

6.1 DESIGN CRITERIA OF PROTOTYPICAL STRUCTURE

The following criteria has been extracted from feedback of the questionnaires and are integrated into the prototypical structure.

› Dimension of structure area covered

Five hundred square meters of coverage is the minimum for the event industry for corporate events and the ability to scale up with a modular system will allow greater flexibility. The prototypical structure is based on a 155m² typical module (14m wide x 11m length) with a 58m² end bay. That allows a modular and scalable range. The smallest is a single standard module plus two end bays that totals 271m². With that system the area range possible is 271m², 426m², 582m² and 738m² to stop at four module structure.

› Structure section profile

Height of the structure is important to create the desired commercial impact. Above five meters and above eight meters is quoted. The prototypical structure in section is based on a parabolic arch with the apex at minimum 6.9m and at maximum 10.5m.

› Layout plan

There is no clear consensus on the shape of the plan. The nature of the event and the constraints of the selected venue tend to dictate. The best method to create scalable areas is to extend a shape and the rectangular plan then works best. Circular and square can only be repeated structurally and then connected. The prototypical structure is a scalable rectangle.

› Equipment weight

The overall weight of the structure is critical to the commercial program. Costs to move the structure over short local distances and long international distances is important. The cost to install and dismantle is based on time and manpower. Keeping the weight of the equipment low reduces overall cost. Limitations of venues and structural slab design loads impact what structure can be installed. The prototypical structure as an inflated pneumatic structure will inherently have a weight advantage over other structures. The raised deck system is the large component that can potentially attract weight. The structural frame and the infill panels need to satisfy safety specifications as well as be lightweight.

› Compliance to code

Compliance to the local building code is paramount to all parties involved in the production to ensure safety. The structure must have the structural drawings, details and calculations sufficient to allow submission and approval by local authorities.

› Production friendly

Understanding the needs of event production and building that understanding into the structure defines the equipment. It makes it easy to use from all interfaces and that will again translate into a favourable commercial reality for everyone involved in the production.

› Dimensional stability/ predictable

To plan out and follow up with short installation durations of the equipment necessary for the production requires the event structure to be dimensionally predictable in both plan and section. For inflatable structures this requires a clear strategy in detailing to achieve and is not a natural consequential outcome like rigid frame structures.

› Externally induced pressure behaviour

An event structure needs to manage externally induce pressure loading to ensure safety. This needs to comply with local authorities building code. In addition how the structure flexes and moves with dynamic loading needs to be kept to a minimum and not create an uncomfortable visual experience to the users and occupiers of the structure. Pneumatic structures can be temperamental with induced external load causing swaying and twisting buckling and this needs to be addressed and minimised.

› Deployability

The event industry, commercially motivated, needs to locate strategically and time is a huge factory in consideration of planning. Flexibility of a structure to deploy supports the agenda. Transport, time, manpower, venue, maintenance and cost are all factors impacted by the ability to deploy. The prototypical structure needs to pack into the optimum number of components, stack for transport, take the least amount of space for road and air transport, use the least amount of manpower to install in the shortest possible time and be lightweight in complete build to locate on many venues. Scalability will add to the ability to deploy.

› Installation & dismantle requirements

Time as a factor of cost is very important for the event industry. There is considerable effort given to load-in of equipment and installation and dismantle. The motivation is that venues are expensive to rent and are normally charged out per 24-hours. For an event that can last four to six hours, the majority of venue rental cost is in the preparation and removal of the equipment. The prototypical structure needs to install safely within the shortest time to allow for the preparation of the internal production to commence as early as possible. The sequence and how the structure installs is a consequence of this and needs to be addressed carefully. Equally this applies to dismantle and removal of the structure.

6.2 COMPLIANCE TO CODE

The industry of event production has grown out of the need for people to gather for many different reasons. From the simple need to celebrate as a group to sophisticated productions in the launch of products and professionally organised events. The use of temporary structures was an immediate necessity however and dependent on country to country was not always well regulated for safety reasons. In the United Kingdom there have been a series of serious incidents involving the collapse of temporary structures at events. This has prompted an appropriate response to make the enjoyment of the events safe for all attending and working.

The Department of Environment, United Kingdom provided the funding for the publication of a guide on Temporary Demountable Structures by the Institute of Structural Engineers in collaboration with the Steel Construction Institute. Further failures have led to the updating of the guide, especially with respect to the actions of wind on temporary structures. The third edition published in 2007 has a clear and defining section on wind load for temporary structures. This is the only attempt by an authority to manage and make safe temporary structures for events, known by the author, with a practical approach to how the industry works and can be guided to an environment of safe implementation and enjoyment. This specifically acknowledges that rigid application of standards and code will in fact produce counter-productive results. (Temporary Demountable Structures 2007: 2) (Temporary structures – tents – Safety: EN 13782:2005)

This is a reality experienced by the author working in Hong Kong where the Hong Kong Wind Code is applied to temporary event structures. The Wind Code specifically addresses typhoon conditions to permanent buildings and does not accommodate temporary event structures. The result is the requirement to comply with a gust wind speed of 48m/s, this is extremely onerous on the temporary structure and cannot be practically applied and is commercially unviable.

Under the Temporary Demountable Structures guide, section 8, on wind load for temporary structures, it states that the safety of tents and marquees, is assured through a two-stage process.

1. Selection of a suitable marquee for the site
2. Active management of risk in service.

Note that the guide does not specifically address pneumatic structures however it will fall within the temporary structure typology when reading the guide. The maximum gust wind speed (V10) is determined by a simplified equation as

V(10) = V(b) x S(m)

Where V(b) is taken from a wind map in BS 6399: Part 2 that determines wind zones across the UK. S(m) is a table of factors that determines the location of the structure with regards to criteria of exposure to wind, altitude, height of structure and the summer and winter seasons.

In application of the equation to determine maximum gust wind speed compliance for the purpose of this thesis, the author assumes that the structure is located in the United Kingdom. That V(b) is taken as a higher rate at 24m/s for coverage of most of the country. For S(m), the structure is assumed to be installed for summers only, reasonable for outdoor events and at less than 9m in vertical height, the maximum factor is 1.37.

V(10) = 24 x 1.37

V(10) = 32.88m/s

This is for a temporary event structure, an extremely high gust wind speed requirement. Translating to approximately 0.7kPa on the structure, the accepted norm in response is to make use of an external guy rope system or counter weighting to prevent uplift and lateral movement. For the end user in events the maximum required wind condition of 32.88m/s are unsuitable, unpleasant and the event production will have ceased well before these conditions are met.

7

EXPLORATION OF FORM-POSSIBILITY

The lightweight principle is used to assess structures …with regards to their ability to transmit forces over a prescribed distances using a minimum of material. This depends on the form of the object to be examined, the materials and the nature of the load to which it is subjected. The form of relatively lightweight structures is rarely a chance occurrence. It is usually a result of development and optimisation process which, be it planned or unplanned, mainly occurs in the field of extreme structures. (IL25 1990: 5.2)

The load bearing capacity of pressure stabilised structures is dependent on the trinity relationship of internal pressure, membrane material properties and geometric form. (Veldman 2007: 9) This motivates the exploration of a form true to the pneu and a form that responds adequately to the functionality of the commercial agenda inherent in event structures. The criteria of which was explored in the previous chapter.

The language and meaning of form is subjective and complex. The IL under Frei Otto spent decades attempting to record, categorize and release understanding. The IL22 publication is dedicated to the description of form under the main heading of Form-Force-Mass. In Frei Otto's own introduction he states that there is much work to be done and more to be understood.

This thesis explores the combination of three initiatives, to develop a lightweight structure, to develop that structure with an event function and to develop the structure to be a greater sum of its individual parts to manage external environmental loading.

The platform the exploration and development builds on is using the valuable benefits that a pressure stabilised membrane structure brings to the requirements of the event industry. The basis is pneu and the form in compliance.

7.1 PNEU FORMS

The spherical envelope is the basic form of pneumatic structures; according to the geometrical principles, it encloses a maximum volume by a minimum surface. (IL25 1990: 2.62). The pressure induces tension into the membrane and is constant everywhere. It is harmonic. Following this principle into building structures leads to forms and examples have been reviewed in the case studies. Most of these examples interpret the principle of the pneu geometry. The Fuji pavilion adopts the repetitive use of long cylindrical tubes that are bent into a plan of circular shape and bound together to create a uniform structure. The Modern Teahouse example manipulates the dual wall construction into the forms of two part spheres joining much like a peanut shell shape. Structurally fixed into the perimeter at ground level the curves give stability to the overall form.

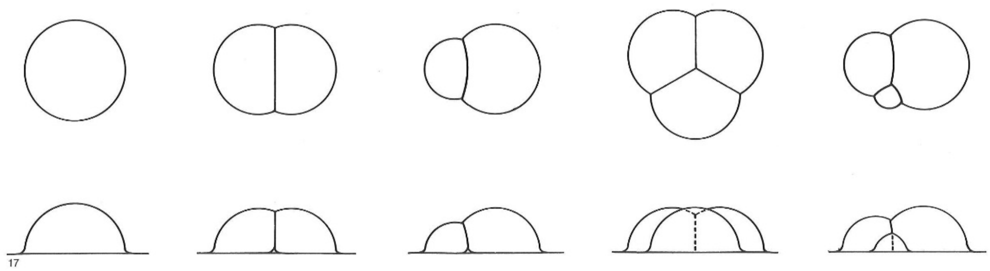


Figure 39. The sphere & generative forms. (IL25 1990: 11)

7.2 FORM GENERATION

In the process of form generation, a dual wall construction of pressure stabilised membrane structure or elements is the only consideration. Air supported membranes are considered.

The start of consideration is taken from the requirement to cover a certain area for event purposes. That has certain constraints as there is no one event activity the same and at the same time, most events are of a similar nature. The structure for commercial purposes needs to be neutral in the plan configuration to retain flexibility of functional use. A simple open space, without obstruction of structural support, and of a basic layout configuration. Simple volume of space is generated from a circular plan, be it round or polygon, or a square plan or a rectangular plan.

The circular plan developed into a dome as a pneumatic dual wall construction has been used many times previously with two examples being the Trident Dome and the Pneumocell Dome. Both different approaches leading to the same end result of a circular covered event structure. For events, the round floor plan is not easy to configure as it is symmetrical in every direction, the loci is the centre and difficult to avoid. The planning is dictated to by the shape, flexibility is limited. Human behaviour defines the use of space and in this perfectly symmetrical plan, choice is predefined.

The square floor plan offers a similar challenge, although slightly diluted from the circular plan and was also rejected at a very early stage of exploration. The rectangular plan shape however has neutrality as it does not dictate as the circle and the square.

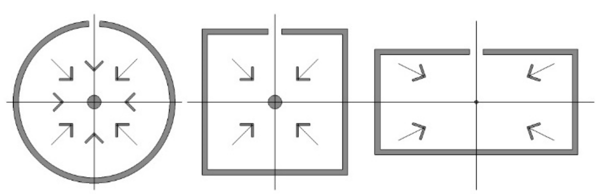


Figure 40. Circle, Square, Rectangle comparative plan. (By author)

Translating the rectangular plan configuration into the geometric language of pneu leads to a few outcomes that have been explored with many precedents. The Solar Impulse Hangar by Pauli (see section 3.58) is one example that utilises a standard unit of arch and through extruded linear repetition, creates long rectangular spaces. Changes in direction are perpendicular and continue the section. The hangar solution has also now been adopted into event structures like the Buildair solution.

Figure 41. Temporary event structure. (Buildair website)

The Pauli hangar and Buildair hangar take the single denominator of the tube, bent into a half circle and repeated. It is very economical and predictable. It also has long linear vertical sides that can be argued is not part of the pneu form. Any straight linear element is not as stable as the curves of the pneu.

Figure 42. Plan diagram of Buildair hangar format converted for event purposes. (By author)

Another strategy has been adopted by the Modern Teahouse example, the rectangle is created within the peanut shell shape. It is two half spheres joined with a concave link. It is without a single linear element and the claim is the structure is very stable in high gust wind conditions. (Schmit 2011: 122) What the resulting space creates is a two spaces joined rather than one single space. The dichotomy of space is inherent in the peanut shape.

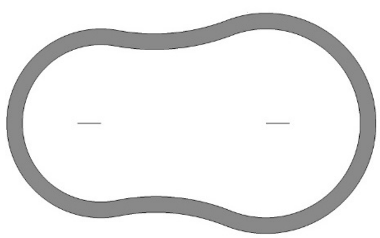


Figure 43. Plan diagram of the Modern teahouse (By author)

The extracted advantages of the hangar solutions are the use of the simple cylindrical tube that can be used in combination and brings economy to the build. Safety is addressed through the ability to isolate failure points from the majority of the inflated tubes and retain the structural integrity. Extracted advantages of the Modern teahouse is the adoption of the pneu form in both plan and section.

This leads to the exploration of a form that accommodates the rectangular floor space requirement, uses a pneu form in both plan and section that is translated through simple use of cylindrical, separate tubes or inflated units.

The diagrams that follow show the opportunity in the use of repetitive circular forms, overlapped closely to create a single rectangular space with curves.

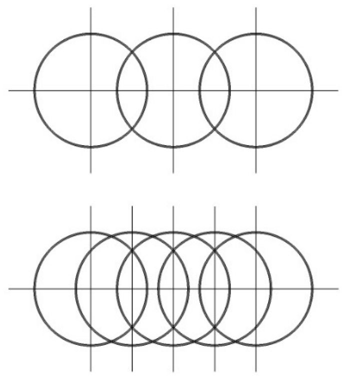


Figure 44. Diagram of rectangular space generation from spherical volumes. (By author)

The plan generates into a series of part spherical volumes that overlap and are not too dissimilar to the soap bubble test photos from the IL. How the cylindrical tube is used to describe the volumes is the opportunity of structural exploration. What is achieved through the application is circular plan form to enclose rectangular space.

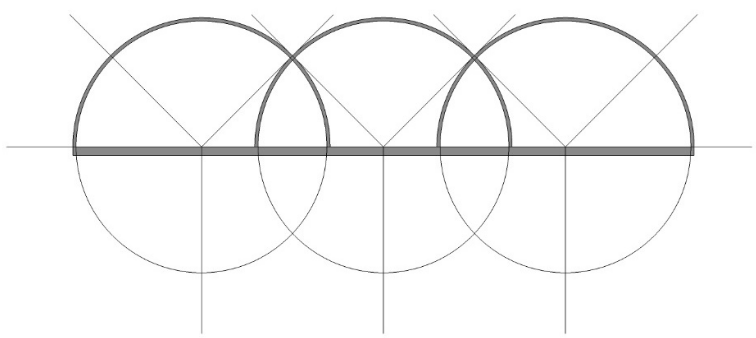


Figure 45. Diagram of diagonal generating lines in section (By author)

The section diagram shows the initial idea of following diagonals for the primary structural elements as a distinct departure from the vertical arrangement used by the Pauli and Buildair hangar examples. The motivation is to explore a pneu form that is greater than previously expressed and that it will unlock further potential.

8

DEVELOPMENT OF PROTOTYPICAL STRUCTURE

8.1 HYBRID PRINCIPLE

The purpose of the thesis is to explore a new form possibility for an event structure that inherits all the benefits of pressure stabilised membrane structures plus, does not suffer the same weaknesses particular to the inflatable structure typology. Preventing the wrinkling compression zones under load that lead to buckling deformation and failure in load bearing is the key to overcoming the weakness. The approach of high pressure systems deployment, as adopted by the US Army in quick deployable structures, is for the author a viable, safe and economical route for commercially used structures.

The strategy is to have a low working, operating pressure well below the 15kPa.

This leads to the adoption of a hybrid solution that will achieve an outcome greater than that of the individual systems or assemblies employed. The integration of a bending-active approach to the pressure stabilised membrane arches is proposed to be a solution. The stored energy of the deformed GFRP element is used against the formation of compressive, wrinkle zones of the pressured membrane under load. The selection of the GFRP tube is considered suitable as the element can be deformed or bent into the geometry of the inflated arch. The question of geometry is dealt with in the next section. The GFRP tube is also lightweight and can be easily transported, in smaller units that connect, to suit the vehicle or in a bent geometric state to take less dimension in the vehicle.

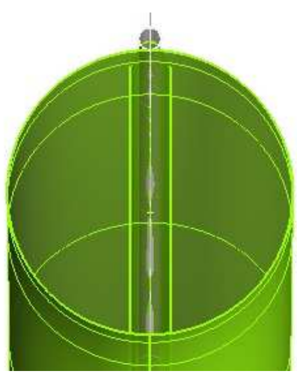


Figure 46. Hybrid arch, front view & apex cross section of primary unit. (By author)

The above diagrams show the primary inflated arch unit with a single GFRP tube bent into position on the apex of the circular cross section. The component is held in the deformed state in a containment sleeve with a closed end to prevent slipping.

8.2 GEOMETRY

8.21 GENERATOR

The adoption of the half circle for the geometric section is not a given and is open to exploration as a pressure stabilised membrane arch. Precedent shows that the half circle is perhaps the most economical commercially in engineering and fabrication. The Fuji Pavilion demonstrates the many configurations a tube can be manipulated into to create a structural arch. The arch taking up different spans each time to describe a circular plan illustrates the flexibility of the principle and that the plan does not have to be rectilinear.

The diagram below shows the comparisons of the geometries selected to explore and excludes complex freeform curves. The three are the half circle, the parabola and the elastica. There has been very little research completed, that the author is aware of, that has comparatively tested the structural capabilities between the three geometries as inflated arch tubes. Some research has been done with a Tensairity® half arch and parabolic arch however that has no relevance to the behaviour of a pressure stabilised arch. Other research has been done using the half circle or the parabola however no substantiation has been provided as to why the geometry has been selected.

Dimensionally the diagrams below demonstrate the vertical height achieved between the three given the same horizontal span. Both the parabola and the elastica provide a much greater vertical dimension than the half circle. From an event functionality perspective, the greater height is preferable. The greater volume of the elastica is considered unnecessary and the half circle too low in section. The parabola provides a good vertical height to span ratio.

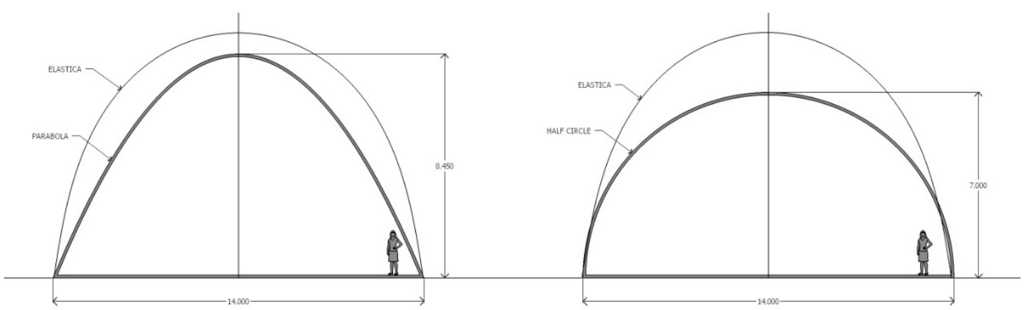


Figure 47. Diagram of half-circle, parabola and elastica curves. (By author)

The form of the parabola is considered to be more desirable from a heavy rain and snow load perspective as the angle of inclination will shed both better than the half circle. From a wind load perspective, the lower profile of the half circle will present less area to the prevailing wind and therefore attract less load. The parabola has been selected as the most appropriate generating geometry.

8.22 FORM SECTION

“The form of the membrane has a decisive influence in the architectural and structural quality and this on the long term behaviour of the structure.” (IL15 1987: 38)

Taking the lead from the words of the Institute of Lightweight, the form is given priority. The long term behaviour of the structure is critical as an event structure with a commercial bias as it will be used multiple times per year over a long a period as possible.

The geometric plan and section has been selected. The repetitive use of the circle and expressed in a parabolic section. The form is a paraboloid intersecting.

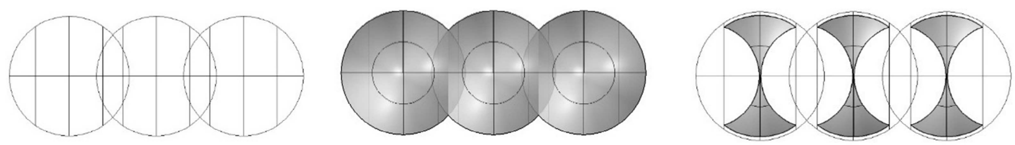


Figure 48. Diagram show the circle and the paraboloid development. (By author)

Creating a continuous space without the use of linear elements is achieved through the cutting of the paraboloids at an angle and rotating the generated section through and between each form. At no point is the form linear. It is from a circle and a parabola, the form is of the pneu family.

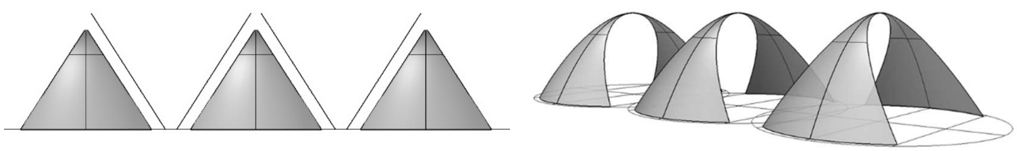


Figure 49. Diagram of the paraboloid cut. (By author)

The form as a basic language has the potential to be developed and researched. The cut paraboloid profile is used to generate the primary structural tubes as indicated in the diagram below. From the primary tubes the opportunity presents to rotate the arch in a radial fan between each element as an infill panel. The two are separate elements in mutual structural relationship. The remaining paraboloid generates into another lower infill panel between the primary structural elements.

Figure 50. Diagram of the geometry generating into structural primary and secondary modular elements (by author)

8.23 TUBE THICKNESS

The primary arches require particular attention to detail as the units transfer the load onto the raised structural deck. Each primary arch is a single tube configured in a parabolic geometry. The relationship between internal pressure, tube diameter and arch span is important in the structural performance.

The design parameters for pressure is covered in more detail a separate section in this chapter. Important to highlight at this point is the strategy of a low pressure beam, as defined by Herzog, is adopted. This parameter dictates in part then the strategy of tube diameter to arch span properties.

Pauli in his correspondence to the author confirms his strategy for tube diameter to arch span range of 1/10 to 1/15. On that basis, the designed span of the primary parabolic arch at 14m translates to a tube diameter range of between 1.4m to 0.93m. Current design has diameter of the tube at the apex of 1.0m and at termination of the tube at 0.8m. The changing diameter reflects the anticipated higher bending moments at mid-span of the arch and is subject to further testing. The dimensions are within the range as advised by Pauli for a low pressure tube.

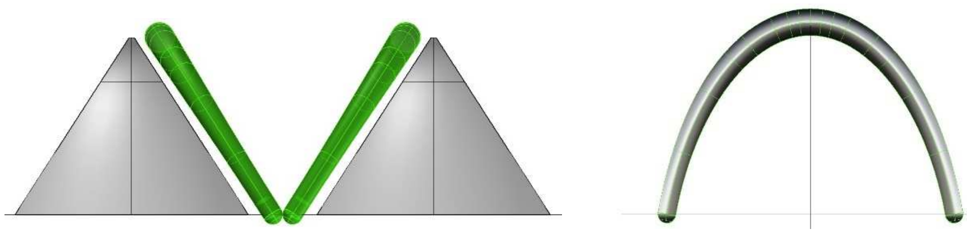


Figure 51. Diagram of parabolic arch (by author)

The integration of the bending-active element on the low pressure tube, acting in a state of deformation to prevent or limited the outer membrane surface of the tube from losing tension forces sufficiently and transforming into a compressive state that induces a snap failure point.

The disadvantage of this strategy is the added complexity of installation procedure that brings a cost and time penalty plus a nominal increase in weight. The author is however of the opinion that the potential benefit far out weights the penalties.

As a comparative example, the Small Tactical Airbeam Tent designed as a highly deployable structure, uses a small diameter tube of 255mm at a pressure of 276kPa to span 6m. (Verge (): 14). That translates to a diameter to span ratio of 1/23.5. The transportability or cube packing dimension are small and installation time short. The penalty is the material specification and related cost that the high pressure system attracts. Safety is claimed to be manageable and is evidently not considered dangerous. Important to note that it is military equipment standard and not something that can be used commercially within the public realm.

8.24 MULTI-TUBE CONFIGURATION

The motivation for the adoption of a multi tube configuration lies in practical reasons of safety and in inflation deployment.

The Fuji Pavilion demonstrates the strategy of multiple tubes deployed that create the enclosure to the structure. Each tube is independent and in the event of failure, it will most likely occur with a single tube and the surrounding tubes are unaffected and continue to support the failure of the single unit. Time to respond adequately and repair the damage is created to the safety of the users.

Multi-tube configuration also allows installation, termed the “form-giving load case” (Hennicke) greater flexibility in the procedure. A single piece structure in inflation and taking its final desired form is not an easy task. The weight and size makes for difficult management into the form. By splitting into smaller units, the process can be additive to achieving form, each smaller module easier to manage. Again the Fuji Pavilion would not have been possible, not without considerable cost, to assemble as a single piece. The inclusion of the bending-active component into the arch of the prototypical structure, makes the shape forming easier as it can be installed before inflation.

For the hybrid, the strategy is adopted and multiplicity is achieved as repetitive units combined to create the enclosure.

8.25 MODULAR SYSTEM

Adopting a similar strategy of the Pneumocell Event Dome, that builds using a series of smaller inflatable elements combined to make the whole. The advantage is in deployment. The smaller modules are easier to pack, transport, move and maintain. The key commercial motivation is that installation and dismantle requires less manpower and arguably less skilled man power.

The structure is made up from the raised flooring system that the inflatable structure mounts. The inflatable itself is made of three components, the parabolic arch as the primary structural element and the secondary infill panels, the top unit and the side unit. All units are attached to each other by means of high quality zipper systems that are commercially available. Example being the TIZIP® zipper systems that are designed to take high tensile forces across the zip unit, abrasion resistant and are water proof under prescribed working conditions. It has a cross breaking strength when in the closed position of 300N/cm. (TIZIP® 2009: 1)

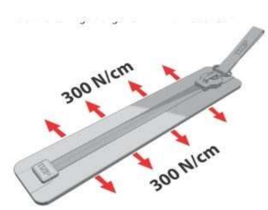


Figure 52. Diagram of TIZIP®. (TIZIP® 2009: 1)

The system is welded to each inflated tube, making connecting a simple zipping process in a predetermined sequence. The modules in combination creating the full envelope enclosure of the structure. Below diagrams show the three elements and their geometric relationship, the primary structural arches in green, the upper infill panel in white and the lower infill panel in grey.

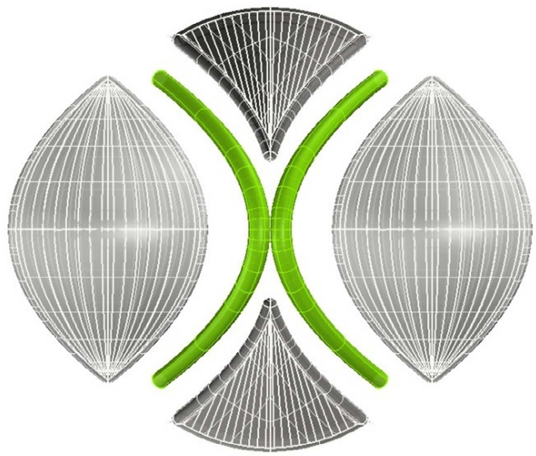


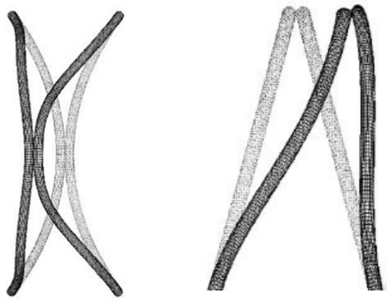
Figure 53. Diagram plan view of the three modular elements in configuration. (By author)

8.26 PRIMARY & SECONDARY SYSTEM

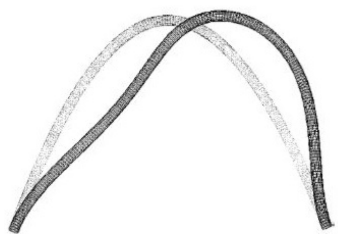
Integration of the hybrid strategy is to be considered carefully to bring maximum benefit. The bending-active element as a GFRP tube lends itself to being deformed into a geometry, not as an inherent elastica but matching the parabolic geometry of the tube arch. That allows for direct application and contact of the GFRP tube with the outer membrane of the pressure stabilised tube. This will induce the maximum benefit as the objective.

The hybrid arch will be stiffer and have greater load bearing and is positioned and utilised as a primary structural element within the inflated envelope. The secondary components are infill components that support the arches and work against the actions of buckling when under induced load.

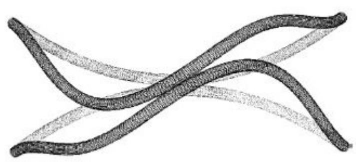
The arches are not located in the vertical plane as in examples of the Fuji Pavilion or in the hangar solutions of Pauli or Buildair. The geometry has provided the opportunity to rotate the primary arches out of the vertical plane by 33 degrees. This allows the arches to lean against one another in pairs. With the tube ends fixed and the apex of the arches fixed together, the leaning arch pyramid format has a buckling load capacity of approximately 5.5 times greater than that of a single arch in vertical position. Further, the resistance to lateral loads is much greater for the leaning structure than for the vertical arch. (Molloy et al 1999: 5) In their study on the behaviour of a pair of leaning inflated arches under load, Molloy et al, identified three types of buckling modes as demonstrated in the diagrams below, the side sway, the longitudinal sway and the twist. Key variables are the manner of end fixing, fixed or pinned and the degree of arch rotation out of vertical. The corresponding buckling mode was side sway if the end points were fixed and twist if the end points were pinned. The structure is more stable when the ends are fixed rather than pinned. This begins to inform how the tube ends are secured and how to counter the corresponding and anticipated buckling modes.



Sideways sway buckling mode



Longitudinal sway buckling mode



Twist buckling mode

Figure 54. Diagrams of the three modes of buckling. (Molloy et al 1999: 2 & 3)

The author anticipates that the hybrid arch configuration will work against or resist the side and longitudinal sway with the GFRP tube returning to the original position on release of induced load. Buckling through twisting can be reduced by not adopting a pinned end fix and utilising the lateral support from the secondary infill panels located on either side of the primary tube. Twisting will further be prevented by the infill panels located either side of the primary tubes. The primary and secondary systems are anticipated to work in unison.

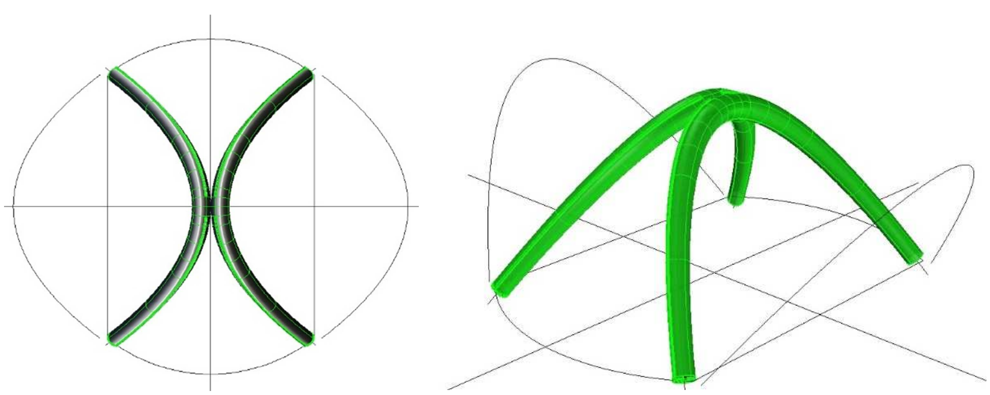


Figure 55. Diagrams of the leaning arch pyramid configuration. (By author)

8.3 MATERIAL

The material to enclose, hold and maintain air pressure that is also subjected to induced loading and operational rigours needs to have multiple good properties within one. Materials such as Pes PVC that is weldable has been adopted in many inflatable structures as it tends to satisfy most requirements including lower cost. Small air leakage is a continual challenge and with higher pressures, is very difficult to resolve. Air pressure management therefore needs to be adopted and active 100% of the time when installed.

A strategy that provides the best practical benefit is to employ a double membrane system. The exterior membrane material should be lightweight with high abrasion qualities, high UV resistance and high tensile strength that correlates' with the anticipated tensile forces induced by internal target pressure and external loading induced pressure. Good air containment and prevention of potential leaking as a common problem, is best managed with a separate, internal polyurethane bladder. The bladder should be made from a suitable property material, that folds easily, is lightweight and can be welded together to create the best condition for airtightness. The dual component approach responds well to the criteria for the structure. Durable, robust, predictable and lightweight will contribute to a commerciality viable event tool or event structure.

Internal component or bladder material is proposed as thermoplastic polyurethane or abbreviated as TPU. Commercially available from a number of multinational companies distributed under registered trade names and available in a variety of extruded film, sheet and profile applications. Typical products made include outer cases of mobile phones and computer keyboard protectors. Properties of the commercially available material include low module weight in sheet form, abrasion resistance, low temperature performance, rubber-like elasticity, shear strength, transparency plus oil and grease resistance. (Wikipedia website) The materials flexibility is without plasticisers that attract fungal challenges and can be folded, packing in small volume. Joining sheet material is through a heat press process achieving air tight compartments ideal for inflatables.

Example of the application of TPU is the Pneumocell product. The application is a single membrane compartment achieving beautiful, lightweight, translucent structures. As a single membrane application, internal pressure has to be limited to a working pressure at 2kPa due to tensile strength of the material.

External component material has a specific role of outer protection and containment of the internal bladder and the resulting forces induced from internal and externally applied loads. Specific properties include low density or weight, high abrasion resistance, certified fire rating, high UV resistance, high tensile strength, high burst strength, high shear stress capacity and low cost per m^2.

Commercially available woven Nylon satisfies the above criteria. As with the TPU, many multinational companies produce the product under trade names. To create the outer protective envelope, the material is patterned, cut and sewn. Particular attention is required on the type of stitch used, the machine and the material of the thread to ensure a minimum tensile strength between panels is achieved. The weave type is important and can be optimised in orientation to align with the shear forces anticipated. Braiding as a solution for high tensile stress application tubes has been adopted by the Natick Research Development and Engineering Center. The material made from Vectran® thread is a highly optimised membrane that attracts an equally high cost that makes it unsuitable for the commercial application. (Verge (): 13)

8.4 PRESSURE

"Increasing the pressure increases the pre-stress in the membrane and makes the structure stiffer so that deflections are less and stresses are greater. The final choice of inflation of pressure will depend on the relative merits of a low deflection or low stress structure for the particular use." (IL15 1987: 206)

The comparative table 1 of pressures in Section 3 and the related case studies demonstrate that the determination of the pressure is critical to many aspects of the structure. As quoted by the IL, being clear on the objective and functionality of the structure will help inform the final choice of inflation.

The strategy adopted by the Natick Research Development and Engineering Center for their rapid deployable structures is to set the membrane tension in the air beam to the maximum compressive bending stress as induced by external dynamic loading. Together with the criteria for rapid deployability, the air beams need to span the maximum and be lightweight at the same time. Small diameter tubes provide the saving in weight. Given their criteria for gust wind speed at 29m/s and a snow load of 0.5kPa this leads automatically to a high pressure system. The maximum pressure is given as 275kPa (Verge (): 14)

The criteria for the structure has been defined in the previous section. A quick deployable structure that accommodates event functions on a short term basis, that is predictable in behaviour, robust and safe in operation for the installation teams and end users. Safe as described by guidelines written to ensure equipment is fit for purpose and to the benefit of all. Particularly the reference document "Temporary Demountable Structures".

The proposed hybrid structure as a strategy is not total reliant on pressure to induce and maintain pre-stress in the membrane. The GFRP tube element located in a sleeve on the external surface of the inflated tube takes on a supportive role in pre-stress induction. Applied dynamic loads will negate the pre-stress induced by internal pressure and the GFRP element will prevent the point of collapse moment in its deformed state. The element will also work against the buckling modes as described by Molloy et al and further it will return the inflated tube to its original geometry in the release of stored energy. In turn, the GFRP element will be subject to buckling and the pressurised tube will stabilise against the behaviour. Both elements working complimentary as a hybrid system.

That anticipated behaviour opens the opportunity for the internal pressure to be within a working low pressure zone. This is the desirable zone that is safe from explosive material failure or rupture and does not attract additional cost through high specification materials, fabrication, details and long term maintenance. The strategy aligns with commercial requirements for lower cost of the full life cycle spectrum from initial investment to ongoing operational and maintenance.

The targeted internal pressure for the primary arch tubes and the infill panels is set at between 2kPa at minimum and 5kPa at maximum. The higher pressure is set to help deal with the compliance parameters for gust wind speed as set in the Temporary Structures Guideline. This is estimated to be a good, practical range of pressure to explore in the prototypical testing.

8.5 FORM-GIVING LOAD CASE

The structures used in the event industry require installation and dismantle in short periods of time and repetitively over the life span of the product. For commercial reasons, the process and sequence is important to understand and optimise.

The form-giving load case, a term introduced by Jürgen Hennicke in the author's thesis discussions, describes how an inflatable is brought into form, from a packed state into a fully realised structural enclosure. The photo in Figure 56 shows a typical scenario of requiring to push up manually into place a complete inflated enclosure. Inflatables are lightweight structures, at the same time manually pushing the form into place is labour intensive and not safe.

Figure 56. Pneumocell dome manually pushed up into shape. (Herzig 2015 lecture)

Given the modular approach of the hybrid, the proposal is to take a similar strategy to deployment as demonstrated by the C.O.D.A project in Figure 57. The photo shows how the typical arch is replicated and fixed together alternatively at the apex and at the ends. Once the complete set is delivered off a truck by crane in a standing or upright position, a lateral pulling action simultaneously on two side expands the structural arches into its deployed state.

Figure 57. Multiple arch, rapid deployment method. (CODA website)

The opportunity exists to deploy the hybrid inflated arches in a similar manner. Using a raised deck (see 8.6) to locate the geometric set out, the arches are expanded and secured into position. With the arches stabilised with temporary stays at each end, the side and top infill panels can be zipped in a deflated state into position and inflated. This would have to take place in a particular sequence to use the pressure of each module to push out the hybrid arches into the final position. Figure 58 demonstrates the proposed sequence that will need to be tested in prototyping.

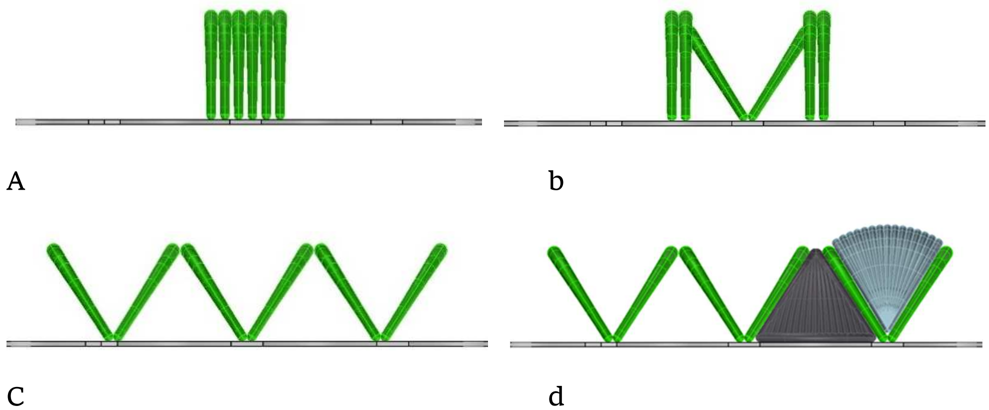


Figure 58. Form giving through lateral movement & sequential addition of side panels. (By author)

8.6 DECKING

The proposal is that the inflated hybrid structure is mounted onto a raised platform. The rigid framework of the raised flooring system has a critical role in the behaviour of the pressure stabilised membrane structure.

Review of the Fuji Pavilion and the Modern Teahouse as examples, reveals that it is important in the creation and maintenance of the pneumatic form, to restrain the footprint of the inflatable to a geometric plan. This principle aligns with the trinity of pneumatically stabilised membrane structures of geometry, pressure and material. The motivation is in the pursuit of a stabilised structure behaving predictably under external dynamic load. The horizontal floor plane restraint supports the retention of the pneu form.

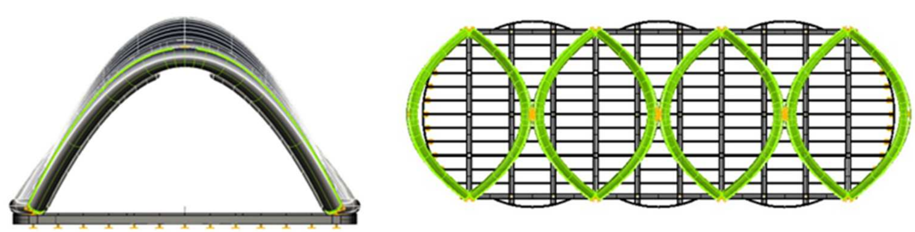


Figure 59. Raised floor structure in section & plan. (By author)

The hybrid arches are fixed into the structure of the rigid floor frame that accommodates the form giving load case as described previously. The type of fixing into the rigid floor frame is also critical and will need to restrain against arch flattening lateral forces. Further the fixing detail, based on the Molloy et al research will need to address the three modes of buckling for leaning arch, inflated structures. Further prototyping is required to understand how the hybrid arch will behave under wind and snow loads and what end restraint and fixing onto the horizontal floor plane is optimum. Important in activation of the hybrid configuration is how the bending-active GFRP tubes are fixed into position as a unified structure. The proposal is to restrain in deformation the tube in a pocket sleeve on the top of the inflated parabolic arches. The apex is fixed to the next adjoining tube apex by means of a clamp mechanism. The tube ends are terminated into a fixed steel clamp that is fixed into the primary truss units of the raised floor. The system is integrated between structural pneumatic enclosure and the raised deck frame.

Figure 60. Bending-active element fixing strategy. (By author)

The same fixing between arch and raised floor detail will need to act against uplift induced from negative pressure wind loading. The section shows the opportunity how counter ballast can be accommodated within and below the floor structure. Should bolt anchoring not be possible and as events require a relatively quick deployment, water from the author's experience, is the best solution to achieve the ballast. Water transported by truck and pumped into the ballast tanks can reduce installation time as this process can take place at the same time as the inflatable structure is installed. The additional benefit of the raised flooring system for events is in the creation of a level surface, free from weather influences and a surface that the end user can use as a creative platform.

The proposal is to use a proprietary aluminium truss system, bolted together in a grid configuration. The truss is anticipated to be 400mm x 400mm box section with 50mm diameter cords, a commercial product that is easily purchased at competitive rates. The horizontal framework created will need a levelling system to accommodate the uneven terrain of the many venues of installation. This is proposed as a simple load distributing base with an adjustable vertical post. The infill to create the working floor is proposed as another proprietary system. A good example would be the Primo PX® flooring system. The lightweight modular system using a half metre square panel with adjustable corner fixing is designed for use in the event industry and packs and transports easily. The system installs at 40m² per man hour requiring 10 hours for a single worker to complete the entire deck. Alternatively 5 hours for 2 workers to install. The commercial agenda works well the both the proprietary truss frame system and the lightweight flooring panel system.

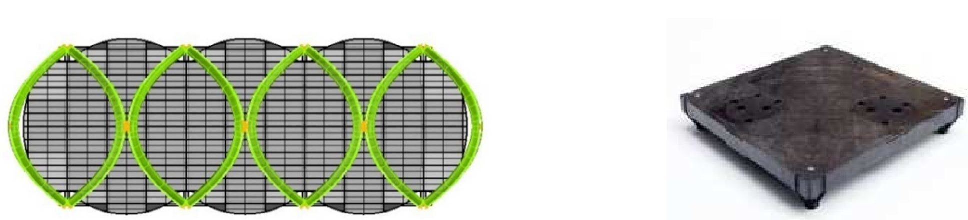


Figure 61. Floor panel system layout & floor module unit. (By author) (Sycon website)

8.7 TRANSPORTATION

Road transportation of the structure from storage to venue and return is the most frequent requirement. Based on a commercial 11 ton truck with enclosed compartment of 7.1m x 2.4m x 2.4m (H) and integrated lifting platform, the complete structure can pack into four vehicles. This requires that the pneumatic membranes are rolled into protective bags and stacked in stillage of 1m x 1m x 2m. Including ancillary equipment and the GFRP tubes, the inflatable structure can pack into a single vehicle. The raised floor assembly comprising of the box truss, adjustable supports and infill floor panels will pack into another three vehicles. All units are on rolling stock and using the lifting platform requires only two persons to unload a single 11 ton truck.

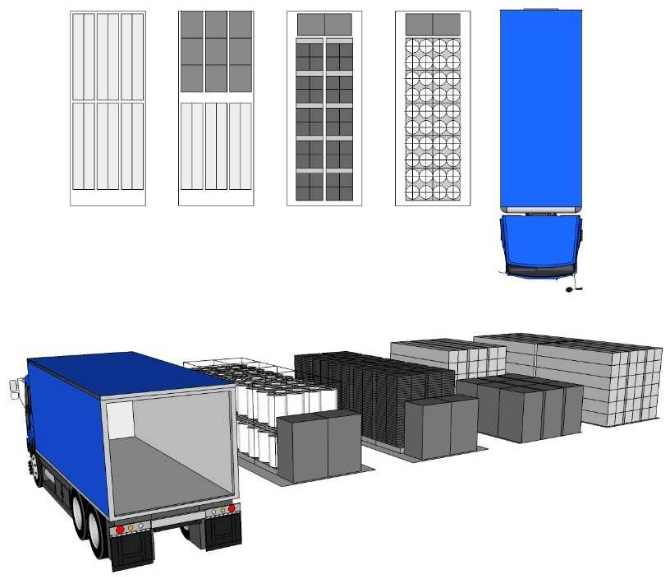


Figure 62. Diagram. Plan and perspective view of equipment packed for transportation. (By author)

8.8 GENERAL ARRANGEMENT DRAWINGS

The follow drawings illustrate the prototypical hybrid structure as a three structural bay plus two end bay configuration with a total floor coverage of 582m².

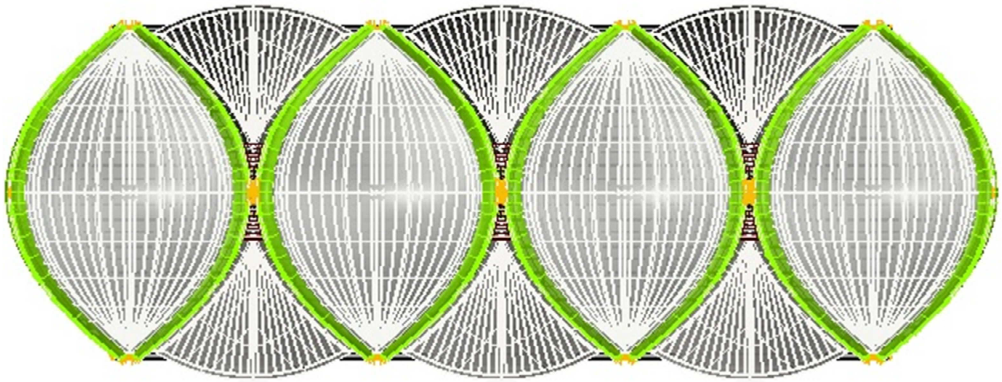


Figure 63. Hybrid structure, top view. (Not to scale) (By author)

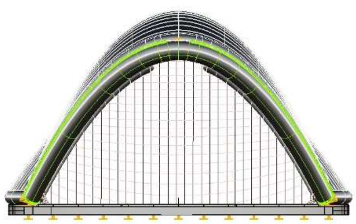


Figure 64. Hybrid structure, typical end view. (Not to scale) (By author)

Figure 65. Hybrid structure, typical side view. (Not to scale) (By author)

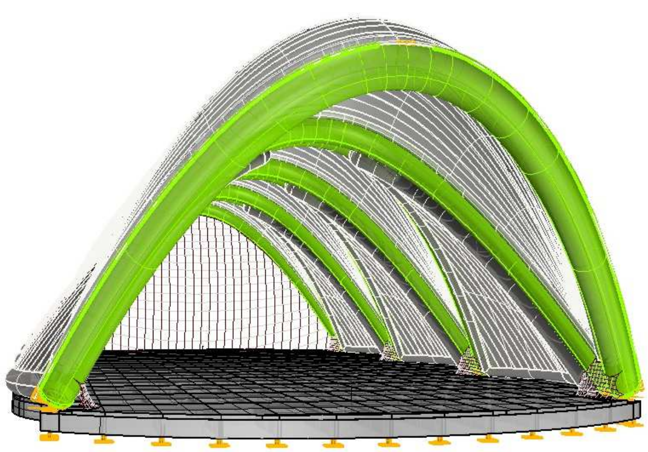


Figure 66. Hybrid structure, perspective view (Not to scale) (By author)

9

PROOF OF CONCEPT

9.1 TESTING METHOD SELECTED

To gain an understanding of whether there is a potential of the concept working as intended and contributing to the structure satisfying the design criteria, testing is important. Whilst there are a few methods to test proof of concept, not all will bring the desired results in one test. Computational simulation modelling as always needs to be correlated against actual physical model testing. And model testing results are challenged by the scale of the actual test model. The author has decided to use a scale model to test, as it will reveal valuable information on pressure, material and detail. How those decisions impact the test will also possibly become evident when the structure is installed and loaded. All of this will inform the future of the structure and whether it is pursued to greater detail.

9.2 AIM OF THE TEST

Proof of concept needs to be demonstrated. A pure inflated arch under point load fails at the point of loading, the membrane in tension converts to compression and folding leads to a snap point of failure unable to resist the point load.

The aim is to establish if the hybrid configuration of the GFRP element and pneumatic inflated tube component will demonstrate a different behaviour from the inflated arch. Whether it will act like a structural arch instead.

9.3 SELECTION OF THE COMPONENT TO BE TESTED

The structure is designed with a clear definition of primary load bearing elements and infill panels. For the test, the primary load bearing elements are to be loaded only. This element is the hybrid combination of a pneumatic inflated arch, with the integrated GFRP tube component.

9.4 SCALING

Ultimately a full scale model will be most desirable to test proof of concept as well as revealing behaviours and failures that will incur in a working product. For the purpose of practicality, a scaled down version will be fabricated, installed and tested. It is important to be able to include as many of the details and materials as accurately as possible to match the full scale version. There are only three materials, the inner and outer membrane of the inflatable tube and the GFRP tube or rod. Of the three components, the GFRP tube is the most difficult to reproduce as a scaled down version. Arguably, the most important in the test exercise. On reduction of scale, the GFRP tube quickly dimensions down to a point where it is only commercially available as a solid section rod. The rod will have different behaviour properties than the hollow section tube. Working with a percentage reduction, at 40% the GFRP tube is at 32mm diameter. Further, the tube is not easily available on the market as a standard product. The solution, as a proof of concept only, is to adopt a solid rod section and to use two smaller diameter units rather than one large solid section unit. This can be sourced commercially as a standard stock item. GFRP is the general material specification to be sourced without exploring the optimum characteristics and behaviours of the polymer material.

At a 40% scale model the plan dimensions of the leaning arch tubes are 5.60m span of the single arch and 4.08m length. The apex at the axis of the inflated arch tube leaning, is 2.8m vertical dimension. Practically that will accommodate for fixing of the tubes together at floor level with webbing belts and allow for fixing of weights for load application simulation.

Further, proper patterning and fabrication of the tube as an internal bladder and external tensioned membrane component is practically possible.

9.5 MANUFACTURING

The process of actually making the scaled down primary tubes brought into question many more considerations and decisions than expected at the outset. Knowing the generic materials for the three components, the outer sleeve as woven nylon, the inner tube as TPU and the bending-active component as GFRP was the beginning of considerable time and effort to source commercial suppliers with material in stock. The final selection was a compromise of material that was within the generic specification, readily available and was a material that the fabricators would know how to work with to produce the desired component.

9.51 DESCRIPTION

The two tubes are matching. Each has an internal bladder of TPU membrane, pattern cut to the parabola configuration. A single valve is located at the one end on the apex of the dome.

The outer tube is fabricated from Weather Max fabric, pattern cut to the parabola configuration. A single large zip is located to one side, located on the “straight” leg for facilitating the inserting of the inner bladder. Sleeves of Dacron are stitched to the top of each tube with a fixable flap at each end for inserting and restraining the GFRP rods in position. Each tube end has a reinforcing belt stitched into the fabric with three termination points for stainless steel O-rings.

The bending-active element is a solid rod of Glass Fibre Reinforced Polymer purchased from a sailmaker and conventionally used in sails as battens for shape optimization. Two rods per sleeve with a diameter of 18mm each.

9.52 CUTTING PATTERN

To create both the inner tube and outer sleeve, the geometry of the tapered parabolic arch was very important to achieve. The Rhinoceros built software models were imported into Form Z and patterned. There are two basic approaches to the pattern layout, one with the direction of the tube to create a very smooth realization to the geometry of the arch, the other divides the tube lengths to short straight sections, the benefit is the reduction in cost comparative to the first method.

The drawings below, figure 67 and figure 68 show both the inner tube fabricated from TPU and the outer sleeve fabricated from Weather Max adopting the most cost effective patterning method.

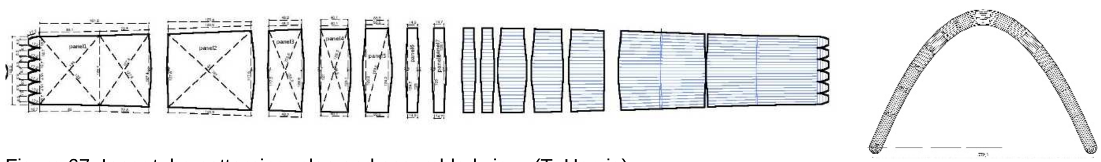


Figure 67. Inner tube patterning, plan and assembled view. (T. Herzig)

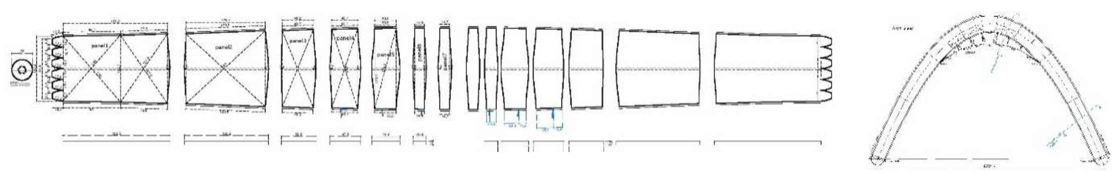


Figure 68. Outer sleeve patterning, plan and assembled view. (T. Herzig)

9.53 FABRICATION

Fabrication of the inner tube completed by the China based factory was supervised by T. Herzig from Pneumocell who had the experience of working with the factory and knowing how to get the best out of the fabricating team. The decision to place the valve at one end of the tube proved difficult to work with during testing as access was complicated when the configuration was set. Further air leaking of one of the tubes required regular re-pressurizing of the unit. Welding details and the junctions with the valves will need further review to reduce the risk of air leakage.

Fabrication of the outer sleeve was managed by the author in conjunction with a committed team from the sailmakers. The patterning had to be adapted to suit the sewing machines and still achieve the final form. The addition of Pes belts facilitated the inclusion of steel pull rings. The pull rings were used for attachment of belts at the lower level and at high level to attach the water ballast device. The inserting of the TPU bladder was not easy through a single small access zipper and needs further consideration. The inner bladder has the potential to twist within the outer sleeve and then not realise its full inflated form under pressure. Similarly, accommodating the GFRP into a sleeve was very difficult and from an operational perspective it is either resolved properly for quick installation or it is left in the sleeve permanently. The latter would be a serious consideration worth exploring. Figure 69 photo shows a deflated tube with the GFRP inserted and tensioned into a deformed state. This could potentially be a way of transport. How the sleeve terminates is a critical detail and for the test model, a standard sail batten detail was used as shown in the photos, figure 71. This detail worked for testing however will most likely not be suitable for the actual end product. This is due to the resolution of the entire termination of the tube and GFRP that is structurally critical and should all be integrated in one solution that connects with the raised decking assembly.

Figure 69. Inner TPU bladder inserted into the outer sleeve with the GFRP rods inserted and bent. (By author)

Figure 70. Inner bladder inflated with two GFRP rods with bottom tension cord in place. (By author)

Figure 71. Termination of the tube with GFRP and valve on one end. (By author)

9.6 DESCRIPTION OF THE TEST METHOD

The GFRP rods are inserted in the sleeves of each tube, the termination ends closed off to prevent slippage under a state of deformation. The arch tubes are inflated with an inflation pressure of 2kPa.

The geometric plan configuration is held in position with belts located at floor level in both the span and length directions. The arches are rotated until leaning against one another, with equal rotation for each arch. The exposed GFRP tubes at the apex are bound with movement and rotation possible however separation is not possible.

The structure is not fixed in position and is free to lateral and vertical movement. There is no counter balance in the structure. In addition there are no lateral restraining devices to stabilise the structure when in a maximum loaded state.

To induce a point load, an empty 1,000 litre water weight is located in the centre under the apex of the two leaning arches. Two belts are positioned over both the GFRP and inflatable tube and fixed to the water container with the container position approximately 0.5m above floor level in balanced suspension. Water is piped into the container at a slow fill rate.

Observations and photo records are taken as the tube configuration takes up the load and buckling occurs. Refer to section 9.8.

9.7 DRAWINGS

The following diagrams describe the test configuration of tubes and GFRP components as a hybrid. This is a 40% scale of the actual with plan dimensions 5.60m x 4.08m centre to centre. Vertical dimension 2.8m centre of tube apex.

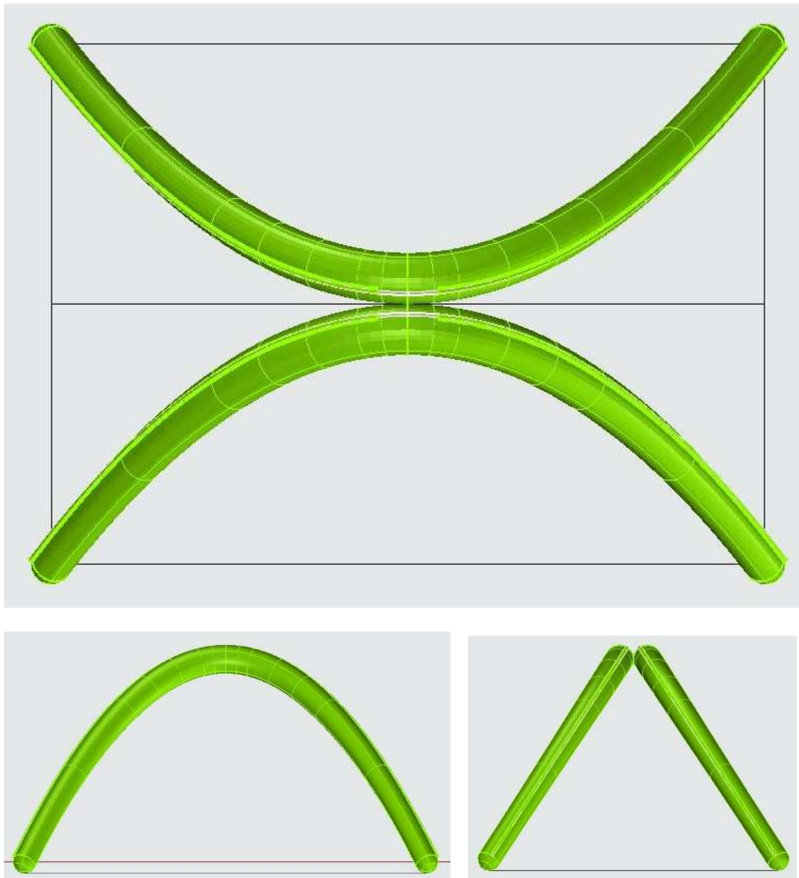


Figure 72. Plan layout, front view & side view of test configuration. (Not to scale) (By author)

9.8 RESULTS & PHOTOS

The following photographs show the setup of the hybrid primary arches in the leaning configuration and under point load condition.

Figure 73. Test configuration setup without induced load. Side and front view. (By author)

The above photos show the two primary inflated arches positioned. The tube ends are held by means of belts in X, Y and diagonal direction. The apex of both arches are rope tied at two points on the GFRP rods approximately 200mm apart. The load is induced by means of a water container filled with approximately 200 litres of water, the belts fixed to both the container and the arches above. The container is supported by the manual lifting machine in a raised position approximately 300mm above the floor so that no load is applied to the arches. The machine is released and the full load of the water ballast is induced as a point load onto the arches.

Belts routed over the top and onto the water ballast. Observed with this method and the load applied, the belts indented the inflated tube locally and without the GFRP in place, would have caused compression zones and a point of folding and possible partial collapse.

Figure 74. Test configuration under point load demonstrating longitudinal buckling mode. (By author)

Figure 74 and Figure 75 photos show and confirms, one of the three modes of buckling as predicted by Molloy et al in the computational simulation. Here the sway under load is demonstrating a longitudinal buckling mode.

Figure 75. Test configuration under point load, GFRP component in bending deformation. (By author)

Figure 76. Test configuration, compression folds under point load. (By author)

The above photo shows the GFRP rods under large deformation, taking the tension forces. There are multiple compression zones observable where the membrane has folded. The inflatable tube configuration has not failed under load.

Figure 77. Point load changed to below tube and resulting twist buckling mode. (By author)

A second test was completed to understand how the tube configuration would behave under a different point load condition. Four point loads were attached to the integrated steel rings located under the apex of both tubes. The same 200 litre load was induced with the same method as the previous test. Figure 77 above shows photos of the attachment method and the resulting behaviour.

Figure 78. Twist buckling mode observed and rotation at apex. (By author)

The termination points have not moved position however rotation was observed. The apex, due to the method of fixing point of the GFRP rods, moved by vertical adjustment between each tube and rotated. The most bending occurred in the "straight" sections of the tube legs. Compression zones and large folds developed in multiple places of the tube membrane. The GFRP rods were in bending deformation from the induced forces. There was no failure observed and the tube configuration continued to support the induced load from the water ballast. The twist buckling observed confirmed another of the three predicted modes of buckling by Molloy et al in their computational simulation paper.

9.9 SUMMARY

The existing fabricated 40% scale, test model has been point load tested and observed to behave differently from a pure inflated pressurised arch. Future testing and beyond the scope of this thesis, is required to investigate the behaviour of the leaning arch configuration under a uniformly distributed load that will simulate wind induced conditions. For this to take place the test model will need additional fixing details to address the apex fixing condition of the GFRP to prevent the observed rotation and vertical adjustment between the two adjacent tubes under load. Further the termination details of the GFRP and the inflated tube will need to be fixed as intended on the actual structure and tested. These details will influence the mode of buckling and prevent early buckling as currently observed in the test.

10

CONCLUSION

10.1 CONCLUSION

The thesis has proposed a new prototypical hybrid structure employing a bending-active component to prevent the snap through point of failure in pressure stabilised membrane arch that is a primary system for a complete temporary structure.

The behaviour of the hybrid leaning arches demonstrated a buckling mode that has been predicted by Molloy et al. Membrane folding as compression zones were observed and did not result in failure of load bearing capacity.

The hybrid does not behave like an inflated pressurised arch under point loading.

10.2 FURTHER DEVELOPMENT

The fabrication process and the end result has also informed the author of future improvements important to create a successful and working end product and as a commercially viable event structure.

Some of the improvements include, the inner bladder welding quality, the valve type, specification and location on the tube. The outer sleeve material will need to be tested to ensure the optimum tensile strength and mechanical wear and tear properties. The locating of the access zip opening are important to the ease of working and adjusting the inner bladder. The sleeve of the GFRP needs to accommodate for ease of installation and dismantle. Consideration of vehicle transport of the GFRP lengths and whether the tubes or rods are always inserted or inserted and removed dependent on the status of install of the structure. Improvements to the fixing of the GFRP rods to each other at the apex and at termination points are extremely important in the behaviour of the primary arches and will need to be tested first to understand further developments required as included in the previous section 9.9.

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LIST OF FIGURES

11.8 LIST OF TABLE

APPENDIX

1. Interview with Chris McDonald, Senior Account Manager, Jack Morton Worldwide, Hong Kong
2. Interview with Faresh Jowharsha, Senior Account Manager, Imagination, Hong Kong
3. Interview with Thomas Herzig, architect and founder of Pneumocell, Vienna Austria

APPENDIX 1

Questionnaire

Design Criteria of the prototypical structure

Item

1. Temporary structure, pneumatic/ inflatable.
   a. What are the benefits of using a pneumatic or inflatable structure for events? *Flexibility in terms of being able to place in almost any venue. Ease & speed of setup. Creates a more dynamic environment.*
   b. What are the concerns for using such a structure,
      i. from the production perspective? *Setup requirements. Safety of Structure. Local government approvals. Overall Cost.*
      ii. from the end-user perspective? *ensuring a unique and creative experience.*
      iii. from the perspective of gaining licensing approval? *Technical details, such as weight loading, safety, wind standards, guest safety.*

2. Temporary structure, dimension of area.
   a. Within the HK market and given the limitations of venues that exist, what would be a dimension of floor area that is in most demand per year from the end user requirements? Describe that in terms of area specification or width and length. *Approx. 500+ sqm. 10m Wide x 50m + in Length. Best to be scalable to fit multiple venue options.*
   b. The described area above is best in a square, rectangular or circular layout shape? Rectangular is usually best, but circular would also be good to give more creative scope. Also different shapes help create more excitement about the event from a guests perspective – rather than a "standard marquee".
   c. The described area above is used mostly for cocktail, banquet, product launch or theatre seating events? *All events need to be considered.*

3. Temporary structure, section profile.
   a. Please specify a vertical height of the structure that is preferred from a production requirement and qualify why? *As high as you can go – anything from 5m+ high is good, as it gives greater creative flexibility e.g. acrobats etc.*
   b. There are many different types of temporary

JACK MORTON

structures available in the market for events that provide different spaces within. The section through the structure varies dependent on the structural system used, for example a dome structure and a typical marquee structure. Please specify what the requirements are from a production perspective that will make one section type more desirable than another section type? *A marquee structure has obvious benefits in terms of structural hanging points throughout the space. A dome structure is limited. The event requirements will dictate the type of structure used.*
4. Weight of structure. a. How important is the weight of the structure to the production of an event typically? Please provide examples. *Very important particularly from a weight loading perspective, if using roof-tops, carparks etc. But also load-in/out of the equipment /structure.* b. Does weight have any influence on the decision of the type of structure selected? Please provide examples. Yes very much so, if its really heavy structure and requires cranes etc. to setup/dismantle – its just adds additional production requirements & increases costs.
5. Compliance to code. a. How important is it for the structure to comply to code requirements for event licensing or approval from authorities? *Very important, as HK local authorities won't let the event go ahead. It also provides assurances for clients that due process/diligence has been done by the vendor/manufacturer.*

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6. Production friendly.

    a. This term is used often within the industry. What does it mean to you if a temporary event structure is called "production friendly"? *Means it's easy to install, efficient and allows greater creative flexibility for AV & Production elements. Has good hanging points; strength and support – eg. Hanging points for Acrobats, hanging projectors etc.*

    b. How would you define that and please provide examples? As above

7. Dimensional stability

    a. Is it important for a structure in plan and section to be dimensionally correct as per detail drawings for production purposes? *Absolutely*.

    b. Please provide reasons and examples? *We expect drawings of the structure to be absolutely sound and accurate – as we plan our creative & production requirements around that. So we can explain to clients, vendors and authorities.*

8. Pressure behaviour

    a. Is it important for a temporary event structure to manage external wind pressure? *Yes absolutely. In HK we have typhoon season and heavy rain storms. We also use rooftops as event spaces.*

    b. Please provide reasons and examples? *Rooftop of Pier 4, Central HK, is a wind tunnel at best but has great views of the city and in the city centre. So its perfect for any type of event, but all infrastructure needs to come in.*

9. Deploy-ability of a temporary structure

   a. What is the benefit of a temporary structure being deploy-able or easy to more and locate? *Quick installation/dismantle = less venue rental to pay.*

   b. Please provide examples? *Central Pier 4 is expensive from approx.. HK$65K per day….*

10. Transportability of a temporary structure

   a. What is the benefit of a structure being easy to transport? *Easy to move around the city and install. Easy to dispatch to odd out-of-town locations.*

   b. What does it mean when a structure is easy to transport? *Relatively flexible and doesn't need a huge truck or cranes to move around.*

11. Installation & dismantle requirements

   a. Cost. How much is installation and dismantle time at a venue a factor of the overall production cost? *It can add up – particularly for clients with limited budget or limited availability of venue. I.e. Overnight setup for event the same day.*

   b. Time. What percentage of the time for an overall production is dedicated to installation and dismantle on average? *Approx. 10% of time*

12. Have you ever worked with a large inflatable structure in a production? *No*.

APPENDIX 2

IMAGINATION

This questionnaire is an important part of my thesis pursuant to a Master of Engineering Degree, Lightweight Membrane Structures at the Vienna University of Technology, Vienna, Austria.

The preliminary thesis title is HYBRID PNEUMATIC EVENT STRUCTURE, a prototypical, and deployable, temporary structure.

The thesis objective is to complete a proof of concept on a new prototypical hybrid pneumatic structure that will accommodate outdoor events, satisfy all necessary criteria as set by the event management industry including and most notably, high gust wind speeds that cause temporary pneumatic structures to fail and make it difficult for authorities to approve installation of at events.

Design Criteria of the prototypical structure
1. Temporary structure, pneumatic/ inflatable.
a. What are the benefits of using a pneumatic or inflatable structure for events?

Typically, these structures are easy to transport requiring less trucking, helping to minimize logistics; quick to install and dismantle allowing more time to be focused on other areas for décor, technical set up, rehearsals, etc., or simply reducing venue hire time by as much as 1-2 days, whilst using less manpower to do so. All of these have a significant impact on time and cost and generally provides a more aesthetically pleasing and more interesting structure with the variety of shapes and sizes that are being developed these days.

b. What are the concerns for using such a structure.
i. from the production perspective?

Predominantly safety. Inflatable structures are very temperamental to external weather conditions, which can result in an event cancellation or, in a worst-case scenario result in injury or death. Inflatable structures rely on a good, constant supply of air – should there be a significant puncture, or a failure from one or more fans, the whole structure could deflate in a matter of seconds. Most structures have limited exits, so depending on audience sizes and set elements within the structures, this could also prove catastrophic. Weather also plays a huge part on the stability of the structure. Typically, temporary structures such as a standard marquees have a better weather durability than an inflatable, however - strong weather surges will significantly affect any temporary structure which is why these are typically used during calmer months.

Additionally, there are limitations to using these type of structures given that there are no fixed weight loading points in the ceiling in which to hang lighting, truss or video equipment.

ii. from the end-user perspective?

From the end-user perspective it's more about aesthetics, space, people flow which ultimately results in the overall experience. Clients and guests always want a different experience than what they have become accustomed to. While most have attended events in marquees, not many have been in inflatable structures which offers different shapes (domes, peanuts, etc) providing a different look, feel and experience.

iii. from the perspective of gaining licensing approval?
Licensing such structures require such precise engineering and calculations to determine the stability and safety of a structure. Considerations to weather and the severe forces that the structure will need to withstand need to be tested and proven to ensure licenses and insurances are granted. Checks before and after the build are required to be carried out to ensure that installation has been done correctly and to the manufacturer's specification before approvals are given, and in some instances the use of anemometers are required to be installed throughout the event to keep an eye on wind conditions.

Unlike in most countries in the West, in regions like Asia where temporary structures are not widely used, there are a lack of regulations in which cover this, making it even harder to gain licensing approval. More testings and documentation is required to cut through the red tape and satisfy regulatory bodies.

2. Temporary structure, dimension of area.
a. Within the HK market and given the limitations of venues that exist, what would be a dimension of floor area that is in most demand per year from the end user requirements? Describe that in terms of area specification or width and length.
In my experience the average size of a corporate cocktail or launch event in HK ranges from 300-500pax. This would mean approximately 500-700sqm to allow for people flow, staging and technical. You will need to allow for more if a seated banquet that includes a dance floor.
b. The described area above is best in a square, rectangular or circular layout shape?
Difficult to say as each event will have its requirements. Square is probably safest as it allows for a more functional space. Circular is always more interesting and allows for 360° projection surface. I'm not particularly keen on rectangular structures as these make a space more narrow and as a user, can feel claustrophobic.
c. The described area above is used mostly for cocktail, banquet, product launch or theatre seating events?
Cocktail and product launch.

3. Temporary structure, section profile.
a. Please specify a vertical height of the structure that is preferred from a production requirement and qualify why?
The higher the better! Height makes a space feel bigger than what it may actually be. Also, height will allow for the technical elements to be placed higher, keeping them away from the audience and additionally helps keep the internal temperature down. Recommend a height of around 8m minimum.
b. There are many different types of temporary structures available in the market for events that provide different spaces within. The section through the structure varies dependent on the structural system used, for example a dome structure and a typical marquee structure. Please specify what the requirements are from a production perspective that will make one section type more desirable than another section type?
This really depends on the specific requirements for a particular event or design. Ideally, production managers will look for a mainly seamless visible structure throughout - particularly without a centre support beam, as this not only looks more impressive, but provides much more flexible use of space.

Dome structures offer a mainly seamless transition between sections, however some structures like inflatable domes will have a main ribbed structure that runs through the centre which acts as the main support for the entire dome. This is good as there are no support beams running through the inside of the space, however, marquess which have fixed beams running across them offer some flexibility in which to hang decor items or even lightweight technical fittings off from.

4. Weight of structure.

a. How important is the weight of the structure to the production of an event typically? Please provide examples.

The lighter the weight the less manpower and heavy machinery are required for loading, unloading and setup. In the case of logistics, particularly shipping to overseas destinations, this has a significant impact on costs and budget. In most occasions, the structures are built on hard grounds outdoors which can support extreme weights. There could be an issue if there is something under ground such as a basement carpark, tunnel, etc., which has a very thin ground separating it.

b. Does weight have any influence on the decision of the type of structure selected? Please provide examples

From my experience, no. However, I could see it being a problem if the structure was purchased or under a long term hire to be used on a roadshow to be taken around the world as the cost for a heavy unit.

5. Compliance to code.

a. How important is it for the structure to comply to code requirements for event licensing or approval from authorities?

Extremely important. This not only ensures that relevant testing has been made on the structure by manufacturers according to specialist engineers, but has also got the approval from third party and government regulatory bodies to ensure that complete safety has been considered. This in turn affects insurance policies and coverage for yourself, your client, your vendors and your audience.

6. Production friendly.

a. This term is used often within the industry. What does it mean to you if a temporary event structure is called "production friendly"?

Production friendly essentially means that considerations have been made to the design, detailing and manufacturing from a production and licensing point and of view. This may include considerations for hanging of technical fixtures as well as cable management which often gets forgotten as well as logistics (packing, shipping and storing)

b. How would you define that and please provide examples?

There are more and more modular units being developed for event, exhibition and pop-up promotional use which focus on layout flexibility, easy pack and install. These units either break or fold into smaller pieces to enable them to be stack packed and tightly fitted onto a pallet or crate for easier handling and shipping. Some of these units factor in under floor cable management systems and include tubing systems for most AC units to simply plug into.

7. Dimensional stability

a. Is it important for a structure in plan and section to be dimensionally correct as per detail drawings for production purposes?

IMAGINATION

Yes

b. Please provide reasons and examples?

We work in a very detailed field. In most cases, plans are drawn up utilising as much of the space as possible to create that unique experience. In the case of a temporary structure this is paramount as space is particularly limited, therefore designers use CAD software to ensure that not only the design fits, but to check and see if the space will comfortably fit the total number of guests that will float around it.

8. pressure behaviour

a. Is it important for a temporary event structure to manage external wind pressure?

Yes

b. Please provide reasons and examples?

As mentioned prior, temporary structures are very susceptible to external weather conditions. Wind in particular is one of the main concerns for production managers when consider using these structures. Walls and ceilings of such structures are prone to disfiguration by the force placed upon it by wind compression, which may, in the worst case scenario, knock over a ground supported truss holding technical equipment whilst the show is live, causing injury or death.

Much consideration and calculations must be made on ground anchoring and support ballasts depending on the type of structure used to prevent it being blown over, particularly on the type of ground in which the structure sits on (e.g. grass vs concrete). Venue managers may not allow the piling of anchors to the ground, where ground pitches in to grass may easily be pulled out if not piled in enough.

All these above factors are related to the wind load bearing of any temporary structure.

9. Deploy-ability of a temporary structure

a. What is the benefit of a temporary structure being deployable or easy to move and locate?

Temporary structures get the best usage for roadshow and pop-up type events where you need to ensure a consistent experience wherever you go. It negates the need to go to hotel venues where each space is different impacting layout and ultimately experience. If these are quick and easy to move or relocate you can get through numerous events in several locations in short period of time reaching higher audience numbers in far-out areas delivering that specific message or experience.

b. Please provide examples?

Automotive brands used temporary structures very regularly when promoting a new product. Pop-up inflatable structures have made an extremely cost effective option to move across China promoting to far flung regions outside the scope of the larger car exhibitions in the main cities. This is also the case out West with brands such as Virgin and Coca-cola.

10. Transportability of a temporary structure

a. What is the benefit of a structure being easy to transport?

It saves time and ultimately cost.

b. What does it mean when a structure is easy to transport?
Typically, it is simple and quick to pack and move from one location to the next. Crates or units are durable to handle the rigours of shipment and stresses from constant loading and loading from vehicles. Larger units will have design considerations for easy rigging to be lifted using heavy machinery (cranes or forklifts).

11. Installation & dismantle requirements
a. Cost. How much is installation and dismantle time at a venue a factor of the overall production cost?
It does take up a fair amount of a budget - if this time can be reduced, this can be put towards strengthening the experience or savings.

b. Time. What percentage of the time for an overall production is dedicated to installation and dismantle on average?
This is determined predominantly on the size, type and scale of an event. For a corporate outdoor event, I would say about 60-70%

12. Have you ever worked with a large inflatable structure in a production?
Yes

13. And if yes, please describe the approximate size and section profile?
We had custom 25mØ and 12mØ domes linked with an 8mL section. It was a larger peanut type shape.

14. What was it's outstanding benefit?
We didn't have much time for both install and dismantle due to venue bookings either side of our dates so the quick transport and loading and unloading capabilities along with a super fast inflate, meant that more time was allowed for the set and technical setup and rehearsals. Additionally, it allowed for the structure to be creatively lit at night projecting branding to the outside which provided a unique branding opportunity, and the dome shape allowed for a seamless 270° projection on the inside.

15. What was it's outstanding disadvantage?
It was extremely temperamental. The inflatability of the structure and lack of solid support beams meant that some sagging took place which resulted in some doorways or archways were significantly lower than others. There was constant concern on wind conditions and more ballasts were included as a precaution which cost extra.

The lack of rigging points meant that the technical rig was ground supported and took up valuable floor space and impacted on the layout, and the dome shape hindered the height of the trussing rig. This meant that all lighting, audio and video gear were only approximately 4m from the floor. In hindsight, we should have built vertical walls up to around 8m before it domed.

Thank you for your time and bringing your expert opinion to the benefit of this thesis paper.

APPENDIX 3

20 August 2015

Interview with Thomas Herzig, PNEUMOCELL

With reference to the Pneumocell Event Dome structure you have successfully designed, fabricated and installed at events.

The inflatable structure is a very clear geometric solution. What was the primary design generator for the structure?

I was in need for a geometry that offers a maximum of different shapes and sizes of closed buildings to assemble. These are flat cells with a 2 dimensional polygonal outline. All cells share the same edge length. So they can be combined in an almost arbitrary way.

What is the idea behind the separate cells of the structure?

Beside geometric flexibility, a construction made of separate cells, is less vulnerable. In case one cell is damaged it can be replaced, while the rest of cells still sufficiently support the structure

Also many small cells linked together for a more rigid structure than just one large inflatable membrane

The cell is a dual wall system, what are the benefits of the configuration?

The heat insulation is better.

Also the inner space is not under air pressure. So you are free to make as many openings as you like in the surface.

Also the shape of the wall is free. Rectangular shapes can be built and not conclastic round shelter.

Geometry

How important is geometry in an inflatable structure?

You need to understand how a membrane will shape under inner air pressure.

You cannot force the membrane arbitrarily into a certain shape, as you might do with a piece of wood or injection moulded plastic.

So the design process is more form finding than determinating form.

Why was the dome geometry selected?

The dome is one of several geometric shapes that can be one by assembling Pneumocell elements

But the dome can takes the highest static load, contains the biggest volume per surface, and it provides good aerodynamics against wind.

How does geometry influence pressure and material selection?

The larger the diameter of one volume, the higher the material stress under the same given air pressure.

For very large elements you either need material, or reinforce the structure with ropes.

Pressure

What is the working pressure of the dual wall cell system?

Between 10 -30 millibar

Why was a low pressure strategy used?

In case of a small air leak a construction of large volume and low pressure will not collapse that quickly.

Air volume is free,

Is the pressure a dynamic monitored and adjusted system or a static system?

It is automatically controlled by a pressure switch that will switch on / off the blower according to required air pressure.

Small objects do not need that. TPU material can stretch when the pressure gets higher under temperature raise

Material

What material has been used?

At the beginning PVC, but now TPU mostly.

What were the criteria for selection of the material?

Flexible at low temperature, tensile strength, UV-resistance, flame retardant, strength of welding joints, environmental friendliness, transparency, price

Where there other materials considered and what were the materials?

PVC (which contains poisoness softeners, and get very rigid at cold temperature)

ETFE, which is only usable for non-mobile structures, since it must not be bent.

Also welding is more difficult and more expensive than on TPU

What testing was done on the material?

Flame retardant

Tensile strength

UV-resistance

Light transmission

Heat transmission (several layers)

How is the material suitable for the function of the temporary structure?

It provides the required flexibility and tensile strength

UV-aging is not critical, since mobile structures are exposed to sunlight part time only

Was weight an important consideration?

The weight is the same for most membrane materials (1100 -1200 kgs/ cbm)

What were the factors for determining whether the structure was light enough?

Inflatable construction generally are very lightweight. Only for special application (floating helium filled objects) weight is a challenge

End.