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Recent Work on the Design and Construction of Air Inflated Structures

Bob Barton*

Barton Engineers Unit 303, Westbourne Studio, 242 Acklam Road, W10 5JJ, London, UK

Abstract

Over the last few years our practice has been responsible for the structural design of a number of lightweight structures that achieve their structural stability by inflating elements of fabric structure. The paper will explain the design rationale of key examples; describing the structural forms, methods of analysis and design, and the detailing, materials, and methods of fabrication. The largest and most complex of these structures to date is a demountable stage set structure for the Cirque du Soleil "Toruk: First Flight" show, comprising two 15 metre high and 20 metre wide structures. The stage set structures form 'trees' on which acrobats climb and perform. Each structure incorporates a high level access gantry with acrobat suspension and counterweight systems, as well as a secondary inflatable skin cladding. The entire primary structure and cladding system is constructed from inflated fabric elements using internal pressures ranging from 0.5 KN/m2 up to 90 KN/m2, and are deflated down to less than 5% of their erected volume for transport between venues. Other examples of our work described will include temporary pavilions with clear spans of up to 25 metres, using a combination of air tight and air permeable elements. Also a range of wide span structures that we describe as "semi-permanent" that are capable of resisting full environmental wind and snow loading, and that are fully demountable but that can also be erected for extended periods of time in a single location

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* Corresponding author.
E-mail address: bob.barton@bartonengineers.co.uk

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1. Introduction

Barton Engineers are a practice of consulting structural engineers, based in London, that carry out structural designs for a wide range of projects. We have a long history of working with lightweight structures; and our principal worked on the Schlumberger Cambridge Research building by Michael Hopkins Architects, engineered by Anthony Hunt Associates and Ove Arup & Partners between 1982 and 1985. An example of the sort of fabric structures that Barton Engineers typically undertake is a canopy for the Colegio Canada Blanch School in Notting Hill, London in 1998, where fabric has been combined with a timber and aluminium truss framework to cover a full size basketball court.

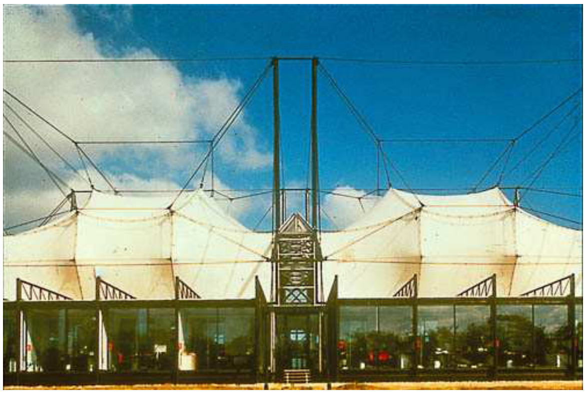

Fig 1: Schlumberger Cambridge Research 1985, Cambridge, UK

Fig 2:Canopy at Colegio Canada Blanch 1998, London, UK

Fig 3: 12 Metre Span Air Roof Structure (Image by Ingenious)

2. Ingenious Inflatables

In early 2013 Barton Engineers were approached by Ingenious Inflatables Ltd, a newly formed company that has developed a range of inflatable pavilions. These are to be used for a range of purposes, but typically for events and shows with generally short term performance requirements. Their products compete against conventional marquee structures, or other rigid frame fabric covered forms. Inflatable structures have some clear advantages over rigid frames with their ability to be erected, dismantled, and transported with minimal labour and space requirements. Ingenious Inflatables wanted us to help them provide a more engineered approach to the design and construction of their existing range, and also to help them develop other products with larger spans and improved structural performance.

Fig. 4: 20 Metre Span Dome Structure (Image by Ingenious)

Fig 5: 12 Metre Span Dome Structure (Image by Barton Engineers)

Fig 6: 24 Metre Span Arch Structure (Image by Barton Engineers)

Fig 7: Typical Polyester Wall and Roof Panel (Image by Barton Engineers)

The structural form and method of construction used by Ingenious Inflatables employs a twin walled fabric skin that is inflated to form a ‘rigid shell’ structure that will support its own self weight and moderate wind loading. The wall panels are typically 300 to 600 millimetres thick and comprise two skins of rip stop nylon or polyester, sewn to internal baffles or diaphragms that give shear stiffness to the shell. Once inflated the fabric shell surfaces become prestressed, so giving them a rigid structural form and the ability to withstand positive external wind pressures. The double skin shell construction means that the pavilion structures created by this method can have permanently open doors or larger openings, and do not rely on an internal pressurised volume to keep the roof inflated, as in a single skin air hall type structure.

Because of the stitched construction and the use of a lightweight air porous materials, the volume of the double skin wall needs to be continuously inflated as air leaks out through the stitch holes, and through the fabric skin itself. The typical inflation pressure generated within the wall of the sewn nylon structures is in the range of 0.4 to 0.6 KN/m2 (or KPa), and this is created by a series of high volume low noise fans that are positioned around the base of the wall of each pavilion. The structures, being very light, are anchored to the ground either by ground anchors, or by kentledge in the form of sand bags laid within a perimeter ‘skirt’.

Larger structures in the range have tubes made of PVC coated polyester fabric that form a primary framework and that are inflated to higher pressures and when sealed hold their internal pressure. These elements are typically 600 to 900 millimetres in diameter, and provide a stiffer, more robust structural form compared with the continuously inflated walls. The internal inflation pressure within these components is typically in the range of 2.5 to 15 KN/m2 (or KPa). The sealed tube elements are combined as arches ribs, or beams, between which the wall panels span. In the event of a power failure to the wall inflating fans, the sealed tube structures provide an emergency support structure for the pavilions.

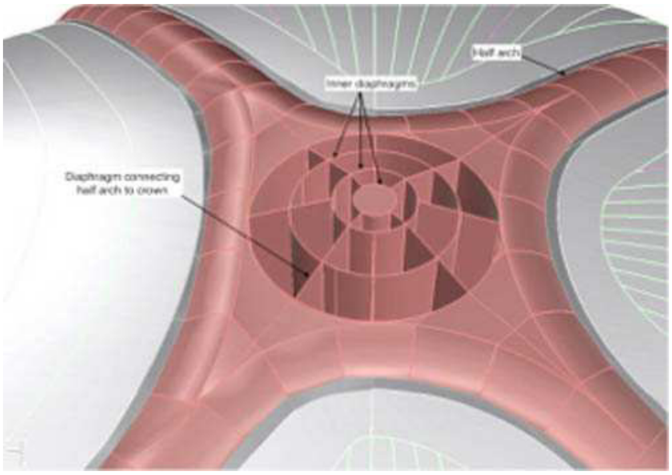

Fig 8: Sealed Tube Arrangement at Crown of Dome (Image by Barton Engineers)

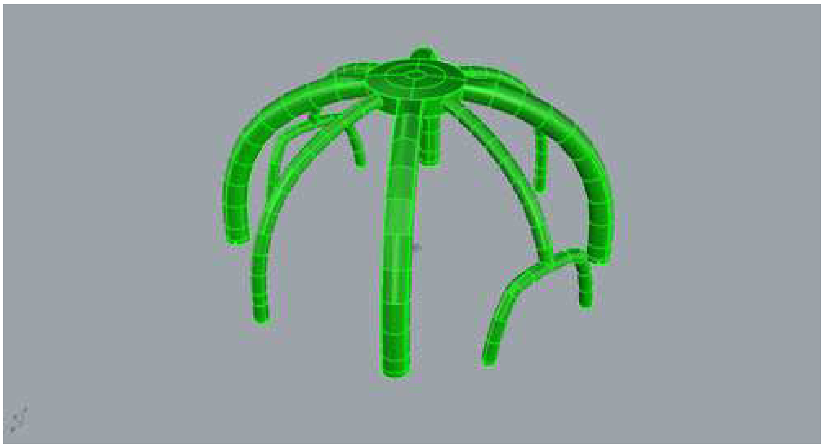

Fig 9: Typical Arrangement of Seal Tubes within a Dome Structure (Image by Barton Engineers)

The materials used allow graphics to be easily applied, and once a generic set of components has been developed these can be combined to create elaborate bespoke shapes. The relatively low stress levels allow cutting pattern production using simplified methods without stress/deformation compensation being applied, although this does impose constraints on the quality of surface finish, especially where multilayered fabric stiffens the surface and creates discontinuities. These structures demonstrate an economy of form and production appropriate for their market, but do also provide a valuable insight into further more profound design development.

3. Structural Behaviour of Inflated Structures

The structural behaviour of inflated structures is well understood; internal air pressure puts tension into the envelope, or skin, and this tension gives the structure a prestress that enables it to resist applied forces that would induce compression or bending in a rigid structure of similar shape and form. Obviously a critical point exists where the tension prestress is just overcome by the resulting compressive force generated by applied loading or self-weight. Inflated structures have two fundamental modes of failure;

1. The rupture of the skin material, caused by the induced force in the skin material being higher than its strength,
2. When any induced compression force in the skin exceeds the tension prestress resulting from inflation, causing collapse of the skin and a structural hinge to form.

To analyse these structures we use the GSA Software package by Oasys Ltd, the software arm of Arup. This software contains a dynamic relation solver that can be used to analyse geometrically non-linear structures, and also has the ability to create 2D elements with material properties similar to fabric. Anyone familiar with the dynamic relation solving process will be aware that convergence is required to obtain a solution. It is therefore essential to create an initial model that has a reasonable chance of convergence, otherwise the analysis process will never complete. When trying to analyse inflated structures this convergence problem poses particular difficulties, as it requires careful trial and feedback studies to establish a good initial model that will run and give analysis results. It is also important to develop initial model geometries that, when inflation forces are applied, can deform without inducing compression or wrinkles within elements, as this will also prevent convergence of a model.

Classical engineering theory demonstrates that the longitudinal stress in the wall of an inflated tube is generated by the inflation pressure on the end of the tube, and also that a hoop stress twice as large as the longitudinal stress is developed around the circumference of the tube cross section.

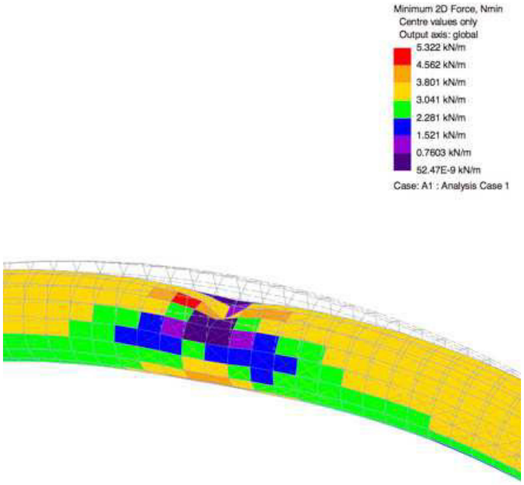

Fig 10 Tube with Point Load Applied (Image by Barton Engineers)

Using dynamic relaxation analysis it can be found that the stress fields within the skin are often very uniform at near collapse loading, unlike the stress fields predicted by classical theory. Where classical bending theory predicts peak and zero stress levels, in fact inflated fabric structures tend to deform and redistribute and smooth these peaks and lows. This smoothing of stress distribution gives an inflated tube a considerably improved structural performance over that predicted by simple classical bending theory, and this enhanced performance makes it very difficult to accurately envisage and predict structural behaviour without using non-linear analytical models. The level of 'enhancement' varies considerably with material stiffness, inflation pressure, and tube diameter, although improvements of 30% increases in load capacity over classical theory are typical. Obviously this enhancement is just a demonstration of the inaccuracy of engineer's theory of bending when applied to inflated structures. We have found that it is important to be aware of this discrepancy because initially we questioned the feasibility of certain forms based on simple theory, rather than proper analytical non-linear modelling to develop forms.

Fig 11: Inflated Tube Manufactured by Duncan Gray of Superhulk Ltd (Barton Engineers)

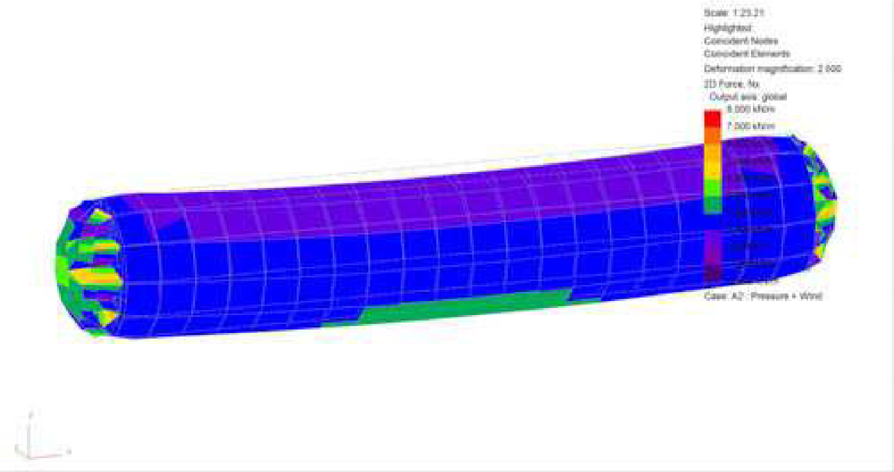

Fig 12: Tube with UDL Applied (Image Barton Engineers)

4. Design Strength of Inflatable Structures

Having developed the ability to model inflated structures, it is necessary to determine the design strengths of materials used. The necessity to analyse geometrically non-linear structures using unfactored or working loads, rather than ultimate loads with partial factors applied is well understood. This necessity is most clearly demonstrated in the case of inflated structures, where applying load factors to inflation pressure or external actions would create completely unrealistic load actions and behaviour. We have therefore adopted an allowable stress approach where the forces generated by an unfactored or working load analysis are compared with the design strength or allowable stress determined from fabric strength tests, with a suitable factor of safety applied. The factor of safety will vary depending on the nature of the actions applied and so separate analysis load cases are required for each combination of applied loading.

When determining the design strength of a fabric there are two strength properties that need to be considered; tensile strength and the tear propagation strength, or the stress at which a small tear will propagate with little or no increase in applied stress. The first of these parameters is well understood and there are a number of methods used to determine the design tensile strength of fabric. The tear propagation strength is less well defined but is a very important parameter and needs to be carefully understood. Trapezoidal or tongue tear strengths are often quoted by fabric suppliers, although these tear tests are difficult to relate to any real damage likely to be encountered in architectural and/or inflated structures.

The method we use to determine design tensile strengths is based on a combination of DIN 4134 and “Mechanical behaviour of Connections of Coated Fabrics” by Minte. This approach is fully explained in the “European Design Guide for Tensile Surface Structures” by Brian Foster and Marijke Mollaert. To determine the tear propagation strength of the fabric we have adopted an approach using wide panel tear tests and an analysis of these test results developed by Labor Blum, now part of DEKRA. The design tensile and tear strengths of the fabric can now be determined by applying the appropriate factor of safety to tests results of both tensile and tear strengths. Typically we generate a tensile strength factor of safety of around 4.5 (using the above methodology) and we choose a minimum tear propagation strength factor of safety of 1.25. The tear propagation factor of safety, whilst seeming sensible to us, is arbitrary as there are no published recommendations. These values correspond with the relative magnitudes of tested tensile strength and tear propagation strength found with the PVC coated polyester fabrics that we have used, meaning that the tear and tensile strengths are equally important and both potentially providing the critical design strength depending on the ratio between tensile and tear propagation strength.

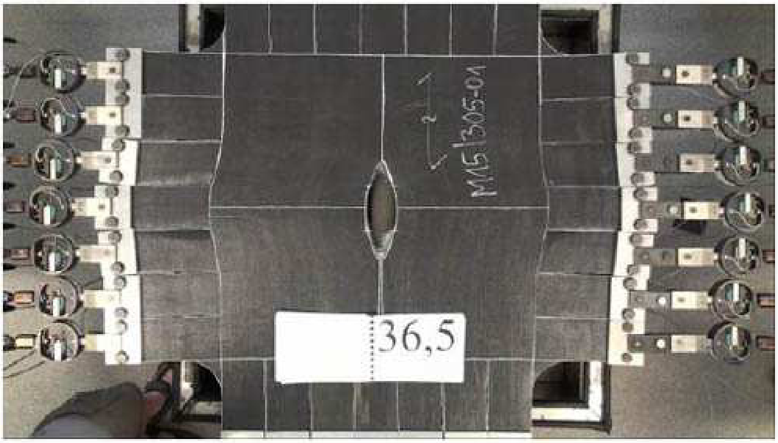

Fig 13: Wide Panel Tear Test on Coated Polyester Fabric (Image by DEKRA)

5. Typical Performance of Ingenious Inflatables

The largest span structures manufactured to date by Ingenious Inflatables comprise 26 metre clear spans, and these pavilions are able to safely withstand wind gust speeds of 45 to 55 miles per hour. The structurally critical elements vary between designs. The generic curved dome shapes typically generate wind suction forces over much of their surface, with localised areas of positive pressure on the windward face. These wind suction forces, applied over the full width of the dome, often combine with the inflation prestress tension to make fabric rupture within the walls of the main tubes a critical condition. The wall panels are generally susceptible to positive wind pressures, and often the critical wind gust speed is determined when collapse of the wall panels occurs, particular in square sided structures; rarely do fabric stresses reach rupture values within the walls before instability of the panel occurs.

Fig 14: Typical Primary Tube Analysis (Image by Barton Engineers)

6. Cirque du Soleil “Toruk: First Flight” Stage Show

In May 2015 we were asked by Tait Towers Inc to assist them in engineering their design for a stage set, and to act as third party engineer for the whole structure. Tait Towers Inc are a USA based company that operate throughout the world and who design, manufacture, and operate travelling music and event tours. The set is part of the current Cirque du Soleil stage shows, one that is based on the Avatar film, and will tour in the USA and Canada throughout 2016. The specific set that we were involved with is known as the “Home Tree” and comprises a primary framework of inflated tubes, clad by an outer skin that is also inflated and that provides a scenic and climbable surface over the primary frame. The inflated structures are deflated and packed into containers for transport between venues.

Fig 15: Image from Show (Image by Tait Towers Inc

Fig 16: Axonometric Image Showing Concept for Stage Set

The framework comprises a series of A-frames, braced by purlins at two levels, and is designed to be a self-supporting structure without assistance from the wrap around skin. The set is constructed in two halves, each 15 metres high and 12 metres wide, and each set has a high level gantry from which performers climb and technicians work. At any one occasion there could be up to seven performers or technicians on each half of the set.

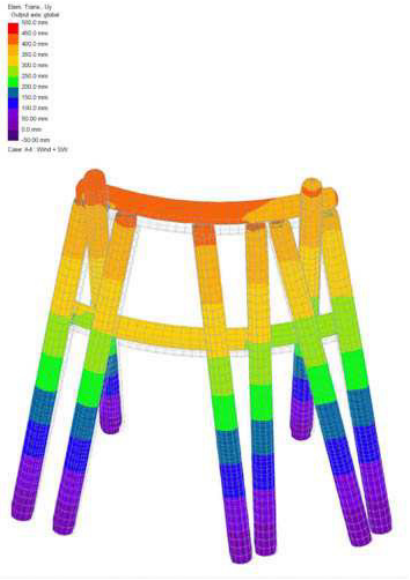

Fig 17: An Analysis Model Showing the Primary Tubes (Image Barton Engineers Ltd)

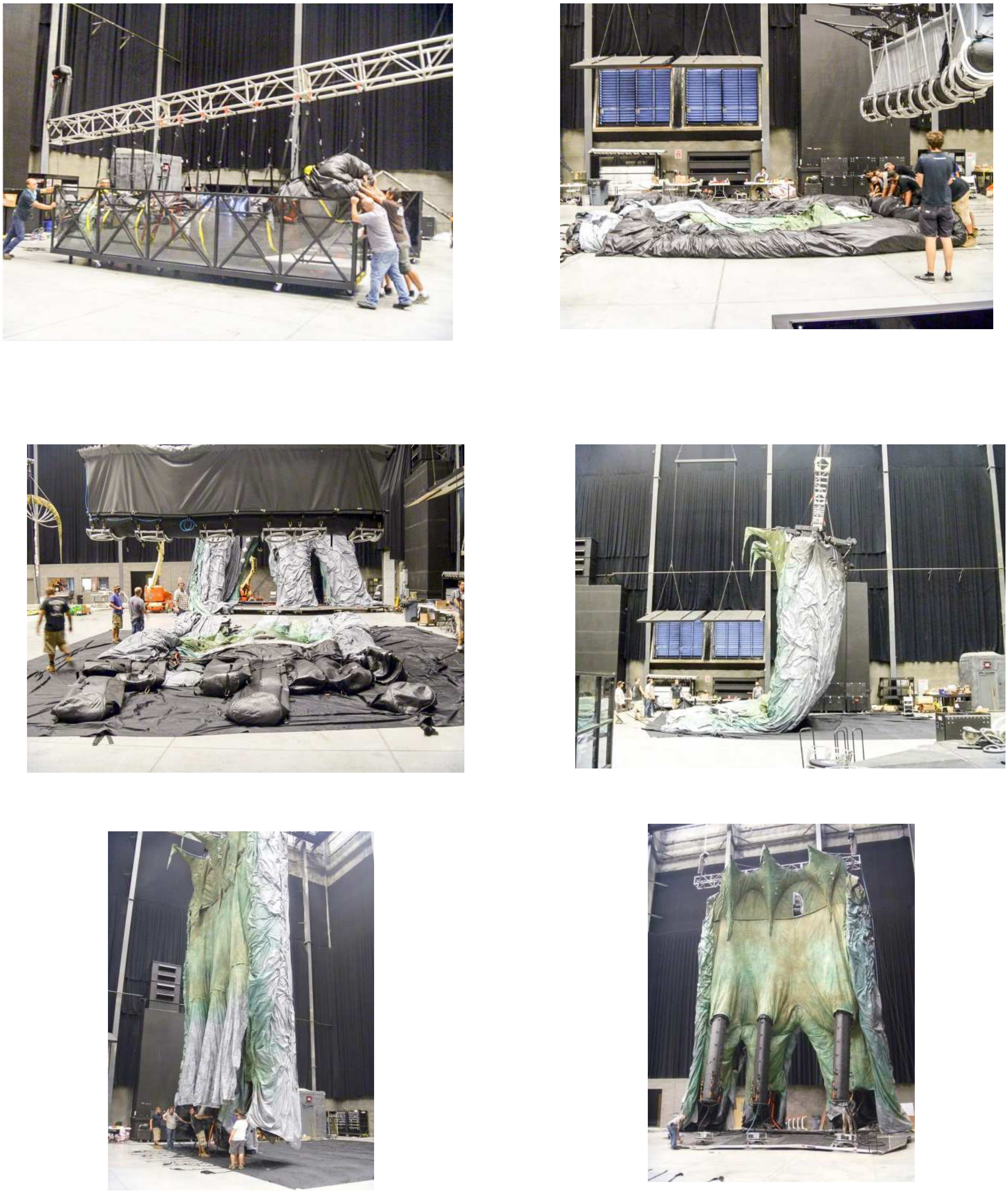

Fig 18: Erection Sequence (Images Tait Towers Inc)

The primary framework comprises tubes of woven and coated fabric with internal inflation pressures of around 90 KN/m2 (KPa). These tubes are configured to create a framework capable of remaining stable should two of the inflated elements fail. An extensive series of load cases were considered and the connections between the tubes are carefully designs to function should the connecting tubes become deflated. The largest deflections under applied actions were 250 millimetres under the worst load combinations.

Fig 19: Completed Stage Sets (Images Tait Towers Inc)

One aspect of the design that needed to be given careful consideration, and one not usually associated with inflatable structures, was the buckling stability resistance of the framework as a whole under gravity loading; each structure needed to support its own weight plus an additional three tonnes of equipment and personnel. The analysis suggested that the structure would performed well, largely due to the high internal pressures and stiffness of the primary tubes, and this has been proven in service.

7. Current Developments - Semi Permanent Inflatable Structures

We are currently developing a series of what we term “Semi Permanent Structures”. These are forms constructed with durable fabric that have the capability to resist full environmental wind and snow loading, and that can be erected for any time period within the design life of the fabric. The structural design is achievable within the scope of readily available materials and construction techniques, and we are in the process of developing the construction details of pressure valves, pumps, and assembly methods. The use of internal pressure cells or bladders within a structural envelope is particularly attractive as a design principle because these remove the need for the structure to be airtight, and therefore allows greater economy in construction.

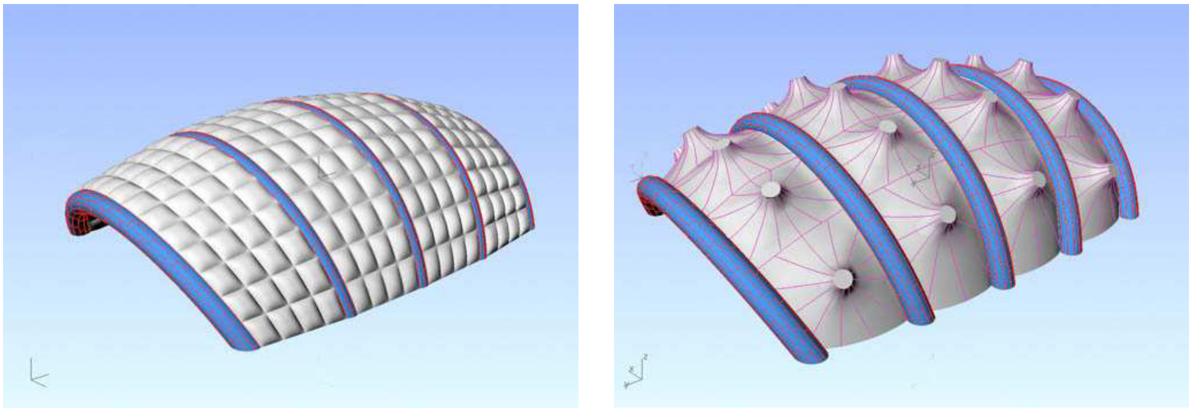

Fig 20: Semi Permanent Schemes (Image Barton Engineers Ltd)

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