In April 2004, Ryerson University, Toronto, Canada, hosted the international academic conference; Transportable Environments. The third in a series of conferences concerning portable architecture, buildings, landscape and design. It was organised and co-chaired by Associate Professor Filiz Klassen of the School of Interior Design, Ryerson University and Professor Robert Kronenburg of the University of Liverpool, School of Architecture and Building Engineering, UK.

During this conference, delegates from around the world examined built or theoretical transportable environments where permanence is either not possible or desirable. Rudi Enos presented a paper. See http://www.ryerson.ca/portable/

Valhalla

Movement of the Worlds Largest Portable Membrane Structures

Rudi Enos

Rudi Enos Design

Abstract.

The event organizers use of structures in the event business has changed in the last 20 years from necessity to choice. Temporary environments have been used for some the largest events ever held. The largest music festivals in the world, the most significant fashion show in the world, the largest one night dance event in the world, the exhibition for the 'Earth Summit' in Johannesburg, the largest business conference held in a temporary structure (Bakersfield CA), the MTV Europe Awards and the first ever European tour of a number one rock band housed entirely in membrane structures (for Radiohead). The driving force for this acceptance of the temporary venue is twofold; first, the high level of engineering that allows the promoter to safely house and insure major events and two, the realization of large span temporary structures which allow the required capacity to ensure economic successes. This is the background to the development of the largest portable event venues the world has ever seen.

1. Background

In the 1950's the world leaders in large scale portable structures were undoubtedly Strohmeyer of Constance, in Germany. They not only built large circus tents but were instrumental in helping Frei Otto (the German architect) to develop the burgeoning market for fabric structures installed permanently. Strohmeyer were the market leaders because of the sheer quality of their workmanship rather than just the size of the tentage. In the early 1980's the promoter would only use a portable structure for an important event if literally no other choice existed. Over the last twenty years that has changed with many of the largest and most profitable events in the music business taking place in portable structures out of choice. Since 1980 the event business has crossed the Rubicon and now has working methods and systems that allow it to face literally any kind of operating conditions, with the knowledge that public safety is not compromised.

In 1980 the market for rental tents was much the same as it had been for many years. If you went horse racing at a track, or to a garden party at Buckingham Palace, or had your wedding in a tent, the resulting installations were much the same as for the previous 150 years. The technical changes from then to the beginning of this new century can be compared to that of the computer industry in some ways.

"If the automobile had followed the same development cycle as the computer, a Rolls-Royce would today cost $100, get one million miles to the gallon, and explode once a year, killing everyone inside."

Robert X Cringely

The temporary structures rental market has seen similar if less obvious changes. The structures are inherently safer than their 1800 equivalent. Modern structures use many new materials and technologies to deliver a product and service that is at the cutting edge of what the events industry can supply. Truly modern concepts of mechanical handling, reduced component count, modularity, improved logistics, vastly improved erection methods and engineering simulation prior to manufacture usually result in a vast improvement of the breed.

“Why not go out on a limb? Isn't that where the fruit is?"

Frank Scully

The use of computer design and analysis software to predict the performance of temporary structures matches the practice of many engineering offices in the aerospace and motor racing industries. These practices are now filtering down into all forms of ephemeral environments. The technology allows the designer to initiate new projects, often outrageous in concept which nevertheless can have the ‘safety net’ of solid engineering practice behind the concept.

2 Scope

To give an example of the size of these gargantuan structures, it is necessary to look at the bare figures of the largest currently available, the Valhalla portable event venue.

Valhalla, in Norse mythology, was the banquet hall where the principal god, Odin, played host to the Einherjar, the souls of warriors who had died a courageous death in battle. Valhalla was the largest building in Asgard, the heavenly home of the gods, and it constituted one of Asgard's 12 realms. There the Einherjar feasted while awaiting the final battle of the world, Ragnarok. The Einherjar were brought to Valhalla by Odin's warlike maidens, the Valkyries, who were sent out by Odin to gather the souls of heroes as they fell on the battlefields.

By one account, the hall itself was so large that it had 540 doors, each one so wide that 800 warriors could march through it abreast. Another account places the number of doors at 640, each wide enough to accommodate 960 warriors across. The enormous hall of Valhalla had rafters made of spears and roof tiles made of shields. The Valkyries kept bringing more and more slain warriors to the hall, but there was always more than enough food and drink to go around.

In Valhalla, Odin gathered his warrior champions around him each day. At daybreak they would go out, clad in their chain mail, and fight on the Asgard plain to maintain their skill and prepare them for the day they would fight the final battle, Ragnarok. Then they all returned to Valhalla for feasting and carousing.

So, Valhalla could be considered a temporary structure, with rafters made from spears and roof tiles made of shields. The doors work out at a minimum of 360 metres or 1,200 feet wide so the scale is beyond anything that we are considering today.

The Valhalla was conceived and designed to provide the same sense of wonder to all who enter for the first time, as the structure in the folk tales. The proportions of the structure do not shame the legend. It is 90 metres (300 feet) wide, 180 metres (600 feet) long and 25 metres (99 feet) high. This makes it 102 metres (335 feet) by 192 metres (630 feet) by 25 metres to the outside of the structure. The internal floor area is 15,634 square metres or 168,000 square feet and the external area is 18,236 square metres or 196,300 square feet. This equals four and a half acres. The original contract for the Valhalla including spare sections required over 28,000 square metres or 300,000 square feet of fabric. This equals seven acres.

Internally, the structure is 18 metres or 60 feet high between the main masts which are 30 metres or 100 feet apart. Each pair of masts can safely suspend 20,000 kilograms or 44,100 pounds universally distributed. The largest mass to be suspended from multiple masts to date is 44,000 kilograms or 97,000 pounds.

The walls are 8 metres or 26 feet high.

The Valhalla membrane structure as conceived and built is, simply put, the largest practical, membrane mobile structure ever built, that has the ability to be moved quickly. It is probably the largest portable building ever built. This was recognized in 1999 by the Guinness Book of Records as the 'World's Largest Portable Venue'.

Guinness World Records, (1999) Guinness Superlatives, London

3 Design

There are no specific standards, written for Engineers, giving the requirements and basis for the design of membrane structures. 1 This is partially a reflection of the size and scale of the industry, its relative youth, and specialism. Relatively few permanent structures rely solely upon a membrane as the primary or sole means, of providing a structural covering. Conventional structures rely on internal rigidity to carry loads and achieve the required stability. Membranes must rely upon their form, and prestress, to achieve the same balances in the absence of bending and shear stiffness.

The design methodology used is a synthesis of experience and best practice. It is in a way a snap shot of the current position in the evolution of this branch of design. The safe operation, maintenance and inspection procedures remain the province of the tent-master.

The structure, including foundations and all components necessary to support the structure, should be designed and constructed such that:

They safely sustain all forces imposed upon them during erection and the period of intended use;

Perform adequately in normal use throughout the design life;

Use materials that have adequate durability; with regard to the erection and dismantling, the intended use of the structure i.e. abrasion, etc., fire resistance i.e. will not readily support combustion, biological and chemical attack and weathering.

Have appropriate levels of safety with regard to the consequence of failure;

Give occupants adequate means of escape, and, or incorporate parameters and an advanced warning and operating system sufficient to ensure that those occupying or using the structure are not placed at undue risk of injury;

Incorporate a robust maintenance and inspection system on all those elements of the structure resisting loads during erection, use, dismantling and transit so as to ensure they are safe to use.

The membrane design for Valhalla is designed2 for a very high gust speed of 50 m/sec. The structure is characterised by the use of a hyperboloid support system around the Kingpoles, divided by some large areas incorporating flattish anticlastic3 panels. This shape is a function of the constraints placed upon the structure in order that it may be transported and erected readily, meeting the required layout criterion set by the client. The principals of this system have been proven in a series of smaller tents made prior to Valhalla 4 such as the Kayam.

Wind is the predominant loading on the membrane as designed. To resist the wind loads, without excessive flutter, the membrane must have adequate curvature and pretension. These curving streamlined forms make the adoption of the wind codes loading formulae and requirements a problem. Wind tunnel testing can help define the loads more accurately, but are incapable of modelling the large deformations, which off load the structure through a combination of shape changes and the alteration of the internal pressure caused by relatively large volumetric changes. The code clauses are a basis for design, but must be treated with caution and laced with judgement derived from experience of the membrane and system under consideration.

1 Institution of Structural Engineers, 1995, Temporary Demountable Structures, Guide to Procurement, Design and Use, SETO, London, ISBN 1 874266 174

2 BS6661 Design, construction and maintenance of single-skin air supported structures, and ASTM codes

3Saddle shapes.

4 Kayam, this has a 15m module and has been built to 130m x 40m internal dimension. Fabric external boundaries are 5m outside of this.

4 Factors of Safety

Factors of safety rather than standards define the design process for portable structures. With the variables associated with site conditions it is necessary to allow for many configurations.

The following gives the factors used in deriving ultimate loads or the FOS appropriate to a system or material. m is the material partial safety factor: l loading partial safety factor. The combined factor ml is quoted below.

Steel structural members: ml as BS5950.

Dead + Pretension

1.4DP

Imposed

1.6I

Dead & Pretension + imposed

1.4DP+1.6I

Wind

1.4W

Dead & Pretension + wind

1.4+1.4

Dead & Pretension + Imposed + wind

1.2DP+1.2I+ 1.2W

Static Steel cables and other static cable and anchor systems: ml as below.

Breaking strength

Dead + Pretension

2.2DP

Dead & Pretension + Imposed the greater of

1.6DP+2.7I or 2.2DP+2.2I

Dead & Pretension + imposed + wind

2DP+2I+2W

Erection and dismantling

2 Min with no personnel exposed to danger

5 otherwise.

Dead & Pretension + wind

2DP+2W

Webbing and polyester ropes, permanently fitted: ml as below.

Breaking strength

Dead + Pretension

2.5DP

Dead & Pretension + Imposed the greater of

1.6DP+2.7I or 2.5DP+2.5I

Dead & Pretension + imposed + wind

2.5DP+2.5I+ 2.5W

Erection and dismantling

2E

Dead & Pretension + wind

2.5DP+2.5W

Fabric and webbing reinforcement: ml as below.

Breaking strength (Based upon mean uniaxial breaking strength). .

Self weight + Pretension

4DP

SW + Pretension + Imposed 0.2kN/m2

4

SW + Pretension + Wind 50m/sec

3

Erection and dismantling

4

SW + Pretension + 1.5kN point loads

5

Moving ropes and cables: ml

Breaking strength .

Erection only

5E

Any static load system

2.0 as replaceable cables

Erection + pretensioning

2.2

5 Anchors

Stakes and anchors in granular cohesionless soils.

The tent is totally dependent upon the stakes and ground anchors for stability. Therefore the stakes and anchors capabilities should always be proven using site tests, or from the tent-masters previous knowledge of the soil and site conditions. Hydraulically driven screw anchors are used on the Valhalla to provide holding forces of up to 30,000 kilograms or 66,000 pounds.

There are many types of stakes and ground anchors available. In addition, manufacturers make systems for this type of temporary structure. The following (shortened) data has been compiled using data and research undertaken by Ovesen and Stromann (1972) for computing the ultimate resistance of ground anchors in sand; and by Mackenzie (1955) and Tschebotarioff (1973) in cohesive materials. For comparison, other work by Broms (1964) has been valuable.

Two types of stake have been considered in this exercise, and one pullout anchor. The stakes are a pin of 50mm nominal diameter with an embedded length of 1.37m, and a 175mm wide beam of 3 metres embedment. These are similar to the systems currently used on the Kayam, and have been used successfully for a number of years. The values given below in the graph represents an anchor loaded at the centre of area in the ground. For stakes loaded at the top, parallel with the ground surface, these loads should be halved (1/2) where the soil acts plastically as it deforms, or if failure occurs at the point the soil mass reaches the elastic critical stress, by one third (1/3). As the load on the stakes is usually inclined from the ground contour to give a vertical component the later value of 1/3 is probably more appropriate. The following chart shows an anchor of 50 mm by 1400 mm embedment in dry granular soil.

Ovesen, NK and Stromann, H, 1972, Design Methods for Vertical Anchor Slabs in Sand, Proceedings, Speciality Conference on Performance of Earth and Earth-Supported Structures, American Society of Civil Engineers, Vol. 2.1, pp.1481-1500

Above tables and quotes taken from Special Structures Lab/Stuart Holdsworth Valhalla operating manual ©Rudi Enos/Stuart Holdsworth 1998.

6 Development

The development of the Valhalla concentrated on the reduction of components. Compared to other portable membranes, the Valhalla has a low steel to membrane ratio, probably lower than any other structure of it's type. From concept to first erection, the byword was minimalism. Our design team used the following as our goal.

“Perfection, then, is finally achieved, not when there is nothing left to add, but when there is nothing left to take away."

Antoine de St. Exupery

Choice of fabric materials, alloy steels, cables, motors and controls and configuration of fabric fields were crucial in the early stages of design. Since the original design phase, not one component has been modified and the structure is in regular use. Three examples have now been manufactured. With the knowledge gained from operating the Valhalla we now know how to design a better structure, but at that point, the design information was all we had.

“If you are in a shipwreck and all the boats are gone a piano top buoyant enough to keep you afloat that comes along makes a fortuitous life preserver. But this is not to say that the best way to design a life preserver is in the form of a piano top.”

Fuller, B (1963) OPERATING MANUAL FOR SPACESHIP EARTH: E.P. Dutton & Co., New York.

Depending on its size, a tent may not have a one piece roof, and in order to extend the usability of most modern tents they are modular in some form or other. This allows sections to be added or taken away to change the shape and size of the roof. The structure of the roof may be broken down into more or less sections to ease transportation, movement and erection. The Valhalla family of structures not only features this modularity but use many processes and technical features which were developed specially for the structure.

Specifically, the method of joining the membrane fields allows not only for rapid deployment but allow the draining of surface water if necessary, bearing in mind that even light rainfall on 4 acres of fabric laid on the floor can take days to clear. The covers over the section joins are able to admit light or to provide blackout.

The lifting motors have been custom designed for the structure. Lifting dead weight loads of the membrane and pre-stress loads of the system can require 7,000 – 10,000 kilograms or 15,000 – 20,000 pounds of force. The Valhalla motors power these loads yet occupy a space only 40 centimeters by 40 centimeters by 95 centimeters or 16 inch by 16 inch by 38 inches. There are three motors per pair of masts, one for lifting the poles and two for lifting and tensioning the membrane.

The main masts lift themselves from the floor without external help. On the 16 mast structure, the poles are lifted in two banks of 8. The first bank of 8 are hoisted into a position 90% of their service height to allow for checking prior to final positioning. Then the second bank of 8 are lifted by the first bank.

The control systems and cabling allow for variable amperage control of the lifting operation. The overload trips are set at a low level for general lifting of the membrane and then individually increased for the pre-tensioning of the roof.

The ‘A’ frame supports on the perimeter of the structure not only support the roof but prevent twisting while the membrane is not under stabilizing pre-stress and allow for minor adjustment of the form. They also allow for relatively easy lifting of the 40,000 kilogram membrane into it’s service position.

The form of the structure take into account the aerodynamic action of wind. Typically, temporary structures are loaded by wind in several ways. Direct loads on the roof, direct loads on the walls and suction due to boundary layer attraction are the main forces. The conics of the main masts break up the suction of the air flow over the central area of the roof. The masts were specifically moved further outwards of the center of the structure due to this. The severe shape change at the perimeter of the structure not only provides stability but reduces the wind load on the walls. On the lee side of the structure (away from the direction of the wind) the pronounced upturn acts to break up the airflow which tends to generate lift.

One of the main design concepts of the Valhalla is it's internal height. This gives a lot of internal clearance for stage lights, trussing and rigging etc.

7 Operation

The structure travels in 9, custom built 12 metre or 40 foot ISO shipping containers. The structure self erects without the use of cranes. The containers are unloaded with the use of standard fork trucks. The largest version has been erected in only 96 working hours.

Typically the site will have been marked out prior to the equipment arriving. Marking out will take some 3 hours. Anchor tests will have been undertaken and certified. An 80 kva 3 phase power supply is required to supply the motors in the structure.

The main masts travel dressed. This means that the motors are a permanent fixture and are required to meet IP 57 (European standard for electrical equipment used outdoors), and must be shielded, and that all cable guys are coiled and travel with the mast.

No threaded bolts are used in the structure to assemble it. All connections use pins and spring clips. No spanners are used in assembly.

The membrane does not have traditional lacing to join fabric fields. The sections use catenary belts and are pinned together. The fabric fields do not connect directly together but join to a webbing sub system. The webbing sub system uses multi layer belts to stiffen connections and to provide redundancy in event of membrane failure.

Specialist techniques have been developed for folding and transporting fabric sections, some of which weigh 2 tonnes or 4,400 pounds.

Methods of packing equipment optimize shipping volumes. It is very expensive to ship fresh air. Specially developed folding trusses provide extreme performance to shipping volume ratios.

Documentation is required at each stage of the movement process. Site surveys, risk assessment, health and safety documentation, employee welfare, structural certification and insurance documentation must all be considered. Event permits are not normally part of operations.

8 Conclusion

The development has not stopped. The future brings much promise of better lighter structures which adapt to their environment. These structures will almost certainly be configurable and may use some WIG (wing in ground effect) technology to reduce surface pressures. Composites will answer many of the problems of slenderness ratios on members. Scissor action trusses will allow for packing ratios unheard of at the present. New weaves and coatings and perhaps seaming methods will improve the performance of membranes while reducing weight and volume. The gap between the 1880's tent and that of the future will be wider still. Who knows at this point what is possible?

In a future of uncertain client requirements, architecture by fashion (glass is the new black) and world access to information, the only surprise will be if membranes are not used as a first choice for large structures. Where the climate allows, the tent as housing may become a fashion feature rather than a building requirement. Modern architecture is moving ever closer to more organic shapes, which membranes can provide. Curvilinear shapes, a unique and distinctive feature of tent architecture, will allow a world of variables where there was uniformity, will allow shade and translucency rather than rigid barriers, and a freedom of spirit engendered by the soaring shapes.

Chopra expressed this so well that I leave you with a quote from him.

"We will take a journey through an inner country that has to be discovered and created at the same time. The goal of this journey will be the end of an illusion…….we will find out if our true nature is bounded or boundless.

I invite you into a realm a realm of infinite creativity where everything is possible."

Chopra, D. M.D. (1999) Journey to the Boundless

9 Biography

Rudi Enos is a design engineer who became involved with his first tent project in 1978, (tents were just starting to be made from plastic composites), and in 1979 built his first Big Top. In a career spanning 25 years to date Rudi has designed and built, or designed for others, more tented, mobile and demountable structures than all other British designers put together. Rudi founded the Kayam rental company in 1991 and acts as a consultant to other companies on projects such as 'WaltIt Disney On Ice' and the 'Earth Summit' in Johannesburg, South Africa. He currently runs Rudi Enos Design and is a leading light at MoonBurst Structures.

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