REVEW: EXPOSURE TIME OF PNEUMATIC STRUCTURES

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ABSTRACT

This paper presents the exposure time of built utilization (service period) within the notion of pneumatic structures so to serve as a' designing handbook' when one tends look up the period of use according to different typology of pneumatics. In the discussion of exposure time, the situation of climate, scale, function, load bearing, material and morphology would be also presented as influential figure for the comparison.

KEYWORDS: *Exposure Time, Service Period, Pneumatic, Handbook*

I. INTRODUCTION

1. Introduction

The word 'pneumatic' (from the Greek 'pneuma'—breath of air) is to describe a membrane structure which is capable of supporting tension and stressed by the differential pressure of gas, normally air. Known usually as 'inflatable', 'air-domes', 'blow-ups', 'air houses', the pneumatic envelope is based on the use of air supported membrane skins, but rather than just a single layer of inflated membrane supported by the pressure of air from the interior pressures (usually called as 'inflated'), the pneumatics system could be specified into different typologies for the classification of their pressure type and morphological properties.

As defined in *Principles of pneumatic Architecture* [1], the typologies of pneumatics [appendix 1] could be divided firstly into '*air controlled construction*' (not generally associated with architecture) and '*air stabilized construction*' according to the mechanical principle, and then deviates into '*air inflated structures*', and '*air supported structures*', for which the previous one is constructed in inflated elements and the later one is supported by the interior air pressure. After that, the '*air inflated structure*' then could be divided into three notions—one for '*rib structures*' one for '*dual walled structures*', and 'hybrid air inflated structure' which integrated with skeleton (for example, the ETFE cushion structure with steel panel). Also, there are 'hybrid air supported structure' for which the air inflated membrane is constructed associating with a primary or secondary support.

In this article, the discussion of exposure time would focus on the air stabilized structure which been adopted for building construction for public function and outdoor environment.

2. Methodology

Exposure time of one structure is obtained in this paper through case studies. However, the exposure time of structure is relatively complex, with no unified calculation method at present. In relation to the relatively short length of development of this technology, the research would be conducted in three part of each typology. First, it will be focused on cataloguing the most representative pneumatic structures both from the highlight pneumatic time of the 70s and recent period, thus to suggest the exposure time of each typology. Second, there will be specifically description of one case after each catalogue to further indicate the architecture characteristic. Third, in the end of each session, there will be an evaluation of each including the scope and limitations to point out the exposure time and also the factors that influence it. Therefore, the objective is to analyze the exposure time with each pneumatic typology and thus indicate the future opportunity of pneumatic design.

As mentioned in the introduction, the exposure time of projects differentiated from their design parameters, hence, there is firstly a common parameter of all which is pneumatic structures under exposed location and also with public function. Moreover, an interactive and open database has been built, in order to facilitate the projects between different parameters. In this sense, selected projects will be organized in a detailed summary sheet (Table 1) which frame the parameters in an organized and self-evident way.

Yet, the evolution of pneumatics such as technological innovations of material and construction has been progressively conducted rapidly in practical field, which could also make a difference towards the exposure time. Then, the new technology of pneumatics will be also proposed in this paper as if it contributes to a specific pneumatic typology.

Table 1. Detailed Parameter Sheet (drawn by author)

Parameter	Function	Scale	Environmental Context	Morphology	Material	Characteristic	Exposure Time

II. EXPOSURE TIME ACCORDING TO CLASSIFICATION

The system of pneumatics was developed in the engineering notion of frame or aeronautics, with the first hot air balloon prototype of Francesco Lana di Terzi in 1670 [3], although the application in architecture of which started to be developed three centuries later, with projects like Carl Koch's Boston Arts Center Theater in 1960, or Victor Lundy's Brass Rail Refreshment Pavilion in 1963. After experiencing a rather drastic construction in the sixties and seventies leading by the Archigram and practical practiced by Superstudio (Italy) as a strategy of 'nomad' [4] for temporary residence and event holder, the pneumatic systems have been have experienced another rather massive growth in the last twenty years with new structural strategies and adaptive envelopes both for the temporary and permanent purpose. [see this notion in appendix 2]

2.1. Air- inflated structures

In air inflated construction, air is contained within a membrane to realize inflated structural elements, (columns, beams, walls and arches) which themselves resist the external loadings as the same way as the structural elements of conventional structures. There are two main types of air inflated structure, inflated rib structures and inflated dual walled structures. The former is made up of a framework of pressurized tubes which supports a membrane in tension. The later consists of two membrane walls between which the air is contained.

2.1.1 Rib Structures

Shortly after the Second World War this type of structure was investigated both in America and Britain. The small volumes of air contained within these tubes make these structures more suitable for small span construction back then.

The investigation of exposure time with air inflated rib structures is shown in the sheets below (Table 2):

Table 2. Rib Structure exposure time (drawn by author)

Parameter / Projects (year)	Function	Scale	Environmental Context	Morphology	Material	Characteristic	exposure time
Ontario Pavilion(2015)	Event Space	H:15m L:60m	High wind (Toronto, Canada)	Shell	Polyester	Translucent	38 days

Microcity Sales Office(2012)	Sales Office	1400 sq.m	Snow load (Moscow, Russia)	Rounded Dome	PVC	Translucent	50 days
The Drift (2012)	pavilion entrance	H: 4m-8m 324sq.m	Mild climate (Miami, US)	Canopy of Cylinders Pile	Vinyl	Translucent	7 days
Expo'70 Fuji Group Pavilion(1970)	Event Space	D:50m H:31m	Mild climate (Fuji, Japan)	Rounded Dome	PVC	colored	55 days

The most recently case of air inflated rib structure is the Ontario Celebration Zone Pavilion which is part of the festivities surrounding of the Pan American Games in Toronto [appendix 3]. The site was a public park and therefore construction time and impact were greatly limited, for that the structure was constructed in one week without a substantial foundation. The structure of the pavilion was constructed of pneumatic rib arches with quilted infill and measured approximately 60 meters long by 15 meters high.

Multiple compressors were used to maintain a constant internal air pressure; some operated consistently and some were kept on stand by for redundancy. The structure stood for 38 days, the duration of the Pan American and Para Pan American Games.

2.1.2 Dual Walled Structures

Inflated dual walled structures, as a development of inflated tubular structures, consist of two membrane walls between which the air is contained. These walls are held together by drop threads and diaphragm configurations. However, recently, the dual walled structure has been mainly erected in units such as 'peumocell' developed by T. Herzig, and 'aiRdome unit' by tat aiRstructures.

The investigation of exposure time with air inflated dual wall structures is shown in the sheet below (Table 3):

Table 3. Dual Walled Structure Exposure Time (drawn by author)

Parameter / Projects (year)	Function	Scale	Environmental Context	Morphology	Material	Characteristic	Exposure Time
aiRdome75 _product by ©tat aiRstructures	Event tent	D:10m H:5m	Strong wind load Moderate snow load	Dome of unit	PVC	Translucent	customized
Cube 12 _product by ©Contemporary Event Structures	Event space	L:12m W:12m H:6.5m	Customized load bearing	Cube of Pneumocell	PVC, rip stop nylon FR treated	Translucent/ Transparent	customized
Kengo Kuma's Tea House (2007)	Tea House	31.3 m^2	Mild climate (Frankfurt, Germany)	Dome of Peanut Shape	Tanara ® membrane	Translucent	13 days
U.S.A.E.C.Portable Exhibition Pavilion (1960)	Portable Event Space	L:90m W:38m H:15m	Mild to warm climate (Santiago, Chile)	Shell	Vinyl coated nylon membranes	Translucent	10 days

The problem of dual walled structure is about two point. One is that the pressure within need only be topped up occasionally due to the air scarcity. Thus, even though the recent company had launched series of pneumatic rib products that without a exposure time subscription, however, according to the rather high operating cost, this kind of structure normally only last one week. The other is the 'air mat' which is difficult to repair after a puncture. However, with the 'pneumacell' structure (a kit of inflatable components analogous to biological cell structures) the inputs problem has been solved.

Also, the new material and joint technology developed recently makes dual walled structure more reliable than before as the tear resistant material developed by 'tat aiRstructures' which is acclaimed as stab-free that 'a stab would not be a problem since the cut will not get bigger after puncture and the fan can also compensate a cut of 10 cm length' [5]. Also, the zipper connection between the dual wall's inner and outer skins of Kengo Kuma's tea house [appendix 4] made the dual wall 'free of air locks for having the same pressure as the air pressure from the outside' [6]. Though the 'sandwich' structure (outer membrane-coupling cables-inner membrane) may make the whole construction as 'hybrid', compared to the construction method with membrane unit with steel frame as joint between units as well as secondary support, it would be better to still refer this one as dual wall structure in this session.

2.1.3 Evaluation

In all, the air inflated structures are mainly applied for short-term temporary use with a exposure time around one month. Even though, the new innovation of techniques has made it more reliable as mentioned above, the two fundamental modes of failure still drive the air inflated structure to be rather short-term, and the two failure are:
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 pre-stress resulting from inflation, causing collapse of the skin and a structural hinge to form.

2.2 Air Supported Structure

An air supported structure consists of a single structural membrane supporting by a small air pressure differential. This means that the internal building volume is at a slightly-above-atmospheric pressure with in-and-out access accomplished by crossing a pressure differential.

The investigation of exposure time with air supported structures is shown in the sheet below (Table 4):

Table 4. Air Supported Structure Exposure Time (drawn by author)

Parameter / Projects (year)	Function	Scale	Environmental Context	Morphology	Material	Characteristic	Exposure Time
Loud Shadows (2017)	Temporary performance space	D:15m H:4m	Summer: mild climate Terschelling, Netherlands	Dome	Plastic	Transparent	10 days
Skum (2016)	Festival bar	120s.q.m 170 capacity	Summer: mild climate (Roskilde, Denmark)	Clouds Shaped Canopy	PVC	Translucent	8 days
Ark Nova (2014)	Temporary theatre	L:36m W:30m H:18m	Autumn: mild climate (Lucerne, Switzerland)	Dome	Polyester	Translucent (purple)	10 days

Memorial Pavilion (2004)	Temporary pavilion	120s.q.m 170 capacity	Summer: mild climate (Madrid, Spain)	Cylinder	PVC	Translucent	15 days
Oase No. 7 (1972)	Temporary art installation	D:8m	Summer: mild climate (Kassel, Germany)	Protuberance	PVC	Transparent	5 days

The exposure time of the air supported structure are relatively short, for which the reason might be deviated from the three structural problems presented by the air supported structure; firstly, the need to maintain the pressure differential across the membrane with a constant air supply; secondly, the need to minimize air leakages; and thirdly the need to counteract the up-lift forces with some means of anchorage.

With air supported structures, some special attention should be given to the design of certain features where load concentrations are likely to pre-dominate, thus the most insured building environment is mild climate without severe load of snow, wind and rainfall. Other features requiring special attention are such things as cable attachments, where a point load has to be uniformly distributed into the membrane around openings for access and ventilation, and also the attachment of the membrane to rigid elements. In addition to this the form of the structure must be carefully chosen to avoid development of stress concentrations which are recently detected by pressure or wind sensor that automatically enters into action immediately after power failure as well as managing the operation of the structure and economizing the running costs [7].

The most representable case of the air supported one is the Memorial Pavilion [appendix 5] which is made of ETFE membrane with glazed facade at Atocha Station in the center of Madrid serves as a reminder of the victims of the terrorist attack. The Memorial Pavilion consists of a glazed cylinder facade above ground and a commemorative space immediately below. Within the glass cylinder is a 150 μm thick ETFE foil stabilized by air pressure, and the inner skin of it is printed with messages as condolence in different languages. Instead of using the PVC in the old time, the ETFE membrane makes it more sustainable and resisted to load bearing with a exposure time of 15 days.

2.2.1 Evaluation

In all, the air supported structures are mainly applied for short-term temporary use with a exposure time around 10 days in mild climate especially with low positive pressure systems that the majority of the projects are located between 51º-60º North latitudes (47 %), followed by 41º-50º North latitude ranges [8]. The mild summers allows the structure with natural ventilations and low cooling loads. The reason of why this kind of structure is mainly erected for temporary usage is for two fundamental modes of issue below:

1. High cost of utility – you are responsible for fans that require 24-hour function and monitoring. This leads to extremely high utility cost. if one plans to use your air structure year round, monthly utility bills can reach $10,000+ [9].
2. Danger in certain weather situations – weather is a key factor when using your air dome. With no support framework, air domes are not safe in high wind or snow.
3. Lack of support for accessories – your air dome has no frame system; therefore, it cannot support important accessory items.
4. Fabric Maintenance – your structure could be severely damaged with vandalism or tears and deeming it unusable without repair.

2.3 Hybrid Structure

Whereas the group above might be termed 'total pneumatic hybrids', the group in this section would be described as 'partial pneumatic hybrids', this structures combine pneumatic construction with other more conventional forms of construction, normally supported by a primary or secondary skeleton. This kind of structure is erected for a more stabilized purpose of design as one persist increased loading while under heavy loads of wind and snow, or for the permanent use which calls for a more stabilized interior environment. Almost certainly, it is through hybrid construction that the truly sophisticated pneumatic architecture had been emerged.

2.3.1 Air supported Hybrid Structure

Since air supported structures are dynamic structures, in which loads are balanced and redistributed by membrane distortion, rigid elements will restrict their movement and induce stress concentrations large enough to cause membrane failure. The hybrid structure which integrates the pure air supported structure with secondary support (usually metal stiffeners known as cables or nets) make it possible for the membrane to be stabilized with small radii of curvature, so to reduce the stresses to the membrane.

The investigation of exposure time with air supported hybrid structures is shown in the sheet below (Table 5):

Table 5. Air Supported Hybrid Structure Exposure Time (drawn by author)

Parameter / Projects (year)	Function	Scale	Environmental Context	Morphology	Material	Characteristic	Exposure Time
OMA Serpentine Pavilion (2006)	Temporary gallery	D:21m H:5m	Summer: warm climate (London, UK.)	Ovoid-shaped canopy	Polyester	Translucent	92 days
Coolhurst Tennis Airhall (2006)	Winter sports court cover	L:30m W:12m H:10m	Cold climate (London, UK.)	Rounded Dome	Mesh Reinforced PVC	Transparent	60 days
12th World Orchids Conference Pavilion(1987)	Event Space	D:75m H:19.5m	Mild climate (tokyo, Japan.)	Rounded Dome	Mesh Reinforced PVC	Translucent	85 days

The most representable case of the air supported hybrids is the Serpentine pavilion by OMA [appendix 6] as the exposure time of air supported structure (described in chapter 2.2) appear to be rather short within a period of 10 days. The hybrid air supported structure of OMA's pavilion, however, combine the air supported canopy (constrained with cable and nets) which is set upon the polycarbonate circular below [10] showed that the air supported structure could also reliable for a longer period more than 10 days if it only serves as one's roof. It could be concluded that the air supported hybrid is possible to serve for a seasonal when one combined with secondary supports.

2.3.2 Air Inflated Hybrid Structure

The air inflated hybrid structure allows the air inflated elements to be the outer envelope of a building as a façade cladding.

The investigation of exposure time with air inflated hybrid structures is shown in the sheet below (Table 6):

Table 6. Air Inflated Hybrid Structure Exposure Time (drawn by author)

Parameter / Projects (year)	Function	Scale	Environmental Context	Morphology	Material	Characteristic	Exposure Time

Aufblasbarer Dome/1000,400 (2016)	Event space	D:10.9m H:6.25m	Temp. -30°C - 45°C(customized environment.)	Dome	Cushion with frame	Semi-Translucent	customized
Drijvend Paviljoen (2015)	Permanent pavilion	D:12m H:12m(one of the three)	wind loading Snow loading(Rotterdam, Netherlands.)	Dome	ETFE panel (steel support)	Semi-Translucent	2015-?
Allianz Arena (2010)	Permanent stadium	75,000 capacity H:50m	wind loading Snow loading (Munich, Germany.)	Boat Shape Stadium	ETFE panel (steel support)	Semi-Translucent	2010-?
National Space Center (2001)	Permanent museum	D:21m H:5m	Heavy rainfall (Leicester, UK.)	Rockets shape	ETFE pillow (steel support)	Semi-Translucent	2001-?

The most representable case of the air inflated hybrids is the Allianz Arena by Herzog and De Meuron [appendix 7] as with the 'multiple load bearing system' behind the ETFE cushion [11], the exposure time and scale of which is rather long and large compared to traditional air inflated structure.

2.3.3 Evaluation

For the air supported hybrids, it could be concluded that it is possible to serve for a seasonal time of period (up to three month) with the secondary supports (usually directly join with the membrane such as mesh or cable). Also, the larger scale of air supported structure could be accomplished with the secondary supported which plays a dual role of increasing the reliability and durability—maintaining the differential air pressure between exterior and interior as well as resisting the tension by both the external loads and internal air pressure. Thus the air supported hybrid structure normally has longer service period of exposure time and larger scale than pure air supported ones.

For the air inflated hybrids which in this chapter are mainly about cushion units with frame, the exposure time of which is rather long. Especially for the ETFE membrane which the inflated pillow serves as façade cladding [12] with 'conventional' supported skeleton, the service life of which could be permanent.

III. CONCLUSIONS

The purely air inflated structures and air supported structures could be described as 'semi-permanent' that are capable of resisting environmental invasion as wind or snow loading to some degree. However, due to the high demand of maintaining and low fire reliability, they are always applied in a temporary period—for the air inflated one is within two months, and for the air supported one is around 10 days, thus these two kind of structure is typically for events or shows with generally short term of service time.

For the hybrid pneumatic structures, the secondary supports make it last longer to seasonal use as sports hall canopy or conference pavilion up to three months' service span. Moreover, there is also permanent period of use within the typology of pneumatics which is the ETFE cushion structure (air inflated hybrid) which acts as façade cladding along with primary and/or secondary structure.

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APPENDICES

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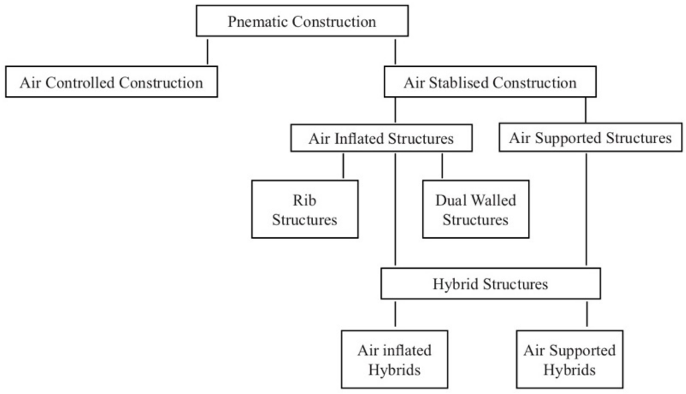

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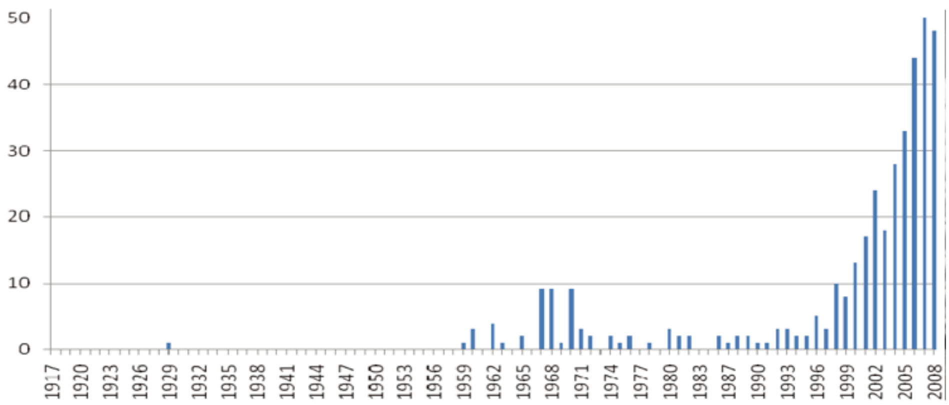

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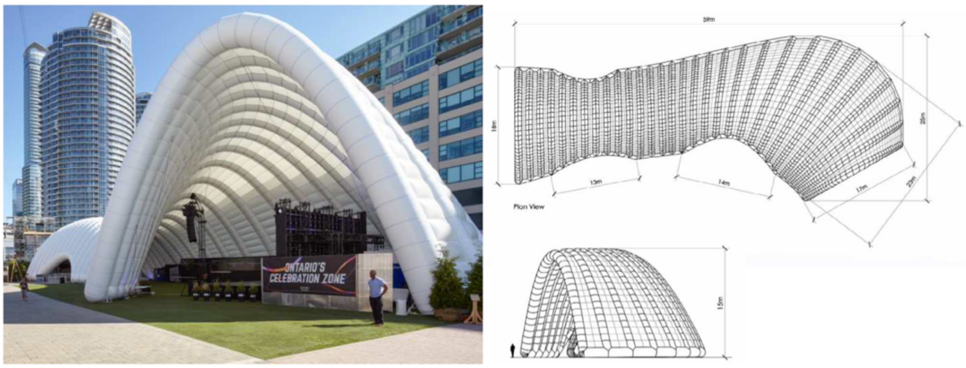

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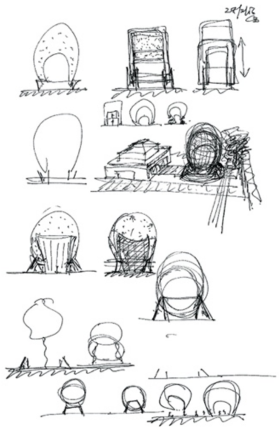

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