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Pneumatic skins in architecture. Sustainable trends in low positive pressure inflatable systems

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Abstract

The research has been focused on the review and critical analysis of the architectural low positive pressure inflatable systems, since the first patents to the most recent trends. While first pneumatic buildings were focused on air-supported structures, large volume of inflatable examples has been built in the last decade, favored by the improvement of transparent, high-strength and low maintenance new membrane materials. The study of more than 400 representative example shows that new sustainable strategies are being developed in order to take advantage of the flexibility, lightness and climatic adaptive properties of inflatable skins.

Keywords: Architectural pneumatic skins; inflatable systems; new sustainable trends

1. Introduction

Pneumatic envelope systems are tensile structures, based on the use of membrane skins, which are stabilized by the differential pressure between their inner and outer sides; in order to acquire enough stiffness to maintain an equilibrium position and to be able to support external loads.

There are different typologies of pneumatic systems, and the most common classifications have been made according to their type of pressure and their morphological properties. The most developed systems are stabilized with positive pressure (air-supported and inflated), while negative pressure systems (vacuumatics) are still in emerging researching period.

According to their formal configuration; while air-supported systems are based on the use of unique membranes that surrounds the living space; the inflatable systems are based on the use of closed structures

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made with different number of layers and whose interior is pressurized and not accessible. Although first ones had experienced an important development in the sixties and seventies, the inflatable systems have been improved more in the last decade, allowing new sustainable strategies in climatic adaptive envelopes.

Table 1. Most common positive pressure pneumatic systems in architecture (pressure values in normal conditions) [1]

Air supported	200-300 Pa
Inflated with low positive pressure	200-300 Pa
Inflated with high positive pressure	Until 100.000 Pa

The inflatable systems were firstly developed in the frame or aeronautical engineering, with the first hot air balloon prototype of Francesco Lana di Terzi in 1670 [2], although their application in architecture started to be developed three centuries later, with projects like the Boston Arts Center Theater, designed by Carl Koch in 1960, or the Brass Rail Refreshment Pavilion in New York, designed by Victor Lundy in 1963 [3]. The following chronological analysis, shows the volume of inflatable projects documented in the present research, where has been made special enphasis on the last decade (fig. 1).

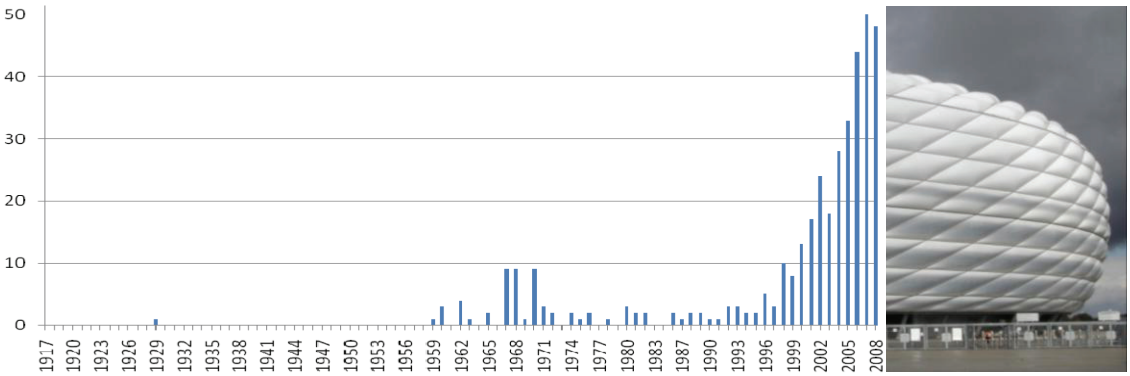

Fig. 1. (a) chronological study. Source: Own elaboration (b) Allianz Arena Stadium in Munich. Source: Own photo

2. Methodology of the study

In relation to the relatively youth of this technology, the research has been focused on the cataloguing and selection of the most representative inflatable systems, since the first patents to the current proposals. The objective is to analyze their current trends and future opportunity research areas, in order to improve more effective and sustainable strategies. Until January 2010, the total amount of 412 projects has been studied, according to the following qualitative parameters of analysis: design, functional, morphological, constructive, climate and comfort-energy efficiency parameters.

An interactive and open database has been built, in order to facilitate the proposals compilation and the comparison between different parameters. In this sense, selected projects can be organized in different ways, allowing their grouping depending on the study that will be conducted. Thus, projects has been grouped and compared in relation with their geometries, sizes, design dates, type of substructure, function in the building, etc.

In parallel, a detailed summary sheet has been developed to facilitate an easy reading of the different data from each project. Values from database and summary sheet are coordinated, so by selecting a project in the first one, data are configured directly in the summary sheet. The main parameters of study have been subdivided as follows:

Table 2. Main Parameters of study. Source: Own elaboration.

Contextual parameters	Functional parameters	Morphological parameters	Constructive parameters	Climatic parameters	Comfort and energy efficiency
Chronological Location (city, country) Type of project (built, in progress, non built, conceptual) Author (Designer, promoter and constructor)	Building use Pneumatic application New construction / Retrofitting / Enlargement	Main dimension (1D, 2D,3D) Form finding Form units geometry and number Size (of units and envelope system) Types of morphological modification Constructive parameters	Substructure typology and materials Type of anchoring Auxiliary reinforcements Type of membrane (material, number of layers, material junctions, maintenance, fire resistance, recycling possibilities) Supporting gases	Latitude Altitude Climatic zone (main climatic parameters: Temperature, humidity, rainfall, snow, solar radiance)	Thermal control Ventilation Natural lighting / shadowing Acoustic conditioning Solar energy capitation Maintenance

3. Trends in low positive pressure inflatable systems

After analyzing the 412 selected proposals, according to the main parameters and sub-categories previously described, there have been established the following trends related to the low pressure inflatable systems. This study has been made to determine the current state of the technology and to help the proposal of new sustainable strategies to be improved or developed.

3.1. Contextual parameters

According to the chronological evolution of this technology, the study shows that the low pressure inflatable systems have experienced an important development in the last decade. The improvement of new materials with higher resistance and durability, like ETFE or coated fabrics [4], allows the use of membranes in large quantity of buildings.

In relation with the geographical situation, 40% of the studied projects have been made in Germany or United Kingdom, where these systems have been more accurately researched and manufactured. Also, the climatic conditions of these areas, with solar radiation gains in winters and mild temperatures in summers, benefit the application of these systems. However, in the last decade the use of this technology has been developed in other zones with more extreme summers, like south Europe or some regions in Asia.

3.2. Functional parameters

In relation to the building uses where the pneumatic system has been designed, most of them are still focused on exhibition or cultural programs. But in the last decade, the range of uses has been extended to permanent typologies, like coverings of courtyards in educative buildings or offices. The lightness of inflated systems, compared with glass, and the improvement of the membrane resistance materials; but also, the design of highly mass media projects, like the Allianz Arena Stadium in Munich (2006) [5] or the Water Cube Swimming pool in Beijing (2008), also have favored the international promotion of this technology.

Table 3. Main building uses where low pressure inflatable systems have been identified. Source: Own elaboration

uses	percentage	material	percentage
Aquatic	8,76 %	Medical	2,68 %
Art	3,16%	Multi-functional	4,14 %
Botanical	3,89 %	Museum	2,68 %
Commercial	8,27 %	Office	15,09 %
Cultural	17,27 %	Public space	1,22 %
Education	12,17 %	Sport	3,41 %
Energy	1,22 %	Transport	4,38 %
Housing	5,60 %	Zoo	1,70 %
Industrial	1,22 %	Other	2,17 %

In other way, the specific functions of inflatable systems in the building have been studied. The most common functions are still the envelope (79%) and structural-skin (20%); specially the first one, which is focused on the improvement of inside comfort conditions. The mainly inflatable envelope strategies are the protection from raining, snow, wind and solar radiation. But also, new strategies of solar energy integration have been developed in the last decade, although it only represents 1% of the total inflatable proposals of the study.

In relation with retrofitting strategies; only 15,58 % of the studied proposals have been developed in the frame of existing buildings; while most of them are still focused on new constructions (84,41%).

3.3. Morphological parameters

The main morphological classifications of Roger Dent, Thomas Herzog, Gernot Minke, developed in the seventies, had organized the pneumatic systems according to their dimensional properties in one-dimensional (1D or lineal), two-dimensional (2D or superficial) and three-dimensional (3D). But for the study, it has been added a fourth-dimensional category (4D); where will be included all the projects which modify their form to optimize their behavior in different temporal conditions. These projects can also take the name of Kinetic or adaptive. In this case, most of the theoretical proposals were developed in the sixties and seventies of the 20. Century, like the Dr. Nikolaus Laing [6] researches of multilayer systems in 1967 or the Dynamat prototype of Conolly in 1972. But the lack of high performance materials in this moment and the seventies oil crisis, avoided the development of new research lines. Currently, new membrane properties has been improved and incipient strategies has been identified, like the observatory tensairity roof in Tenerife, by Airlight in 2008; although the 4D systems represent still a low percentage.

According to the surface of pneumatic skin used in each building, it has been found proposals in almost all size ranges. There have been defined two main types of covering: the use of unique units that covers the whole surface by itself and the combination of multiple units with substructure systems, frequently beams and formworks. While the first types take advantage of the maximal properties of the membrane, the required envelope thickness is higher than in the substructure systems. These requirements and the continuity of traditional architectural designs related to other constructive patterns, like glass envelopes; contribute to that most of the analyzed projects still use the multiple cushions typology.

Table 4. Surface of pneumatic skin in the analyzed proposals. Source: Own elaboration

Surface of inflatable skin (m^2)	Size	percentage	Surface of inflatable skin (m^2)	Size	percentage
0-50	XS	9,32 %	1.001-5.000	L	30,14 %
51-300	S	25,48%	5.001-20.000	XL	6,03 %
301-1.000	M	26,30 %	>20.000	XXL	2,74 %

Also, the form finding processes related to this technology have been analyzed. Although, by definition the pneumatic systems morphology depends directly from the pressure effects over the membrane, the inflatable typologies are frequently designed under other parameters. In this way, the systems based on the optimal membrane behavior or minimal surface, are a minority (2%); like the ones projected with pre-defined geometrical forms are frequently used (95%). In relation with the most common geometries, the cushion typology represents 70% of the total geometric proposals that have been analyzed. Rectangular frame shapes represent the most common cushion geometries (54%), which support the fact that many designs use this technology as glass replacement, but continuing its construction patterns without taking advantage of maximal properties of flexible membranes.

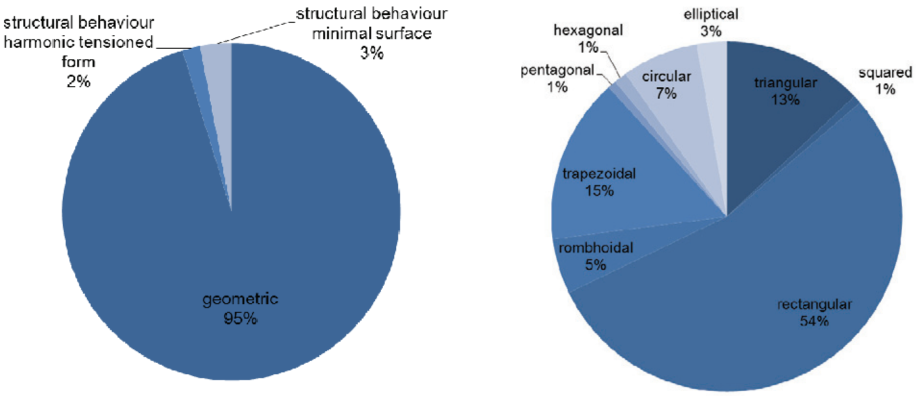

Fig. 2. (a) form finding processes. Source: Own elaboration; (b) cushions geometry. Source: Own elaboration

3.4. Constructive parameters

Low pressure inflatable systems have been organized according to the type of elements, where load transmissions from membrane are discharged. In this way, studied inflatable systems transmit loads to the following structures typologies: Perimeter (19,41%), lineal (80,26%) and punctual (0,33 %).

The most common perimeter substructures are frameworks (46%), frames (30%) and rings (24%); while lineal substructures are beams (42%), arches (35%), trusses (13%) and vertical substructures (10%). Respect to punctual substructure, it has only be found masts and punctual cable supports in inflatable systems, like the German Pavilion of the Seville Expo in 1992.

The substructure materials have been studied according to the different typologies (figure 1). According to the studied proposals, most of them are built with metallic substructures, although in linear systems, wood substructures are also frequently used with almost 10% of the total linear structures. Concrete substructures are mainly used in rings of large inflatable units or in some linear beams or frameworks, where architectural aesthetical design prevails over the lightness of inflatable systems.

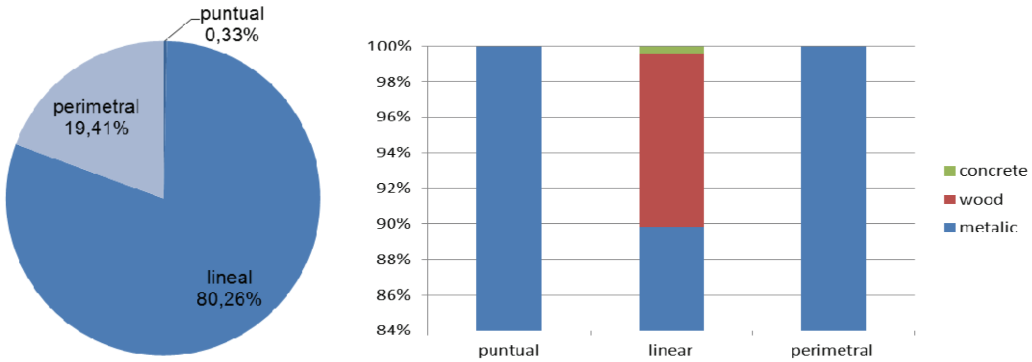

Fig. 3. (a) types of structures where membrane loads are transmitted. Source: Own elaboration; (b) substructure materials. Source: Own elaboration

Respect to the used materials, since the birth of ETFE foil it has been used in the most of the studied proposals (84,75%), mainly in the last decade. The self-cleaning, durability and high light transmission have favored the use in many permanent envelopes, breaking the traditional relation between inflatable systems and temporally buildings. Other membranes, like PES or fiberglass coated with PVC, are also used in large cushions, where higher membrane resistance is necessary.

Table 5. Membrane materials used in the proposals which have been analyzed. Source: Own elaboration

material	percentage	material	percentage
ETFE	84,75 %	Fiberglass/PVC	1,53%
PES/PVC	4,14%	Fiberglass/Silicon coated	1,74 %
PVC	3,70%	Others	4,14%

3.5. Climatic parameters

The majority of the proposals studied are located between 51º-60º North latitudes (47 %), followed by 41º-50º North latitude ranges. In a more accurate analysis, the most projects are built in the Cf zone (84,39%), according to the Köppen-Geiger climatic classification [7]. The warm temperature climate and high humid conditions, favor the use of transparent inflatable envelopes, taking advantage of solar radiation gains in winter. Also, the mild summers, without high temperature, allows that with natural ventilation systems or very low cooling loads, it is possible to achieve good internal parameters of comfort. However, this technology is increasing in other climates with more extreme summer conditions; like some Spanish and Mediterranean cities in Cs (7,51 %), or also Bs (1,45%).

The main climatic parameters, which affect the behavior of low pressure inflatable systems are the following: Maximal and minimal temperatures, relative humidity, rainfalls, wind and solar radiation. According to these parameters, the main problems are related to the discontinuities and thermal bridges between membrane and structure, where superficial condensations can appear. This pathology can diminish the membrane durability and the water presence can increase the mold growth and the metallic elements corrosion.

Table 6. Climatic zones [7]

Climatic zone	percentage	Climatic zone	percentage
Af (Equatorial rainforest, fully humid)	0,58 %	Cs (Warm temperature climate, dry summer)	7,51 %
As (Equatorial savannah with dry summer)	0,29 %	Cw (Warm temperature climate, dry winter)	0,58 %
Bs (Steppe climate)	1,45 %	Df (Snow climate, fully humid)	2,89 %
Bw (Desert climate)	1,45 %	Dw (Snow climate, dry winter)	0,29 %
Cf (Warm temperature climate, fully humid)	84,39 %	ET (Frost climate)	0,58 %

Also, in climates with high temperatures and buildings without good ventilation and conditioning systems, are frequent the problems of greenhouse effect, mainly in skins with transparent membranes without shading strategies. Related to rain and snowfall, the main problems are associated to the evacuation strategies, the water leakage of the envelope, and the low acoustic isolation of membranes in rainfall situations.

3.6. Comfort and energy efficiency parameters

The main sustainable trends related to comfort and energy efficiency parameters are the following: Thermal control, natural lighting and shading, ventilation and solar energy management.

Respect to the use of inflatable active systems for thermal control, many strategies where proposed in seventies, although low of them where built as prototypes and monitored. Currently, the thermal control strategies are focused on the use of new gases, like Nitrogen, and the combination with other materials, like aerogel, which improve the isolation properties of inflatable systems.

In addition to isolation, the control of natural lighting and solar radiation has been the most improved strategy in the last decades. New materials like ETFE, provided high light and UV transmission levels and self cleaning properties, which favor the reduction of electric energy demand. But the most important developments have been reached at the shading strategies and the control of solar gains in the building.

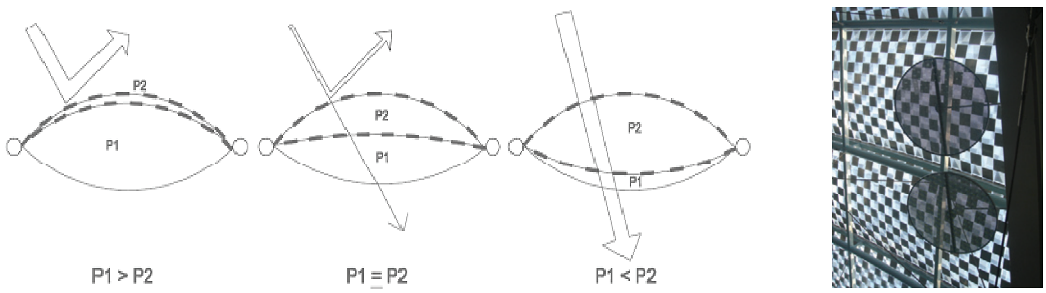

Fig. 4. (a) active shading strategies. Source: Own elaboration; (b) active shading inflatable envelope in Esslingen, by Form-TL. Source: Own photo

These strategies can be organized in two main groups: Passive and active shading. The first are based in the use of printed patterns over the transparent membrane, either with superficial patterns or with the combination of large opaque and transparent surfaces, defined with the help of sunlight masks. In other way, active systems are based on positive and negative patterns over different layers, whose separation varies in function of the inner pressure levels and the radiation values that are necessary on each moment.

In relation with ventilation strategies, the studied proposals maintain constructive schemes of glass roofs or facades, using windows or movable cushions, in order to favored natural ventilation strategies. These designs, which use membrane systems as it they were rigid materials, show that it is still necessary the improvement of new integration strategies according to the flexibility properties of inflatable cushions.

Respect to solar energy strategies, the improvement of thin-film photovoltaic technologies (TFPV) has opened an important research line. However, no significant built proposals have been found in this study, with the exception of the Solar Next prototypes in Rimsting, Germany. Also, thermal energy integration is already more developed with the solar inflate concentrators, although they are used at large scale projects.

4. Critical review

The paper summarizes the most relevant trends, according to the study of a large quantity of international proposals, mainly in the last decade, which have been analyzed through a broad range of qualitative parameters. In this way, inflatable proposals quantity has increased considerably, mainly related to roof covering and less to façade systems. The improvement of membrane materials and the influence of some media-mass projects have also helped to this development. The higher durability favors the application on permanent buildings and the incipient integration in retrofitting processes, taking also advantage of the lightness and easy maintenance of this technology. Energetic retrofitting represents one of the most interesting areas of improvement.

New energetic applications have been developed in the last years, although their integration should be more researched. New TFPV technologies suppose an important development opportunity. On the other way, solar inflate concentrators are more improved, but the adaptation to smaller scales is yet unusual.

The use of kinetic or adaptive inflatable systems, which are low developed, can help to optimize the membrane flexibility and morphological properties. The inflatable envelopes can be adapted to different climatic situations, but more accurate research should be made in order to improve their efficiency.

The design of many buildings conserves substructure patterns typical of scaled glass constructions. In this sense, new morphological inflatable modules can be improved, in order to take advantage of structural membrane behavior and to diminish the envelopes weight. Also, the improvement of adaptive climatic strategies, should be made in countries with extreme conditions and hot summer. The possibility of lighting and solar control radiation, allows the use of these technology in different climatic zones, taking advantage from the conditions of each region. Also, the design of natural ventilation systems, integrated in the membrane morphology, will help to improve the efficiency of the envelope.

In this sense, a new research line is being currently developed, in order to improve sustainable strategies of low pressure inflatable envelopes, focused on energetic retrofitting in Cs climate zones.

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