AN OUTLINE OF THE EVOLUTION OF PNEUMATIC STRUCTURES

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ABSTRACT

This paper presents the preliminary results of a research on pneumatic structures under development at the Faculty of Architecture and Urban Planning and the Polytechnic School of the University of São Paulo. It describes the evolution of pneumatic structures –the tension structures *par excellence*–, relating their historical context with their structural performance and technological characteristics. The work is based upon a selection of relevant manifestations of this type of structures, from its origin until today, and tries to recognize the general lines through which their evolution occurred. It is presumed that this analysis can bring further understanding to the present moment, when the architecture of tension structures has attained remarkable maturity, with the introduction of high technologies in the field of design, constructive techniques and materials, besides accumulation of knowledge due to decades of experimentation and of technological, formal and operational research.

Keywords: *pneumatic structures; inflatable structures; tension structures; membranes; historical evolution; technological characteristics.*

1. INTRODUCTION

This paper seeks to recognize the general lines along which the pneumatic structures evolved, emphasizing their proliferation during the 1960's and 1970's and analyzing the reasons that led to their apogee at those times. Also based on this analysis, the work sets forth a hypothesis on the reasons that lead to the revival nowadays experienced by pneumatics.

Practical applications of pneumatic structures are quite recent and can be traced back to the period spanning from the beginning of the 20th century to the Great World Wars. From then on, pneumatics have always fascinated the public with unusual shapes and concepts. Indeed, although tension structures (which include pneumatics) constitute probably the oldest and most spontaneous structural system, their modern configuration is a recent phenomenon, since relevant manifestations require sophisticated materials, building techniques and theories, such as the case of synthetic films, high strength cables and the nonlinear computations employed in their design.

2. PRIMORDIUMS

The first experiments with pneumatic structures were undertaken during the development of hot air balloons. Brazilian priest Bartolomeu de Gusmão, in Lisbon, conducted a pioneering experiment as soon as 1709. However, an effective start for the development of balloons just occurred at the end of the 18th century, when the Montgolfier brothers built an 11m diameter hot-air balloon, made by linen and paper. At the same year, Jaques A. C. Charles built the first hydrogen balloon (Figure 1b), whose apogee were the *zepellins,* the large rigid dirigibles of the end of 19th century and beginning of the 20th century (Herzog, 1977; Forster, 1994).

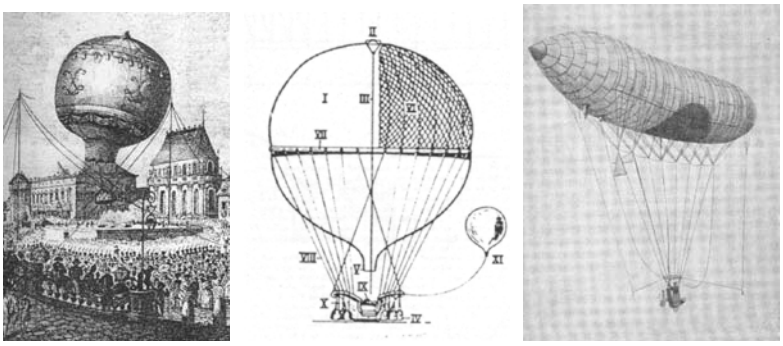

Figure 1: (a) Montgolfier Brothers' hot air balloon (1783) (Herzog, 1977)
(b) Jacques Charles hydrogen balloon (1783) (Herzog, 1977)
(c) Santos-Dumont No 1 Dirigible (1898). (Santos-Dumont, 1904)

The Brazilian Alberto Santos-Dumont, before achieving, in 1906, the first effectively controlled flight in a vehicle heavier than air – a feat sometimes attributed to the French Clement Ader (1890) or to the American Wright brothers (1903) –, pioneered also the construction of dirigible balloons (Figure 1c). In 1901, Santos-Dumont won the Deutsch Prize, offered by the Aero Club of Paris to the first person to round the Eiffel Tower, without touching the ground, departing and returning to the Saint-Cloud Station, in a maximum time of half an hour. In Santos-Dumont (1904) an elegant first person account on the contributions of this eminent Brazilian to the technology of dirigibles is found.

The idea of transposing the dirigibles technology to architecture tracks back to the English engineer F. W. Lanchester. His patent of a pneumatic system for campaign hospitals (Figure 2) was approved in England, in 1918, but was never actually constructed, due to the lack of adequate membrane materials or appeal to possible clients.

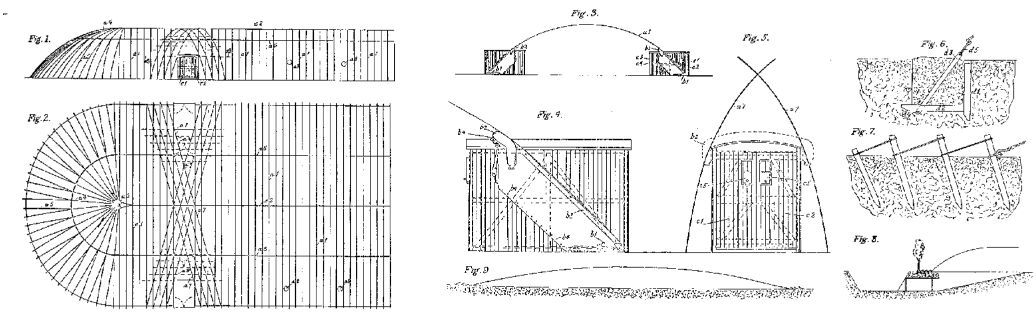

Figure 2: Details of Lanchester's patent for insuflated tents (1918) (Herzog, 1977).

3. THE WORLD WAR II AND THE U.S. ARMY

During the Word War II, and after the invention of *nylon*, pneumatics started to be used in military operations, as emergency shelters and decoys (Figure 3). At the end of the War, the increase in the number of military air operations demanded implementation of a large and sophisticated network of radars over the American territory. In order to protect these radars from extreme weather conditions, such as in Alaska, the American Army sponsored a group of researchers at the *Cornel Aeronautical Lab*, led by Walter Bird, to develop thin non-metallic shelters, avoiding interference with the radar signals (Topham, 2002). In 1948, Bird and his team achieved the construction of a 15m diameter pneumatic dome, the prototype for a series of large “*radomes*” (as they have been called) built by *Birdair Structures* (Figure 4). This company, established by Walter Bird, also pioneered, during the 1960’s, the commercial application of pneumatics, as covers for warehouses, swimming pools, sport facilities and factories. Other similar companies soon appeared in Europe and Japan.

Figure 3: Rubber inflatable tank and truck used as decoys by British Army during Word War II (Topham, 2002).

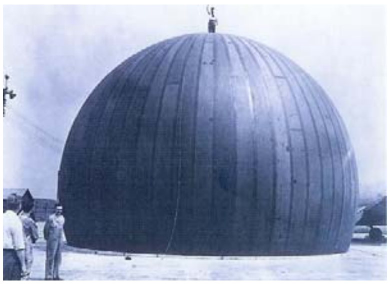

Figure 4 - The first *radome* prototype (1948). Walter Bird stands on top (Topham, 2002)

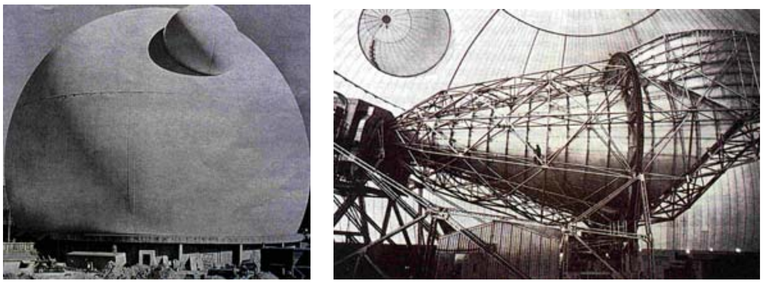

Figure 5 - *Radome* in Maine, USA (1961) (Forster, 1994).

4. THE BEGINNING OF THE ACADEMIC RESEARCH

If engineers like Bird and Stromeyer were the pioneers on the commercial applications of the pneumatics and acquisition of empirical knowledge, it was Frei Otto the first to undertake academic investigations, specially about the process of form finding. Through the *IASS Pneumatic Colloquium* (University of Stuttgart, 1967) and several publications and designs, Otto broadened the landscape, not only of pneumatics, but of tension structures in general. Pneumatics were also part of the repertoire of Richard Buckminster Fuller. His proposal of a pneumatic dome to cover New York (1962, Figure 6) is a famous example of Utopian pneumatic architecture. Realization of this project would require a radical environmental transformation, a sterilized enclosure without dust, pollution, exhaust gases and so.

Figure 6: Proposal of a pneumatic dome for the New York city. B. Fuller, 1962 (Herzog, 1977).

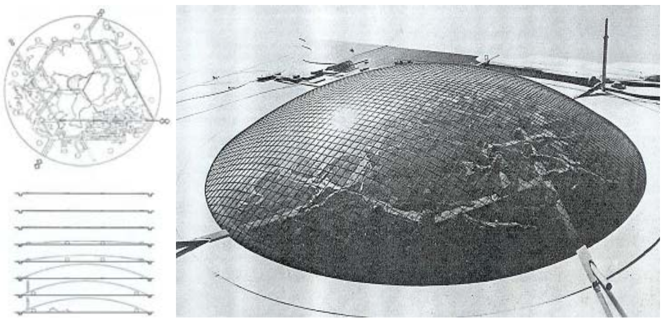

Figure 7: *The Artic City* of Frei Otto and Ewald Bubner, 1970. Plan, insuflating process and model (Herzog, 1977)

5. GROUP *UTOPIE* AND THE *STRUCTURES GONFLABLES* EXHIBITION

During the 1960's, a new generation of architects debuted, which disagreed with the principles of Le Corbusier modernist architecture. Radical architecture groups emerged all over Europe in reaction to the monotony of the modernist buildings. Many of these collectives embraced inflatable forms as the perfect tool with which to subvert traditional notions of architecture (Topham, 2002). At the end of the 60's, the Paris group *Utopie*, that included the architecture students Jean Aubert, Jean-Paul Jungmann and Antoine Stinco, and the sociologist Jean Baudrillard, among others, formulated acerb critics about the architecture, the urbanism and the daily life of the French society. They also reinterpreted the aesthetic of pneumatic structures, using them as form of social expression, related to buoyancy, ephemerality and mobility, in contrast to the inertia of the postwar European society (Dessauce, 1999).

The *Utopie* group was strongly inspired by Buckminster Fuller, by the technological research of the US Army, and by the American comic books, from which they adopted a pop and futurist visual. It was also influenced by the *Archigram Manifesto* (Figure 8), published in England, in 1961: "a chaotic mishmash of collage, comic strips, and playful typography, all united by the group's exceptionally specific drawings, elevations, and plans… the content championed similar sensibilities to those of Pop Art: 'Popular (designed for a mass audience), transient (short-term solution), expendable (easily forgotten), low-cost, mass produced, young (aimed at youth), witty, sexy, gimmicky, glamorous, big business' as declared by Richard Hamilton of the *Independent Group* in 1957" (Tophan, 2002).

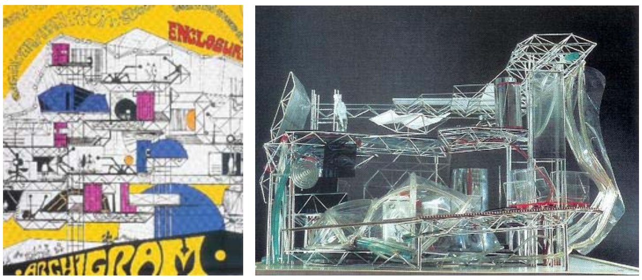

Figure 8: *Control and Choice*, *Archigram*, 1967.
House for future (Topham, 2002)

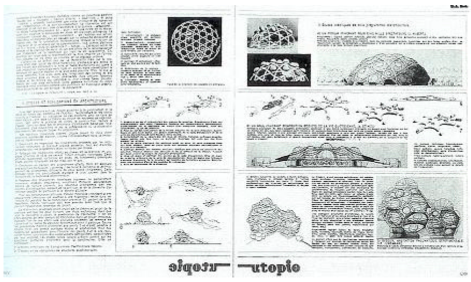

Figure 9: *Utopie* publication, 1967
(Dessauce, 1999)

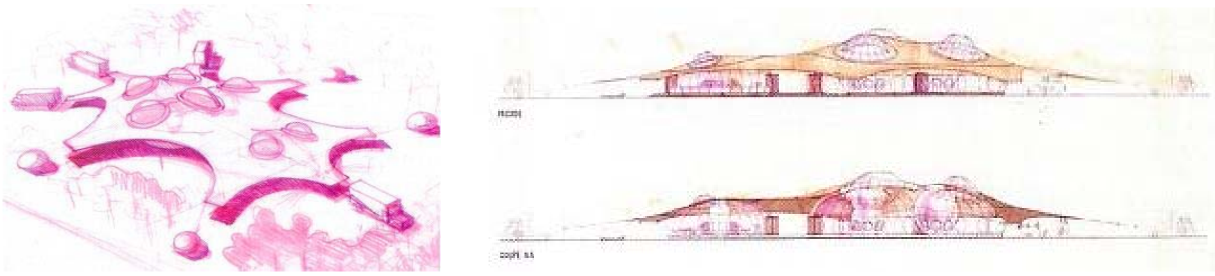

Figure 10: *Itinerant Exhibition Hall for Objects of Everyday Life.* Antoine Stico, 1967 (Topham, 2002)

Following the principles of the *Utopie* Magazine (1967, Figure 9), in which the formalist urbanism was criticized, in 1968 occurred the exhibition *Structures Gonfables* at the *Musée d´Art Moderne de la Ville* of Paris, which raised a large interest in architects and designers from Europe, Unites States and Japan. One of the main works in exhibition, the *Dyodon* (Figure 11), showed Jungmann aesthetic investigations on pneumatic forms, specially inflated ones, presenting a rich diversity of patterning and structuring of the membranes. Even though an economical design could not be achieved, the architect’s formal intentions were considered satisfactory (Herzog, 1977).

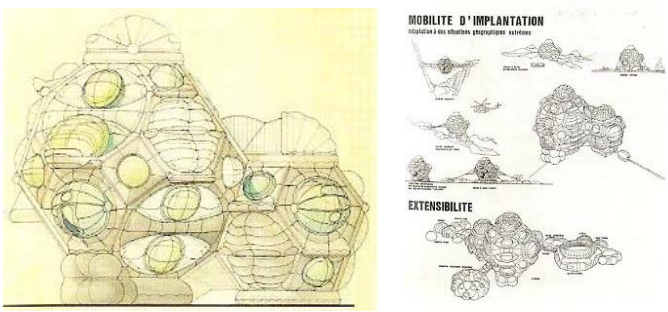

Figure 11: *Dyodon – Habitation Pneumatique Experimentale*, Paul Jungmann, 1967 (Topham, 2002).

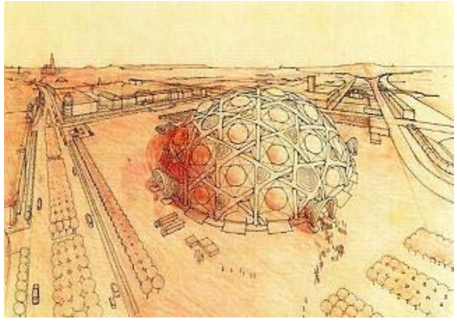

Figure 12: *A Traveling Theater for 5000 Spectators*. Jean Auber, 1967 (Topham, 2002).

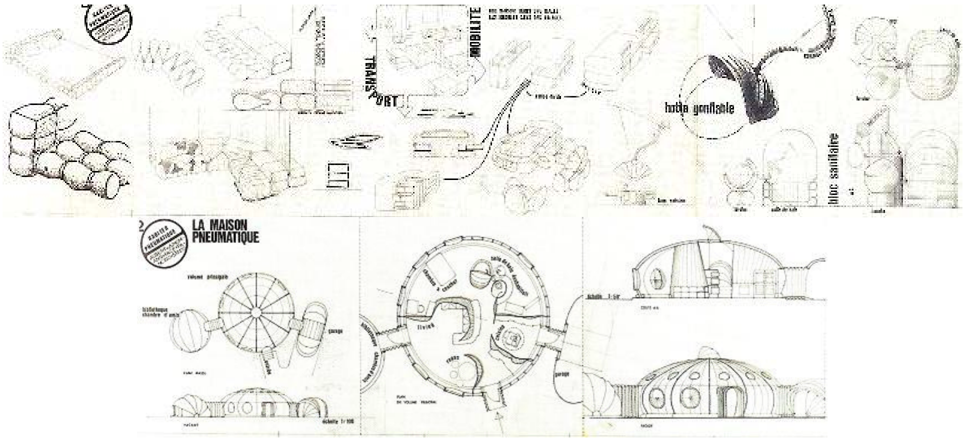

Figure 13: *Habiter Pneumatique*, Jean Auber and Paul Jungmann, 1967 (Topham, 2002).

6. EXPO’70, OSAKA

The inherent portability of pneumatic structures soon inspired their use in temporary and itinerant exhibitions. A paradigmatic example was given by the *Atoms for Peace Pavilion* (Figure 14), designed by Victor Lundy and constructed by *Birdair*. The pavilion hosted an exhibition of the US Atomic Energy Commission, traveling through Central and South America in (1960).

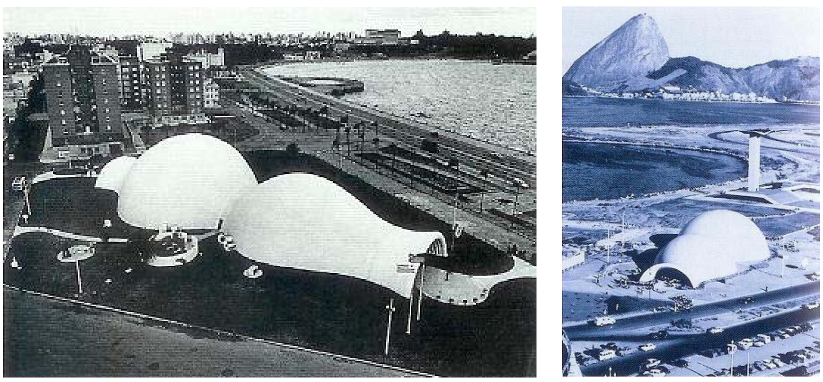

Figure 14: *Atoms for Peace Pavilion* (Topham, 2002)

The use of pneumatic structures in exhibitions reached a peak the EXPO’70 in Osaka, when they have been widely adopted due to the poor quality of the soil and high seismicity of the region. Among many pneumatic structures at EXPO’70, two are especially relevant: the *Fuji* and the *American Pavilions* (Figures 15 and 16). The first, designed by architect Yutaka Murata and engineered by Mamoru Kawaguchi, awed the public with its unusual form, composed by 16 inflated arches. The second, designed by Davis Brody, David Geiger and Walter Bird, introduced a low aerodynamic profile dome with oval plan (142m long and 83m wide, but only 6,1m of sag), funicular to the loads of the reinforcement cables. According to Herzog (1977), the repercussion of the structure was not due solely to its size, but also due to its discreet and sophisticated design.

Figure 15: *Fuji Pavilion*, 1970, Osaka (Dessauce, 1999; Topham, 2002; Herzog, 1977)

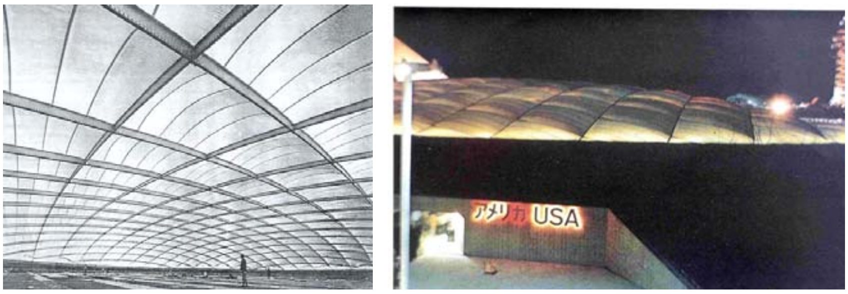

Figure 16: *American Pavilion*, 1970, Osaka, Japão (Herzog, 1977; Forster, 1994).

Another interesting example was provided by the *Floating Theater* (Figure 17), which was realized by the same team of the Fuji Pavilion. The structure was composed by three inflated tubes highly pressurized, connected by a single layer membrane, and the inner space was kept under a negative pressure, providing a rare case of aspirated pneumatic structure (Herzog, 1977).

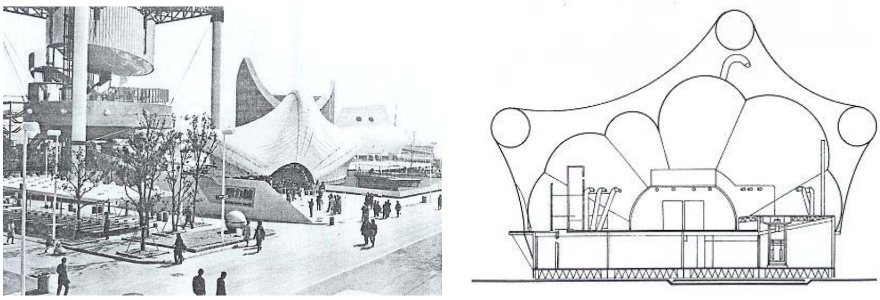

Figure 17: *Floating Theater*, 1970, Osaka, Japan (Herzog, 1977)

LARGE SPAN ROOFS

Inspired by the success of the EXPO' 70 American pavilion, David Geiger developed several projects employing cable reinforced, insuflated membranes, for sport stadiums in the United States and Canada, from 1974 to 1984. The largest of these stadiums are the *Pontiac Silverdome*, in Michigan (1975), the Vancouver Amphitheater (1983) and the Minneapolis *Metrodome* (1982), all of them covering more than 40.000m^2, with capacities above 60.000 persons. (Foster, 1994). These roofs drastically reduced the cost per seat, compared with conventional stadium, and have worked satisfactorily, except for some operational problems, leading do deflations, in the *Minnesota Metrodome*, due to excessive accumulation of snow (Liddel, 1994). It can be appointed as a paradox, that the main factor driving to construction of closed environments – harsh winter– is also the foulest enemy of the large pneumatic domes. Later domes such as the *Tokyo "Big-Egg" Dome* (1988, Figure 18) and the *Akita Sky Metrodome*, designed and built by *Kajima Corporation* (1990) avoided problems with snow using larger internal pressures, smaller distance between cables and higher profiles (Foster, 1994).

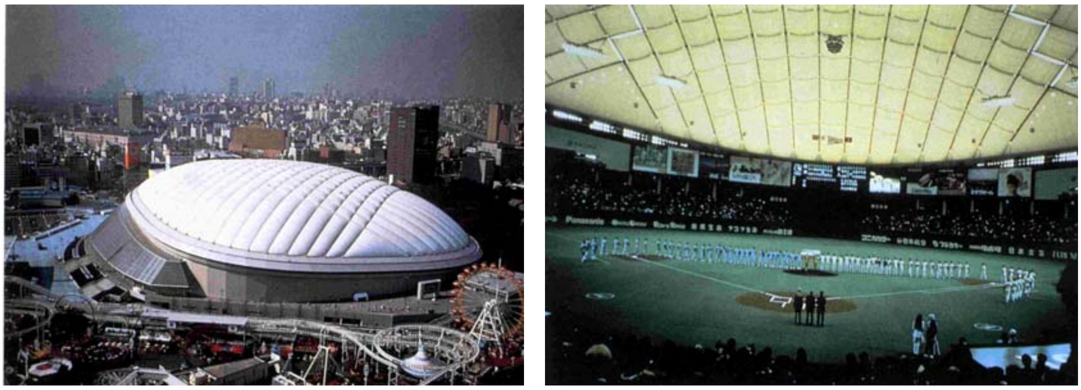

Figure 18: Tokyo Big-Egg Dome (1988) (Forster, 1994)

Another option to cover large spans are the pneumatic lenses, such as the roofs of Nîmes Roman Arena and the Expo'92 *German Pavilion*, in Seville (Figure 19). Inflated lenses have usually lower operational costs respect to insuflated domes, although production costs can be higher. Anchorages are also lighter, since the lenses do not tend to ascend due to internal pressure. The roof of the Nîmes Arena is an eloquent example of the applicability of pneumatics, since the Arena is a historic monument, forbidding any modification in its structure.

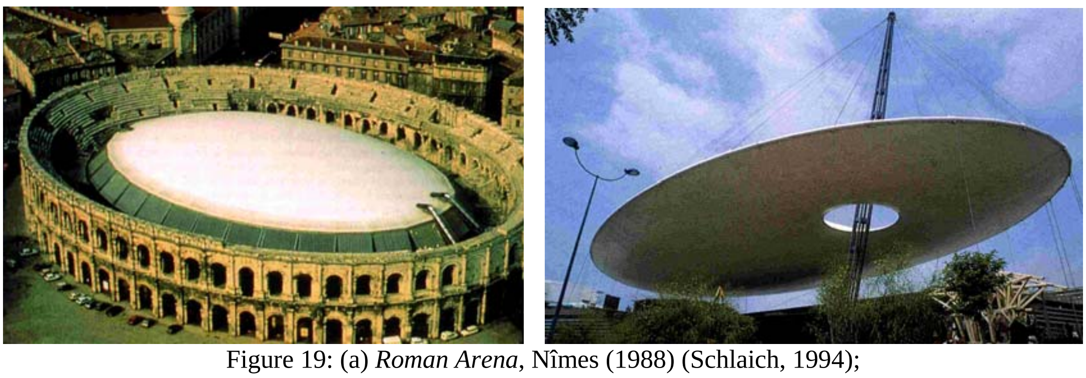

Figure 19: (a) *Roman Arena*, Nîmes (1988) (Schlaich, 1994);
(b) *German Pavilion*, Expo'92, Seville (Forster, 1994).

DESIGN AND ARTISTIC INSTALATIONS

Pneumatics are frequently chosen in smaller and less permanent buildings –for aesthetic, more than for economical reasons– since their sights usually provoke fascination among observers and bystanders, reporting to something futuristic and revolutionary.

Figure 20: *Dreamspace IV*, Maurice Agis, 1998 (Agis, ___)

The pneumatics aesthetic, which was formulated during the sixties, according to the values of the pop movement –curvilinear shapes, strong colors, bright textures and ephemerality- is being retaken nowadays, conferring to the new installations a retro-futurism atmosphere.

The pneumatics return is even more impressive in the field of object design, that are less constrained in the exploration of new shapes, specially with the aid of the modern computerized design tools, and the availability of high tech materials. Eloquent examples are given by the itinerant, colorful and organic pavilions of Maurice Agis (Figure 20), or the *Architects of Air* (Figure 21) and *Buildair* offices (Figure 22).

Figure 21: *Archipelago*, Alan Parkinson, *Architects of Air* (Topham, 2002)

It should be pointed out, however, that pneumatics (as well as other flexible structural systems), are actually quite rigid from a formal and functional point of view, since their shapes have necessarily to adapt to force equilibrium (in other words, they have to conform to funicular shapes). On the other hand, stiff structures, like beams and shells, enjoy more formal flexibility, since, in principle, they can sustain any kind of shape.

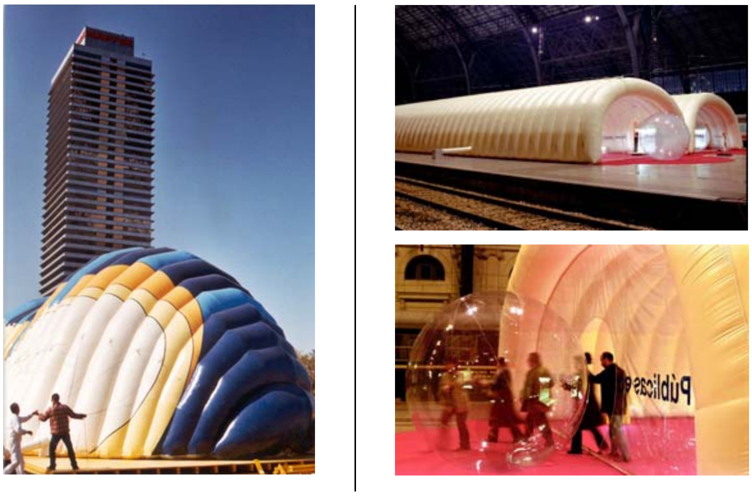

Figure 22: Pavilions for (a) The Gaudí Institute (2002);
(b-c) *Las Obras Públicas en Cataluña* exhibition (2000) (Buildair, ___)

SOME FINAL REAMARKS

The large span, permanent insuflated domes that had their apogee during the eighties became unusual afterwards, having their efficiency questioned due to the high maintenance costs associate to them. According to Shaeffer (1994) and Happold (1994), the future of these pneumatic giants is not very promising, and they are presently loosing competition to other structural systems like the cable domes (for example, the Atlanta *Georgia Dome* or the London *Millennium Dome*).

However, in some recent large buildings, pneumatics have shown good performace as complementary elements to other stiff structural systems. This is the case of two projects of Nicholas Grimshaw: the *Eden Project* (Figure 23), located in Cornwall, and the *National Space Center* (Figure 24), in Leicester, both in England. Moreover, already remarked, pneumatics are blossoming out in fields like object design and small scale buildings, with a more promising scenario to the inflated structures, compared to the insuflated ones.

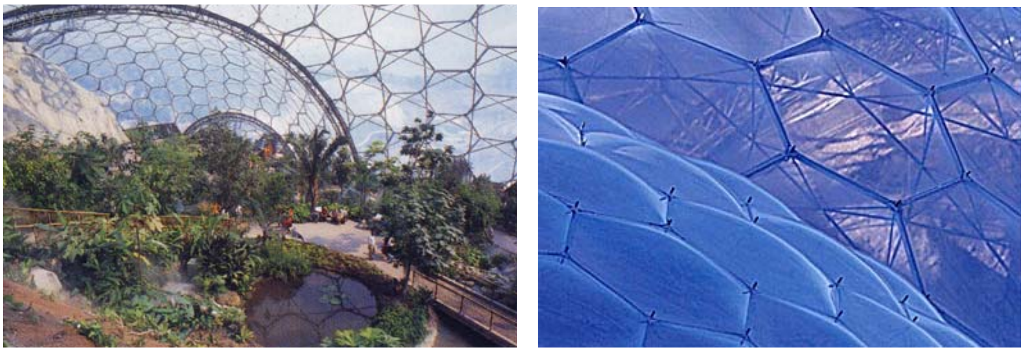

Figure 23: *Eden Project*, Cornwall, Inglaterra (Grimshaw, 2004)

In Brazil, relevant manifestations of pneumatic structures are not very frequent. The recent insuflated pavilion *A Energia de um Sonho*, designed by *Noosfera Projetos Especiais* for Petrobras is shown in Figure 25a. An interesting pneumatic toy, designed and produced by the authors of this paper, is shown in Figure 26.

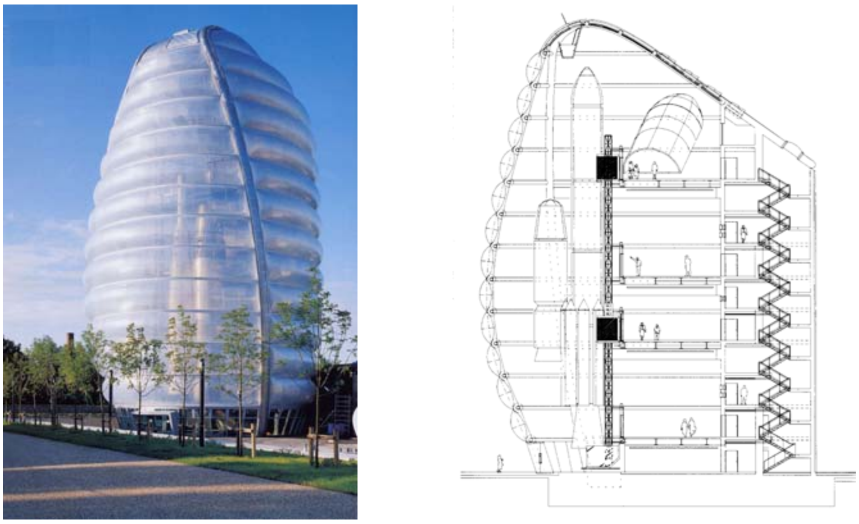

Figure 24: Edifício do *National Space Center*, Leicester (Grimshaw, 2004)

The local market situation discourages expensive studies about thermal, lightning and structural performances, or design methods. Information is not readily available, and normative regulations do not exist at all. However, enthusiasm of the Brazilian public with the few pneumatic buildings constructed so far suggest that there are plenty of opportunities to the growth of a new market.

Figure 25: (a) *A Energia de um Sonho Pavilion* (2003);
(b) Temporary amphitheater for Petrobras (2003) (Figuerola, 2004)

Figure 26: 'The Dodecoid', an inflated double skin dodecahedron (Pauletti, 2004)

ACKNOWLEDGMENT

The authors wish to acknowledge a fellowship granted by *FAPESP – Fundação de Amparo à Pesquisa do Estado de São Paulo*, to the development of the research presented in this paper.

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