ROOF STRUCTURES IN MOTION – ON RETRACTABLE AND DEPLOYABLE ROOF STRUCTURES ENABLING QUICK CONSTRUCTION OR ADAPTION TO EXTERNAL EXCITATIONS

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This paper focuses on roof structures that are movable either for enabling quick and/or safe construction or in order to adapt the structure to external excitations. Roof designs coming from both motives will be discussed in this article. After a short review on historical background an extensive overview will be given on different types of transformable roof structures. Namely retractable roofs with rigidly moving parts, retractable/deployable pantograph structures, the pantadome erection, deployable tensegrity structures, retractable/deployable membrane structures, pneumatic structures and constructional methods of concrete shell structures will be shortly presented. In case of need for a more profound understanding of the different types of transformable systems an extensive reference is given.

Keywords: deployable roof structures, retractable roof structures, pantograph structures, scissor-like structures, adaptive structures, responsive architecture, tensile structures, tensegrity, pneumatic formwork.

1. INTRODUCTION

The history of transformable roof structures goes back to centuries before. Though possibly everybody is familiar with the light deployable nomad Indian tepees (*Fig. 1a*) that could be transported by animals, only very few know that a part of the auditorium of the Roman Colosseum (Amfiteatro Flavio) (*Fig. 1b-c*) built in the first century had a convertible textile roof (Ishii, 2000). The structure of the umbrella is an ancient structure as well, but its principle is used in modern adaptive architecture.

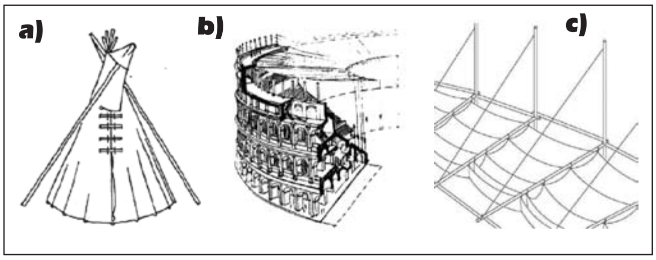

Fig. 1: Early movable roof constructions: a) Tepee tent from the Sioux Indians (Otto et al, 1971; cited by Walter, 2006); b) Roman Colosseum (Escrig and Brebbia, 1996) and c) the reconstruction of its convertible roofing system (Gengnagel, 2001; cited by Walter, 2006)

Evidently higher scale transformable roof structures appeared only in the last century. With the growing demand of hosting sport venues, starting from the 1930s an increasing trend toward building retractable roofs can be observed. As cranes were already common at that time and standards were available for transport tracks, control and drive, the first constructions stem from the principles of crane technology (Ishii, 2000). Thus early designs mainly run on rails. The first retractable big span roof is said to be the Pittsburgh Civic Arena (*Fig. 4*) that was opened in 1961.

After the World War II — parallel to the appearing of retractable roofs opened with rigid body movements — significant pioneer works have to mentioned regarding deployable/ratractable lightweight structures. B. Fuller's reinvention of the geodesic dome (*Fig. 2a*) and his lectures on 3D geometrical forms for architecture, space frames and structural efficiency (Fuller and Applewhite, 1975) inspired several researchers to further elaborate his ideas. The invention of the tensegrity system by K. Snelson (Snelson, 2009) and B. Fuller in 1949 is still the main topic of several ongoing research work that try to widen the application possibilities of these systems and to adapt them to deployable structures (Motro et al, 2001). Furthermore the works of F. Otto in the field of tensile and membrane structures (Otto, 1973) and his systematic research work on deployable and retractable structures (Otto et al, 1971) in the 1960s led to a big variety of retractable membrane roof structure designs in the second half of the century (e.g. retractable roofs of Montreal Olympic Stadium, bullfighting ring in Zaragoza). Membrane structures can be combined with scissor-like deployable structures. E. P. Pinero's movable theatre (*Fig. 2b*) presented in 1961 can be mentioned as pioneer work of this type (Pinero, 1961). Though his deployable trellis design had major structural drawbacks, he motivated further pantographic deployable designs like Escrig's deployable swimming pool (Escrig et al, 1996) and Zeigler's pop-up dome (Zeigler, 1976).

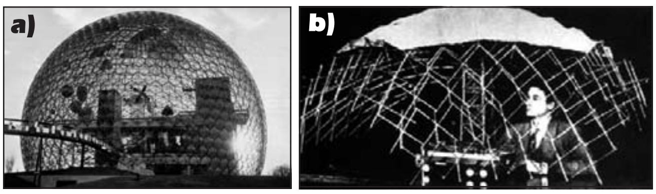

Fig. 2: a) The US Pavilion for the 1967 World's Fair, Montreal by B. Fuller (Hienstorfer, 2007); b) Pinero with his movable theatre (Robbin, 1996)

Transformability can be used not just for lightweight structures. In the last decades promising experiments were made with constructions using transformable systems to combat the main problem of concrete shell structures, namely the expensive, difficult and time-consuming production of them.

In the second half of the 20th century, regarding deployable and inflatable structures developments were in first place achieved in spatial engineering (Pellegrino, 2001; Gantes, 2001) for booms, solar arrays, antennas, reflectors, as the volume and the weight of a structure to be transported there is crucial. Current trends show a re-increasing interest in kinetic architecture due to the growing demand on provisory architecture (Kronenburg, 2008) and the need for sustainable technologies (Kibert, 2007, Friedman et al, 2011). Aiming sustainable architecture there is a remarkable tendency towards adapting seminal ideas of the 60s and 70s (Sadler, 2005; Zuk, 1970) to create an undeterminate architecture that can conform to uncertainty and emergent situations, changing in occupant demand and energetic considerations (Fox and Yeh; Rosenberg, 2010).

As it has been shown above, involving motion systems to structural design is not a novel idea. Nevertheless it seems to be a currently improving segment of civil engineering thanks to the available technologies that are just catching up with these ideas of the 1960s and 70s. More precisely the recent research actuality of transformable structures is due to the continuously improving computer, robotic and nanotechnologies, the ameliorated numerical methods (Ibrahimbegovic, 2009) and the progressive properties of novel and conventional building materials. Though the main research topic of the authors within this theme is just a small slice of the mentioned topics (namely the engineering application and dynamic analysis of snap-through type deployable lattice structures), for the recently started research work an extensive study was carried out to explore earlier and current researches and technologies to approve the actual interest in developing these systems. Herein the reader can see a generalized and shortened version of this demonstrative study, which reflects well that transformable architecture has not just a past but may also have a future.

This article tries to give a general overview on transformable roof structures built from both motivations: 1.: enabling a quick/safe construction and 2.: providing an adaptive design. The most commonly used systems for roofing sport venues, namely the ones that can be opened by *rigidly moving panels* (*2nd chapter*) is presented first. Scissor-like structures or *pantograph structures* are also presented in this article (*3rd chapter*). These structures are preliminary used for smaller span provisory buildings, however they can be applied for a specific structural system enabling a quick and safe construction for large span domes (pantadome erection), as well as for retractable roof structures. Afterwards a different deployable lattice system will be presented, namely the deployable *tensegrity structures* (*4th chapter*) that are still rather in an experimental phase. The *deployable and pneumatic membrane structures* are explained in the *5th chapter*. Pneumatic systems can be used for the erection of *double curved and irregular curved concrete shells*. Construction methods of concrete shells using transformational systems will be discussed in a separate chapter (*6th chapter*).

2. RETRACTABILITY WITH RIGID BODY MOVEMENT

As mentioned in the introduction, first designs for retractable covering of sport stadiums stem from the crane technology. F. Otto classified these convertible roofs by a movement matrix (*Fig. 3*).

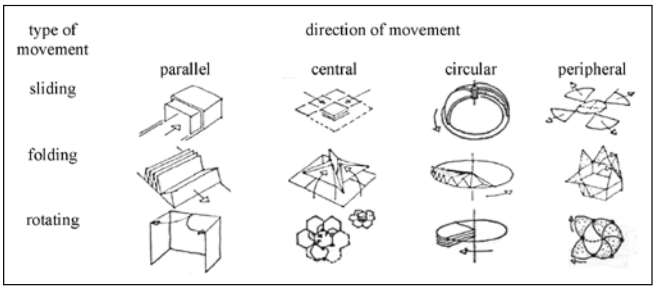

Fig. 3: Classification of rigid retractable constructions: the movement matrix (Otto et al, 1971)

Fig. 3 shows that the retraction can be obtained by sliding, folding or rotating the panels in different directions. The panels can overlap while retracting or move independently. The first retractable dome structure is said to be the circularly sliding retractable roof of the Pittsburgh Civic Arena (*Fig. 4*) opened in 1961 and closed in 2010 summer. The 127 m span roof consists of eight, 300 ton sections, six of which are able to rotate by five motors per panel. All panels are fixed on the top to a gigantic, 80 m tall steel truss cantilever. The roof could be opened in about two minutes (Ishii, 2000).

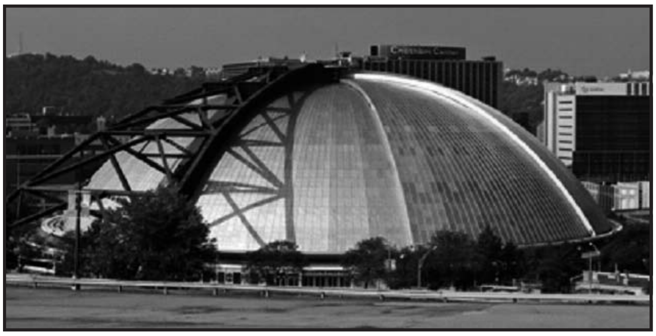

Fig. 4: Photo of the Pittsburgh Civic Arena (architect: Mitchell and Ritchey) (Lorentz, 2008)

The structural form of the civic arena is initially optimal as bending moments are minimal due to geometry. Unfortunately for retractability this optimal shape had to be sliced in parts, thus the cost was the huge cantilever that supports the panels, and the bigger structural height. A similar geometry was achieved by a more recent construction that did not apply an external structure to hold the panels. The Fukuoka stadium in Japan (*Fig. 5.*) opened in 1993 spans 222 m. The three parts of the roof — two of which is rotatable — are independent frameworks, with remarkable bending moments. Though careful shape correction was performed for the geometry of individual parts (*Fig. 6a*) to avoid singularities in reaction forces at the inclination lines (Ishii, 2000), the structural height is still gigantic. Each panel is four meters thick, and the total roof weighs 12 000 tons. The sliding rotation of the two panels is enabled by 24 bogie wheel assemblies (*Fig. 6b*). It takes approximately 20 minutes to open the roof.

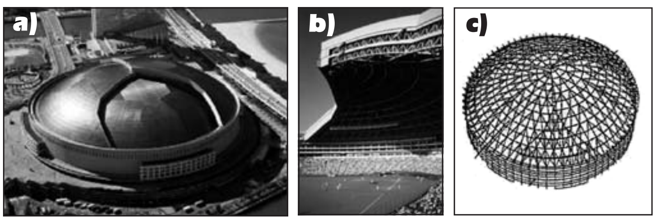

Fig. 5: Fukuoka stadium (architect: Takenaka Corp.) a) photo with closed (Yahoo, 2010) and b) with opened roof (Japan Atlas) c) structure (Ishii, 2000)

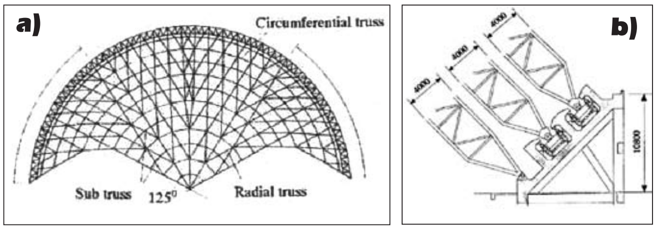

Fig. 6: Fukuoka stadium a.) geometry of a roof panel b.) roadbed section (Ishii, 2000)

Much more slender retractable structure was constructed in Oita, Japan, in 2001 called the Oita Stadium or more commonly the "Big Eye" (*Fig. 7*). A large part of the 274 m diameter spherical roof is fix *(Fig. 8b)*, only the top two panels are retractable, that slide parallel on seven rails to the periphery of the dome. The sliding panels are covered with a special membrane containing a Teflon film that provides better transparency, thus even on rainy days natural lighting is provided. (Ishii, 2000)

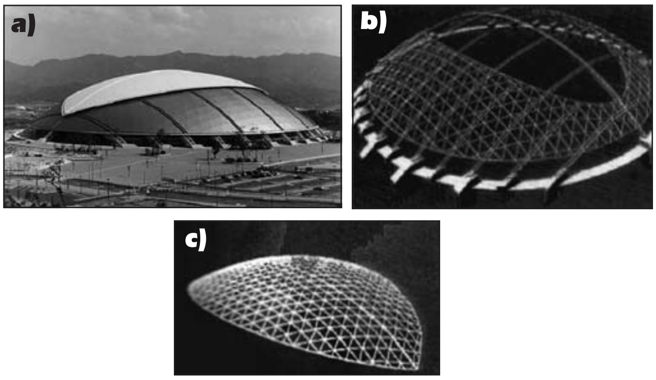

Fig. 7: Oita Stadium (architect: Kisho Kurokawa) a) photo (Ezinemark, 2010); b) fix structural part (Ishii, 2000) and c) retractable top section (Ishii, 2000)

To mention other motion systems for rigid retractable construction just briefly three different examples are shown. A parallel overlapping system was used for the 40 m span retractable roof of the Komjádi swimming pool in Budapest, built in 1976. A more complex system of rigid systems is the roof of the Qi Zhong stadium in Shanghai that opened in 2005. Resembling a flower opening its petals the eight panels rotate towards the perimeter in 8 minutes. Of course not every retractable roof can be clearly classified by the categories of the motions matrix shown in *Fig. 3*. For example the roof of the Toronto Skydome (*Fig. 9*) is a nice example of a mixed system. The 213 m diameter roof is made up of 4 sections, one remains stationary while the two panels slide parallel and one circularly to achieve a high rate of retractability.

Fig. 8: a) Retractable roof of the Komjádi swimming pool (Komjádi); b) Qi Zhong stadium (architect: Mitsuru Senda), (Ezinemark, 2010)

More and more recent architectural designs try to apply transformable systems only for achieving the variability of a shell or an envelope of the permanent structure. Though the motion of the building might not be as spellbound as the ones where whole massive structural parts are in motion, but can offer a nice solution for integrating structural efficiency and

Fig. 9: Toronto Skydome (architect: Rod Robbie) a) photo of closed and b) opened roof c) The structure (Ishii, 2000)

the adaption to external excitation. This was the case with the adaptive sun shading system of the Audencia Provincial, Madrid (*Fig. 10*) designed by Hoberman. The hexagonal shading cells can completely cover the roof, but disappears when retracted into the structural profiles of the structure. The algorithm that controls the movement combines historic solar gain data with real-time sensing of light levels (Hoberman, 2010). Hoberman designed several adaptive shading systems in accordance to his new patented technology (Hoberman and Davis, 2009) to enhance the architectural design of Foster + Partner's buildings.

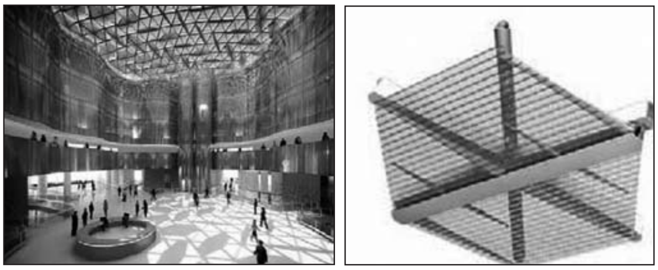

Fig. 10: Adaptive shading system of the Audencia Provincial, Madrid (Hoberman and Fox+Partners) and the model of a hexagonal retractable panel (Hoberman, 2010)

3. PANTOGRAPH STRUCTURES

A large number of structures that can be opened and closed are based on the well known concept of the lazy tong system. The minimum component of this system is the so called scissor like element (furthermore SLE). The SLE consists of two bars connected to each other with a revolute joint. By the parallel connection of SLEs the simplest 2D deployable structure, the lazy tong is constructed. Connecting at least three of SLEs through complete pin joints a ring is formed, providing a secondary unit of this frame structure (*Fig 11a-d*). By the further connection of secondary units almost all kind of 3D-shapes can be formed folding into bundle. Adding tension components like wire or membrane to its developed form, it becomes 3D-truss and gets effective strength, thus towers, bridges, domes and space structures can be rapidly constructed. (Atake, 1995)

3.1 Deployable structures folding into a bundle

Using scissor-like deployable structures for architecture was pioneered by the Spanish engineer, E. P. Pinero. He presented a foldable theatre (*Fig. 2b*) in 1961 (Pinero, 1961), and elaborated several other deployable designs. The biggest drawbacks of his designs were the relatively heavy and big joints due to eccentric connections and necessary temporary support as the structure was stiffened by intermediate bars or tension elements that were added after the structure was deployed in the desired configuration (Gantes, 2010). Despite of all the disadvantages of his structures Pinero inspired several

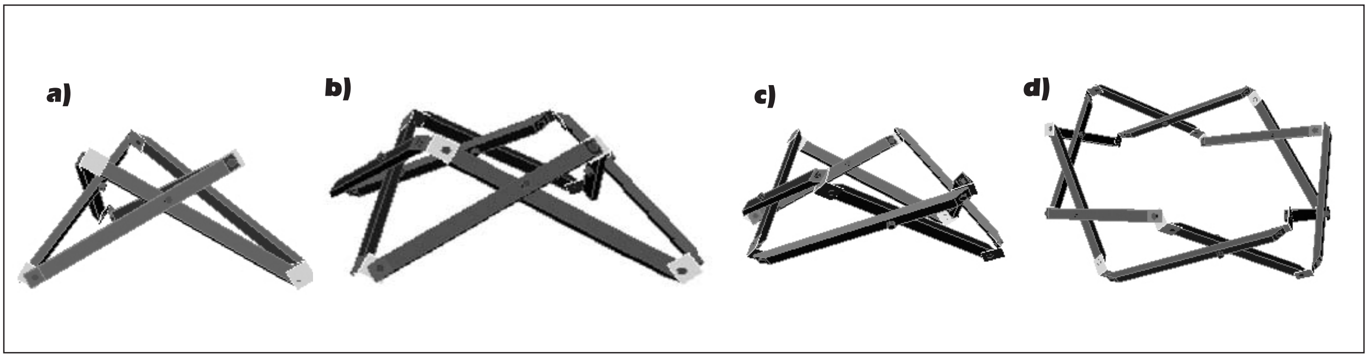

Fig. 11: Some secondary units of scissor like deployable structures (a-d), (Atake, 1995)

researchers. This was the case with Professor F. Escrig, who designed the 30 m×60 m deployable roof for a swimming pool in Seville (Escrig, 1996; *Fig 12).*

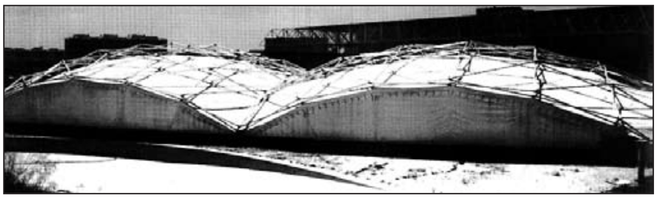

Fig. 12: Deployable swimming pool (architect: Prof. Felix Escrig) (Escrig et al, 1996)

While pantograph structures discussed above need additional stabilizing elements like cables or other locking devices, it is possible to design deployable structures that are self-stable in the erected configuration without any additional member with the application of a special geometric configuration. This can be achieved by adding inner SLEs to the initial secondary units. These inner SLEs deform while unfolding due to geometric incompatibilities thus resulting a self-locking, self-stabilizing mechanism that locks the structure in its opened configuration (Clarke, 1984; Gantes, 2001). The first dome structure of this type was introduced by T. Zeigler in 1974 (Zeigler, 1976; *Fig. 13*). Several pop-up displays and pavilions are constructed in accordance with his patents. About self-stable structures a practical and detailed design guide was published, written by C. J. Gantes (Gantes, 2001), where design examples like airship cover and the adaption of self-locking systems to scaffolding systems are presented.

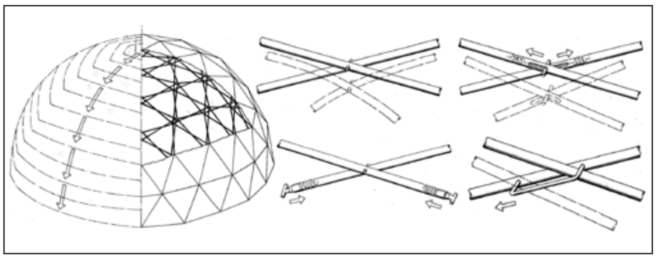

Fig. 13: Zeigler's patent for collapsible self-supporting structure (Zeigler, 1976)

3.2 Retractable pantograph structures

The application of structures that can fold into bundle when continuous transformability needed could be difficult to get. The American engineer, C. Hoberman made a considerable advance in the design of retractable roof structures by the discovery of the simple angulated element (Hoberman, 1990, 1991). By the refraction of the two straight rods of a single SLE the angulated element is formed (*Fig. 14b*). This element is able to open and close while maintaining the end nodes on radial lines that subtend a constant angle (Pellegrino, 2001; Friedman et al, 2011).

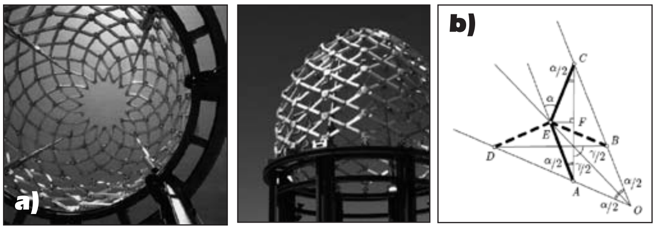

Fig.14: a) Iris dome by Hoberman, EXPO 2000 (Whitehead, 2000); b) angulated element (Jensen, Pellegrino, 2004)

Using angulated elements Hoberman created the retractable roof of the Iris Dome, shown in *Fig. 14a* at the EXPO 2000. Powered by four computer-controlled hydraulic cylinders, the 6,2 m diameter and 10,2 m high retractable dome smoothly retracts toward its parameter and unfolds (Hoberman, 2010). One of the drawbacks of this design is that the structure does not maintain a constant perimeter, thus to connect it to a permanent foundation is quite a challenge especially in case of a bigger scale structure. On the other hand, for the construction of the relatively small span structure required more than 11 400 machined pieces (Whitehead, 2000) which can cause potential problems with reliability and a laborious and expensive manufacturing. Further developments were made by Z. You and S. Pellegrino (You and Pelligrino, 1997) by generalizing these elements to a large family of foldable building blocks and by introducing a new type of pantographic structure based on the so called multi-angulated elements. With multi-angulated elements the number and complexity of elements and joints of retractable trellis structures can be reduced.

P. E. Kassabian succeeded to change the geometry of the structure by rigid body rotation, so that the motion of each angulated element is a pure rotation about a fixed point, and thus allows the application of fixed support points (Kassabian et al, 1999).

An enclosure can be created by covering angulated elements with elastic/folding membrane or rigid plates which are allowed to overlap in the retracted position. Other designs use rigid panel avoiding overlapping of the panels (Jensen and Pellgrino, 2004). Several different designs have been proposed by Hoberman (Hoberman, 1991, 2004). One example is the central part of the responsive dome (*Fig. 15*) that covers a major central courtyard of Abu Dhabi's international airport. The large operable oculus is covered by panels sliding towards the perimeter. The dome's permanent structural part has an envelope that is also transformable varying its permeability. The system performs environmentally both to control light levels and air flows in the space (Hoberman, 2010).

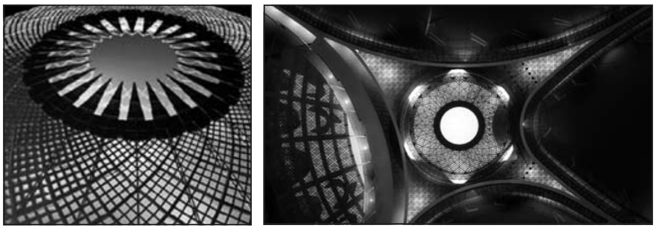

Fig. 15: Development of transformable dome by Hoberman for the dome of Abu Dhabi's international airport, United Arab Emirates, 2006 (Kohn Pedersen Fox Architects) (Hoberman, 2010)

3.3 Pantadome erection

3D spatial structures are extremely efficient ones completed. However the difficulties with installation (big amount of scaffolding, labour and time) often highly decrease this efficiency. This drawback can be significantly reduced with the unique structural system called the Pantadome System invented by M. Kawaguchi and will be herein explained in accordance with (Kawaguchi and Abe, 2002).

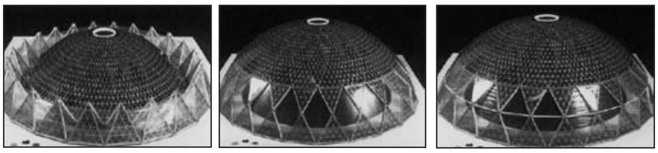

Fig. 16: Schema of the pantadome erection (Kawaguchi and Abe, 2002)

The principle of this structural system is to make a dome or a conical space frame cinematically unstable for a period of construction so that it is "foldable" during its erection. This can be done by temporarily taking out the members lying on a hoop circle (*Fig. 16*) then the dome is given a "mechanism", like a 3-D version of a parallel crank or a "pantograph".

Since such a dome is assembled in a folded shape near the ground level and the entire height of the dome during assembly work is very low compared with that after completion, thus the assembly work can be done safely and economically, and the quality of work can be assured more easily than in conventional erection systems. Not only the structural frame but also the exterior and interior finishings, electricity and mechanical facilities can be fixed and installed at this stage. The dome is then lifted up. Lifting can be achieved either by blowing inside the dome to raise the internal air pressure or by pushing up the periphery of the upper dome by means of hydraulic jacks. The major advantage of this system comparing with different lifting solutions is that no guying cables or bracing elements are necessary for lateral stability. This can be because the mechanism of the system is such that can be controlled with only one freedom of movement in the vertical direction. When the dome has taken the final shape, the hoop members which have been temporarily taken away during the erection are fixed to their proper positions to complete the dome structure. Several designs have been realized in accordance to the pantadome principle. One is the Namihaya Dome with diameter of 127m and 111m, whose erection and its lifting schema can be seen on *Figs. 17* and *18*.

4. TENSEGRITY STRUCTURES

Most of the deployable lattice systems are formed by scissor like structures. However there is a trend to apply also tensegrity systems when deployability needed. This experimental system was born at the end of the 1940s from the artistic exploration of K. Snelson and Fuller's goal of creating maximal efficiency structures (Snelson, 2009). Snelson called his tensegrity sculptures the "floating compression" system. It is worthwhile to mention though that at the same time exactly the same system was patented by D. G. Emmerich, called the "self-tensioning system" (Emmerich, 1964). This spatial truss system's elements can be separated to purely compressed and purely tensile components. With this separation the tensioned members can be as light weight as current material technology allows, resulting extremely light, economical and less visually intrusive structures. Just as the authorship of the invention, the exact definition of tensegrity is still disputed (Motro, 2006). Maybe the first clear definition of this kind of structure is the one that A. Pugh clarified: "A tensegrity system is established when a set of discontinuous compressive components interacts with a set of continuous tensile components to define a stable volume in space" (Pugh, 1976). Clear definition is further investigated and refined by R. Motro (Motro, 2006).

Fig. 17: Erection of Namihaya Dome (Showa Sekkei Corp), Osaka, 1997 (Kawaguchi and Abe, 2002)

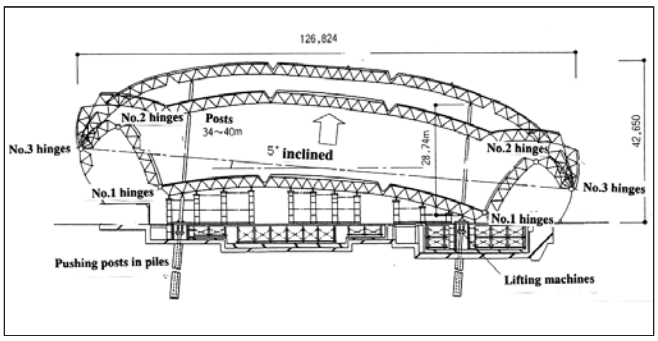

Fig. 18: Erection of Namihaya Dome (Kawaguchi and Abe, 2002)

The simplest tensegrity unit is the tensegrity tripod (Burkhardt, 2008) (*Fig. 19a*) and other tensegrity networks can be derived from geodesic polyhedra (Hugh, 1976, *Fig. 19b-c*). By the assemblage of these units planar and spherical structures can be created, thus it can be used for walls, floors and roofs. *Fig. 20* shows the spherical assembly of tripods designed by B.R. Fuller and a recent design for a tensegrity roof.

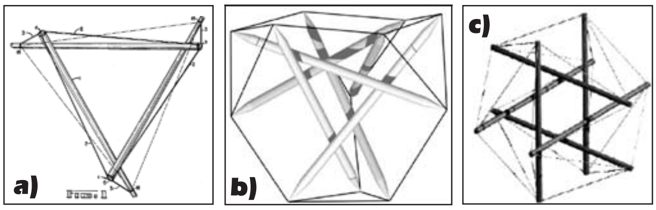

Fig. 19: Some tensegrity system: a) the tensegrity tripod (Fuller, 1962) b) truncated tetrahedron (Burkhardt, 2008) c) expanded octahedron (Jáuregui, 2010).

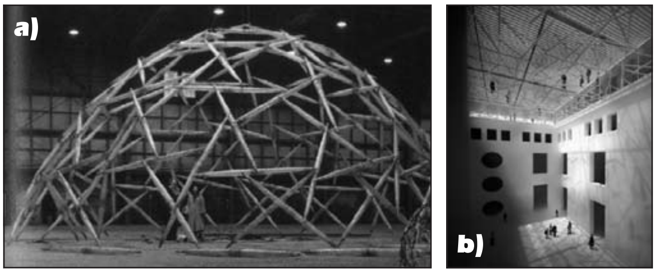

Fig. 20: Architectural applications: a) Geodesic tensegrity dome by Fuller, 1953 (Gengnagel, 2002) b) tensegrity roof design of ABDR Arch. Association (ABDR)

The idea to have only tendons connected to struts is probably the most innovative concept of this type of structures resulting extremely simple joints. Beyond the difficulty of form finding (Motro, 2006) the main problem of this type of non-conventional structure is the difficulty of fabrication as the geometry of spherical and domical structures are pretty complex. Other big disadvantage, similarly to all tensile systems, is the poor load response (relatively high deflections and low material efficiency (Hanaor, 1987) as compared with conventional, geometrically rigid structures and the lack of resistance to concentrated loads.

Another big disadvantage is that conventional architectural structures cannot be applied for connecting structural elements, and for cladding. Thus it requires a complete innovation of complementary technologies. A big advance when comparing with other tension systems is that this tensegrity structures can encompass very large areas with minimal support at their perimeters, obviating the "heavy anchorage devices" needed for support with some cable based technologies, or extensive support structures needed by some composite structures, mixing tensegrity systems and non-tensegrity technologies (Motro, 1987). Deviating slightly from the canonical definition R. Motro explored and tested many different tensegrity systems for architectural application (Motro, 2006).

A new type of deployable structure can be created due to the intrinsic property of tensegrity structures. Foldability can be easily obtained by changing the element lengths. This can be either the changing of strut length by using telescopic bars or the folding can be enriched by changing the length of the cable. The main difficulty of the former method is that in the folded configuration the cable often creates an inextricable tangle, thus unfolding the system is often opposed. The later rather proved to be a usable method concerning assemblies. (Motro et al, 2001)

The trend to design adaptive/responsive architectural applications turns the kinematic indeterminacy of tensegrity structures an advantage (Tibert, 2002). This is due to the fact that only small quantity of energy is needed to change the configuration and thus the shape of the structure.

5. MEMBRANE STRUCTURES

5.1 Classification

Similar to the rigid constructions, F. Otto classified also the membrane convertible constructions in a movement matrix (*Fig. 21-22*). He distinguished two different types; the one with stationary supporting structure and the one with movable supporting structure. Pneumatic structures can be also classified as deployable membrane structures. As mentioned in the introduction these types of structures were already in practice in the very past history. However it was just the end of the second half of the last century when engineers began to apply textile as building material for large-span constructions. The pioneering works of F. Otto motivated plenty of membrane designs throughout the world.

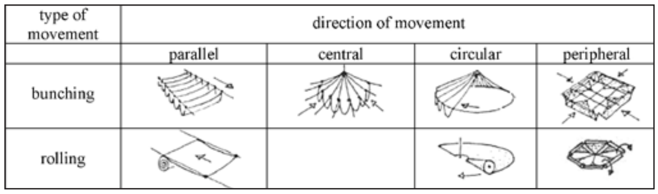

Fig. 21: Classification of membrane convertible constructions: the movement matrix of structures with stationary supporting structure (Otto et al, 1971)

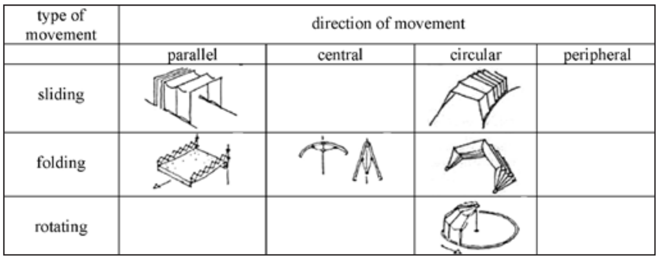

Fig. 22: Classification of membrane convertible constructions: the movement matrix of structures with movable supporting structure (Otto et al, 1971)

5.2 Foldable membrane structures

The main difficulty concerning deployable membrane structures is the stabilization of the membrane in all the possible configurations (folded, during deployment, opened configuration). In the extended position the membrane can be secured with pretensioning, that can be achieved either with the drive system itself or by special tensioning devices at the edge of the roof. The flapping wind effect during deployment resulting quite large deformations with small forces is one of the main difficulties (Walter, 2006).

This difficulty occurred in the case of the Olympic Stadium in Montreal, Canada (*Fig. 23*). The stadium was to open for the 1976 Olympic Game, but the retractable roof was finished only in 1988. The 20 000 m^2 PVC/Kevlar folding membrane roof which was to be opened and closed by the 175 m inclined tower, was repeatedly damaged by local failures due to aero-elastic instability. The structure was replaced with a non-retractable spatial steel roof structure.

Fig. 23: Olympic Stadium in Montreal (architect: Roger Taillibert) (Olympic) an its original retractable membrane roof (Barnes, 2000)

A similar, but more successful design was evolved in 1988, Zaragoza, Spain for the roofing of the bullfighting Arena (*Fig. 24-25*). The roof was separated to a 83 m diameter fixed and a 23 m diameter central convertible membrane roof. For both parts a double spoked wheel system was used. The prestressed outer spokes span between an outer compression ring and two sets of inner tension rings held apart from each other by struts. The membrane of the permanent roof is draped over the lower set of radial cables. The retractable inner roof has similarly two sets of spokes between the inner tension rings and a central hub above the centre of the bullring. The two sets of spokes are connected by an electric spindle. The membrane is suspended to the lower layer of spokes by slides that can be moved by a stationary drive system. When the roof is open, it hangs bunched up in the centre, when is to be closed, 16 electric motors draw the bottom edge of the membrane out to the lower tension rim. Once the edge is secured to the rim, prestress is applied by rotating the top spinder (*Fig. 26*) at the central point, thus the retracted membrane is stabilized (Holgate, 1997; Walter, 2006). Even a 63 m diameter retractable roof was constructed in accordance with this principle over the centrecourt in Hamburg Rothenbaum (Walter, 2006).

Fig. 24: The retractable part of the Bullfighting Arena roof in Zaragoza (architect: J. Schlaich) (Sobek, 1999; cited by Walter, 2006)

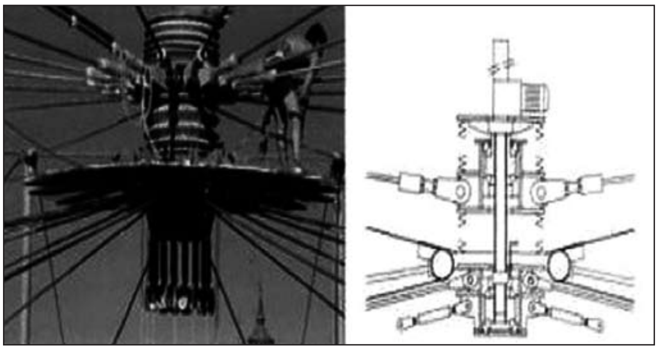

Fig. 25: Central spinder for prestressing the cables (Holgate, 1997)

Different membrane folding can be evolved by the umbrella principle. A nice example is the convertible cover of the two courtyards of the Prophet's holy Mosque in Madinah (*Fig. 26a*). The twelve large umbrellas (17 m x 18 m in the open configuration) are stem from the developed system of F. Otto (Otto and Rasch, 1995). These umbrellas ensure the shading during the day and the ventilation and cooling during the night. The openable roof installed in 2000 in the courtyard of the Rathaus, Vienna (*Fig. 26b*) is an example of a different convertible system where the membrane is retracted with sliding the cross-girders (Walter, 2006; Tillner, 2003).

Fig. 26: a) Architectural umbrellas in the courtyard of Mosque in Madinah (Otto, 1995 cited by Walter, 2006), b) Foldable roof in the Rathaus, Vienna (Tillner, 2003; cited by Walter, 2006)

The ability to provide numerical simulations for increasingly complex membrane is advancing rapidly due to computer hardware development and the improved computational procedures of nonlinear structural systems. This sweepingly advanced development with the inventions in textile technologies is exploring the further architectural and technical potentials of these structures.

5.3 Pneumatic structures

The supporting medium of pneumatic structures is compressed air or gas that creates tension forces on the elastic membrane, thus ensures the strength and the stability of the structure. Probably the balloon is the most well-known classical pneumatic structure. In construction the first inflatable structures appeared in the 1950's. These were mainly shelters with single wall inflatable "bubbles", called air-supported structures constructed from a single layer of pliable material that is supported by the internal pressurized air. This internal air pressure has to slightly exceed the external pressure. Thus this system requires an air lock, a continuous pressurization system that balances the air leakage, and an anchorage that fixes the structure to the ground or to the substructure.

Other inflatable designs use double-layer inflatable configurations. These air-inflated structures use tubular (air-beam structure) or cellular (air-cell building) shaped membrane skin with an internal pressurization that form together structural elements similar to the conventional ones. The skin takes the tension forces whereas the air is responsible for compression forces in a manner like the reinforced concrete. This new generation of inflatable structures has in general no steel, no aluminium, and no traditional supports and yet can handle large structural loads.

Fig. 27: a) Inflatable roof for Heathrow airport central bus station (architect: D5) (Lindstrand, 2006); b) 19.5 m x 40 m Exhibition Hall with air-inflated elements (architect: Festo AG & Co) in Germany (Festo)

Now that fabric and computer technology are catching up with this concept, the possibilities of inflatable structures in commercial, military and special events applications seem limitless. Even cubic interior building can be constructed with the air-beam technology (*Fig. 27b*). While more expensive than comparable aluminum structures, inflatable beams save money on transportation and installation because of their light weight and small packing size. Proving these facilities the inflatable roof designed for covering the central bus station of the Heathrow airport (*Fig. 278a*) is an instructive example. The installation of the roof was effectuated in one only night in 2006. Pneumatic design was chosen because the realization of the foundation of a conventional roof would have been run into obstacles as one of the airport's Tube stations is just underneath the site. (Lindstrand, 2006)

6. CONSTRUCTION OF CONCRETE SHELL STRUCTURES

6.1 Pneumatic formwork for thin concrete shell structures

Concrete shells are extremely material efficient structures as for uniformly distributed loads mainly normal forces appear in the cross sections and moments are insignificant. Moreover these structures are also very popular for their attractive architectural appearance. Nevertheless the time-consuming and expensive production with a conventional formwork is an important drawback of these structures. Similarly to the pantadome system used for lightweight 3D spatial structures, transformability can serve for combating this major problem of concrete shell designs.

Three different pneumatic formwork methods are used for monolithic concrete shell structures (van Hennik and Houtman, 2008). If the membrane is inflated first, *(Fig. 28a)* the concrete can be sprayed on the inside or the outside of the membrane. Evidently the reinforcement has to be placed before spraying the concrete. In case of the shotcrete on the inside *(Fig. 28b)* a special layer of polyurethane foam has to be sprayed on the membrane to hold the reinforcement. The membrane can be either taken off/out for reuse after the hardening of the concrete or can be left as a waterproof layer.

Fig. 28: a) Inflation of formwork; b) shotcreteing on the inside of the membrane; c) irregular shape structure constructed with pneumatic formwork (Pirs SA.)

The principle of the third method, invented by D.N. Bini, is to do all the constructional work on the ground in plane and then inflating the structure into 3D shape. The pneumatic lifting of the reinforcement and the freshly placed concrete can be effectuated with a special sliding reinforcement system *(Fig. 29a-c)* consisting of conventional steel bars and extensible spirals. As the structure lifts and takes its shape, the spirals stretch and the reinforcing bars slide inside them to reach their final position in the structure (Roessler and Bini, 1986). For Binishells two layers of membrane are used. The inner layer is attached to the ring beam being part of the foundation and the outer layer is placed after putting the reinforcement and the concrete on the inner layer. The concrete is vibrated after lifting the structure via an equipment that is attached to the centre of the outer membrane *(Fig. 29c)*. After lifting the outer membrane can be removed and after hardening the inner layer can be deflated and reused for the next construction.

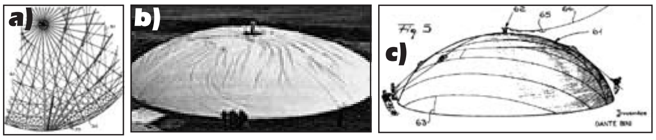

Fig. 29: The binishell system: a) expandable reinforcement (Bini, 1972); b) erection of the dome (Binishell System); c) vibration of concrete after erection (Bini, 1972)

Though pneumatic systems has been already applied for concrete shell structures since the 1960s, these systems seem to regain their popularity due to their aesthetic appearance, improved technological background and renewed structural concepts. Even irregular shell shapes *(Fig. 28c)* are constructed with pneumatic formwork (van Hennik, 2008).

6.2 Erection of segmented concrete or ice domes

Two new and very efficient construction methods for hemispherical concrete shells have been developed at the Institute for Structural Engineering at Vienna University of Technology by J. Kollegger. The novel concepts were tested not just on large scale concrete but as well on ice domes. Both methods start with an initial plain plate that is subsequently transformed into a shell structure (Dallinger and Kollegger, 2009) *(Fig. 30-31)*.

The principal of the first method is to fragment the shell structure into a polyhedron enabling the use of planar precasted parts that can be easily produced at the factory, transported to the site and then quickly assembled. The elements kept together by radial and circumferential steel tendons *(Fig. 30)*. The circumferential tendoms are tightened through winches and are instrumental for the assembly of the elements. The erection is effectuated with a pneumatic formwork that lifts the structure into the desired position. (Dallinger and Kollegger, 2009)

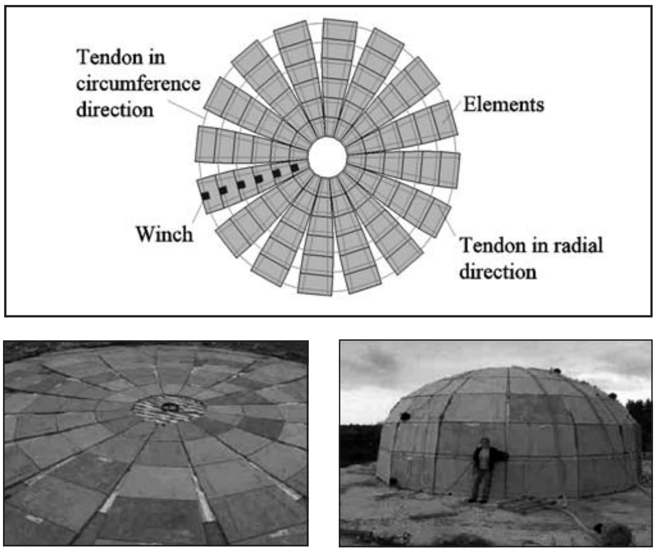

Fig. 30: Transformation of precast divided planar segments into a hemispherical dome (Dallinger and Kollegger, 2009)

In case of the second method the flat plate is divided into segments which are distorted uni-axially and lifted into the final position (Dallinger and Kollegger, 2009). The transformation is controlled by one or more active cable(s) and by either a crane positioned in the centre or a pneumatic formwork placed under the structure (Kollegger et al., 2005). *(Fig. 31)*

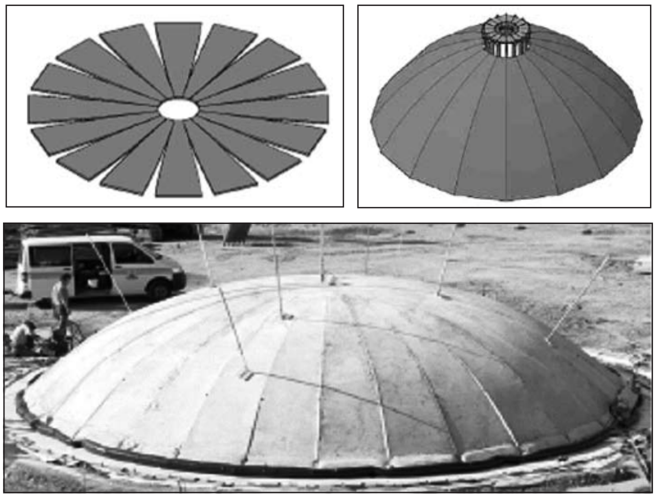

Fig. 31: Segment lift method (Dallinger and Kollegger, 2009)

7. SUMMARY

After shortly summarising the historical background an overview on movable roof structures have been presented. The feature of transformability in case of a roof structure can arouse from two different motivations. The first motivation is to create a fast and/or safe construction method and in some cases it can be also the need for a quick demounting process and the possibility of reusability. The second motivation is to adapt the structure to external excitations like weather conditions. This can either come from energy-saving consideration or from the aim to ameliorate occupant comfort, raise the attraction of the building.

The former motivation resulted in exotic inventions of some *pantographic systems*, like the collapsible movable theatre of Pinero, the quickly retractable swimming pool cover of Escrig, even the pop-up dome of Zeigler and its further developments. The minimal material use *tensegrity systems* also offer the possibility of foldability. Ongoing research works try to find a greater variety of possible architectural applications. Some *soft membrane systems* like cable-stiffened textile structures and pneumatic structure can be quickly installed too. F. Otto remarkable systematic study on foldable membrane structures with the recent available material and calculation technologies led to a wide variety of architectural membrane designs even used for big span permanent structures. Pneumatic systems can also serve as a supplementary system for the erection of 3D structures making the installation easier, faster and safer. The "*pantadome" structural system* invented by Momoru Kawaguchi, and some earlier and novel *pneumatic formwork methods for* constructing monolithic and precasted *concrete domes* can be mentioned among these systems.

Though these structures mentioned above still attract the military and provisory events in first place a trend can be observed to apply them for permanent buildings where translucent or extremely light construction is needed.

With membrane structures roofs that can move while in use can be designed too. The goal to design dynamic structures that are able to change morphological/mechanical/physical properties and behaviour as a response to external excitations and requirements was first addressed in the 1960s and 1970s. Early transformable designs appeared in first place for housing sport venues. With the currently growing media focus on sport events the demand for *retractable structures* seems to be steadily increasing. Most of these designs use *rigidly moving parts* to retract the roof structure. In most of the cases the slicing of an ideal roof shape results in gigantic structural height, and mechanical instruments enabling retraction further increase the costs of these structures. With new generation roofs like the *retractable pantograph* structure of Hoberman and Pellegrino and the application of a *retractable skin* fixed to the permanent structure can rather count with economical aspects. Several research topics focus on adapting *tensegrity and pantographic structures* to adaptive architecture. Combining transformable structures with a highly distributed control system which is already available in today's technology an intelligent responsive architecture is born. This possibility does not only prospect indoor environmental quality enhancement and better occupant comfort but a better use of natural energy resources and thus a rather sustainable design.

8. ACKNOWLEDGEMENTS

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