A Pneumatic Architectural System for an Accessible Children Playground

A Master's Thesis submitted for the degree of
"Master of Engineering"

supervised by
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Vienna, 12.11.2015

Affidavit

I, **Su Mi Moe**, hereby declare

1. that I am the sole author of the present Master's Thesis, "A Pneumatic Architectural System for an Accessible Children Playground ", 74 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

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Signature

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Abstract

This master's thesis presents the design of an accessible children playground using lightweight architecture for both children with disabilities and able-bodied children. The aim is to design an accessible children playground using pneumatic principles and materials. The "pneumatic" principles and technology is one of the best options to design such kind of playground for children if necessary safety measures are taken into account. Use of textile fabrics rich in variety of colours as basic construction material also has an advantage in designing this pneumatic playground to impress and attract children very much.

For that reason, by applying pneumatic principles, the accessible children playground has been designed which provides not only joyfulness and adventurous activities but also a good place to exercise while playing for both children with and without disabilities safely. Furthermore, it also provides interaction between normal children and disabled children so that they can assist each other, learn each other's abilities and improve physical developments, socializing and problem solving skills at a very young age.

The first approach to this master's thesis is to study about types and treatments of physical disabilities to gain good knowledge about disabilities and what types of physical movements provide the best benefits for them. Thus, this knowledge has been incorporated in designing the present pneumatic accessible children playground. Then, discussion about pneumatic principles, technology, their basic structural forms and applications are studied. Finally, the design of the pneumatic accessible children playground with essential play equipment for the benefits of disabled children and able-bodied children has been presented in this thesis.

Key words: accessible children playground, pneumatic structures, air-inflated, lightweight architecture, ground-level play components, elevated play components.

CONTENTS

1. INTRODUCTION..1

1.1. Objectives & Motivation..2
1.2. Structure of the Thesis 2

2. GENERAL INFORMATION ON TYPES OF PHYSICAL DISABILITIES AND TREATMENTS..4

2.1. Types of Physical Disabilities..4
2.2. Treatment for Physical Disabilities 4

3. PNEUMATIC STRUCTURES 6

3.1. Principles..6
3.2. Structural Forms..8
3.2.1. Basic Geometrical Forms..9
3.2.2. Compound Forms 11
3.2.3. Complex Systems 12
3.3. Structural Systems & Classifications..14
3.4. Pneumatic Pressure Systems 14
3.4.1. Low Pressure Systems 14
3.4.2. High Pressure Systems..22
3.5. Tensairity..24
3.6. Pneumatic Motion Systems..25
3.7. Pneumatics Building Workshop..28
3.8. Analytical Method 30
3.9. Load Assumptions..32
3.10. Computational Modeling 34

4. ARCHITECTURAL DESIGN...36

4.1. Design Inspiration 36
4.1.1. Architectural Form...37
4.1.2. Structural Stability 38
4.2. Design Requirements...40
4.3. Design Considerations 42
4.4. Design Development...43

5. STRUCTURE SYSTEMS & CONSTRUCTION DETAILS 50

5.1. Primary Structure 50

5.2. Secondary Structure 53
5.3. Anchorage Details 59

6. CONCLUSION 62

BIBLIOGRAPHY 64
LIST OF ABBREVIATIONS 66
LIST OF FIGURES 67
LIST OF TABLES 70

1. INTRODUCTION

Pneumatic structures are part of living nature and it can be seen everywhere in this world. Each cell of a living substance is in the form of pneumatic and they achieve their stability from the combination of an outer membrane and the inner pressure resulting from a fluid or gaseous medium. Pneumatic principles are widely used in building and construction industry also in mechanical and aeronautical engineering. Pneumatic structures can be built in the form of permanent structures as well as temporary structure due to its lightness and highly transportable properties.

This master's thesis is about designing a playground using pneumatic principles where disable children and able-bodied children can play together without any barriers. It is intended to create a place where all children can access the entire area of the playground and participate in all activities without any difficulties.

Also, it is very important that children should grow up happily and healthily. Furthermore, playing is very important for physical development and socializing skills of all children. Children with disabilities also have same wishes to have enjoyment just as normal children.[1] When children with and without disabilities play together, they learn to appreciate each other's aptitudes, similarities and understand the importance of team building. In addition, physical activity reduces the risk of psychological problems and gains self-confidence.[2] Moreover, playing at playgrounds help children achieve sufficient exercise which promotes their health and physical developments.

The "pneumatic" principles and technology is one of the best options to design such kind of playground for children. Compared to other materials such as steel or timber, technical fabrics provide different feeling and also allow multifaceted range of applications due to its flexibility, availability of different fabric colours and significant product properties. Moreover, its flexibility of fabricability to manufacture required shapes, forms and sizes is an obvious advantage than any other materials.

The present pneumatic accessible children playground has been designed in order to provide a structure which is not only functional but also aesthetically pleasing at the same time attractive to children. This pneumatic accessible children playground comprises elevated play components and some ground-level play components

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[1] http://www.nchpad.org/10/36/Playgrounds~for~All - retrieved on August 21, 2015

[2] https://en.wikipedia.org/wiki/Playground - retrieved on August 21, 2015

which are essential for helping disabled children with their rehabilitation exercises. The play components are designed by referring to the pneumatic principles and their shapes formed by combing basic pneumatic forms such as air-inflated tubes and cushions to form such a recreation playground for all children. The components are carefully designed for the requirements of disable children by applying the knowledge gained from literature studies as well as visits to the children's rehabilitation center at Yangon Children Hospital Child Neurology department in Myanmar.

1.1. Objectives & Motivation

The main objective of this master's thesis is to find possibilities of using lightweight architecture and equipment for an accessible playground for children. There are many children playgrounds in the world. They are constructed using different kind of materials such as steel, rubber, plastics and so on. However, most of these playgrounds are only suitable for able-bodied children and they are not appropriate for disabled children to access. As such, disable children have fewer places to play compared to able-bodied children. In order to provide enjoyment and fun to all children, it has been decided to design an accessible children playground where disabled and able-bodied children can play side by side. Moreover, children can achieve sufficient exercise which promotes their health and mentality by playing happily in this pneumatic accessible children playground.

1.2. Structure of the Thesis

Based on the objectives and motivation, this master's thesis is divided into six chapters.

- Chapter 1 presents the introduction to the master's thesis; it includes objectives, motivation and how this master's thesis has been structured.

- Chapter 2 provides brief study on types and treatments of physical disabilities and handicapped children's behaviors.

- Chapter 3 includes literature study in terms of pneumatic structures which will be widely referred to the accessible children playground architectural design, engineering, structural system and construction detailings. The literature study includes the phenomenon of pneumatic structures, its principles, structure system, structural forms, technical details and so on.

- Chapter 4 describes architecture design of the accessible children playground. In this chapter the author presented the design approach and design consideration by paying special attention to handicapped children's behavior and their requirements. The stages of the design development have been presented by building physical and computational models while referring to the appropriate design guidelines.

- The next chapter is about structural systems and construction detailings. The author presented structural system and construction detailings with necessary technical data and figures.

- Finally, Chapter 6 draws the conclusion on the advantages and benefits gained by disabled children as well as able-bodied children by playing together in the pneumatic accessible children playground.

2. GENERAL INFORMATION ON TYPES OF PHYSICAL DISABILITIES AND TREATMENTS[3]

A physically disabled person is one who cannot perform daily activities such as walking, bathing, toileting, etc., on his own. Physical disability is due to two reasons: *Congenital* / *Hereditary* - disable since birth or developed later due to genetic problems, muscle cells problems or injury during birth and acquired - disability because of accidents, infections or diseases.

2.1. Types of Physical Disabilities

There are two major categories under the Physical Disability Group, they are:

1. *Musculo Skeletal Disability* and
2. *Neuromuscular Disability*.

Musculo skeletal disability defined as the inability to carry out activities that involve movements of parts of the body because of deformities in the bones or muscles, diseases or degeneration, loss or deformity of limbs. *Osteogensis Imperfecta* and *Muscular Dystrophy* comprise this category.

Neuromuscular Disability means some parts of the body can be affected because of diseases or disorder of the nervous system. When this happens a person is unable to perform controlled movements of affected body parts. This category comprises, *Cerebral Palsy*, *Spina Bifida*, *Poliomyelitis*, *Stroke*, *Head Injury* and *Spinal Cord Injury*.

2.2. Treatment for Physical Disabilities

Disable conditions can be improved depending on the cause, type, extend of the disease, disorder or injury. Physical improvement in most cases is seen only in the initial few years of disability. For the few progressive type the treatment goal is to maintain their condition. Planned rehabilitation programmes are of a great help to individuals. The person must be aware that controlled diet also helps to avoid further deterioration or recurrent of diseases. By attending rehabilitation programmes,

[3] http://hwa.org.sg/news/general-information-on-physical-disabilities/ - retrieved on March 06, 2015

individuals learn to manage their disability with confidence. Some of the programmes include the following.

- ***Occupational Therapy*:** In this specialised treatment programme children are trained and perform activities and exercises which have purposes and goals, according to each ones disability. This programme improves children functional abilities and independent living skills.

- ***Physiotherapy:*** According to the children's needs this programme is planned by using physical means such as exercises and electrotherapy.

- ***Speech Therapy*:** This programme treats and trains children to communicate effectively.

- ***Medication / Vaccination*:** To avoid further deterioration children need to follow doctor's prescription concerning medication / vaccination.

3. PNEUMATIC STRUCTURES

Pneumatic structures belong to form-active structure systems which are systems of flexible, non-rigid matter, in which the redirection of forces is effected by particular form design and characteristic form stabilization. (Heino Engel & Hatze Cantz 1997: 41)

Pneumatic structures are one of the lightest buildings in construction industry. One of the good advantages of pneumatic structures is the ability to build extreme spans. (Vinzenz Sedlak et al.1983: 19). Pneumatic structures can be built in the form of permanent structures. Due to its lightness and highly transportable properties, they can also been built as temporary structures. Moreover, they can be produced into special shapes and variety of colours to provide more attractive look.[4]

The term pneu is original from the Greek word pneuma which means air, pneumatos – breath and pneo – to reside. (Frei Otto et al. 1979: 6). "*Technical pneumatics are tension resistant membranes able to form a structure resisting tension, compression and bending when inflated, e.g., car tyres, air and gas ballons, but also water hoses and sand bags. Skins (membranes) for technical pneumatics are made from sheet metal, plastic foils, coated fabrics and paper. Gases, liquids, foams and bulk materials create the filling".* (Frei Otto et al. 1979: 6)

The term structure means *"Any object able to transmit forces is a structure; in other words, any object that has the potential to transmit forces. (…) The capacity for transmitting forces, depending on form, material, and type of stress, can be measured and is known in order of magnitude for all objects from nature and technology".* (Frei Otto et al. 1976: 22)

3.1. Principles

As describe in Figure 3-1 below, pneumatic system includes (a) – a flexible **envelope** for instance a net as in a string net or a fishing net or a skin as in air balloons, rubber or sometimes a combination of skin and net. (Frei Otto et al. 1976: 24)

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[4] https://sites.google.com/site/pneumaticstructure/uses-and-limitations - retrieved on September 03, 2015

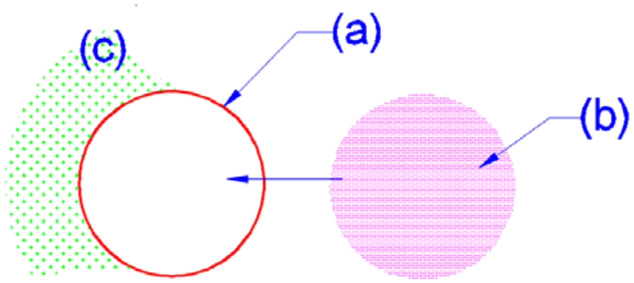

Figure 3 - 1 Envelope – Filling – Medium.[5]

(a) Envelope: A flexible **envelope** for instance a net as in a string net or a fishing net or a skin as in air balloons, rubber or sometimes a combination of skin and net. The envelope has to be flexible to bending and pressure to transmit adequately huge uniaxial and biaxial tension forces. Envelopes should have elasticity, ductility, plasticity and firmness behaviours to the change of form under stresses and external loads. There are several different types of skins. For instance, liquid membranes, plastic membranes, elastic membranes, plastic – elastic membranes and also fleeces of intertwined fibers, triple layer arrays and fabrics. Nets with quadrangular and hexangular meshes are used widely. (Frei Otto et al. 1976: 24)

(b) **Filling**: Filling includes all gases, liquids and liquid filled tissues. Sometimes, crumbly and granular substances of the most different size and structure are also used as filling. (Frei Otto et al. 1976: 24)

(c) Medium: The most common external mediums are air and water. (Frei Otto et al. 1976: 24)

The envelope (membrane) is stressed by internal air pressure generated by fans. Due to the air pressure generated, the membrane will be inflated according to its shape. Once air pressure is being generated, it starts to stretch and reaches to its equilibrium when the pressure applied by the air inside balances the forces exerted by gravity, dead load of the membrane and external loads such as wind, snow and rain. (Jacobo Krauel 2013: 44). Pneumatic system comprises a structural system able to absorb internal and external forces. (Frei Otto et al. 1976: 23). In general

[5] Frei Otto et al. 1976: 23

there are two types of pneumatic structures, air-supported structures and air-inflated structures.

In fact, all living nature develop base on pneumatics principle. (Frei Otto et al. 1976: 6). *Growth in living nature involves complying with the laws of a pneumatic construction and varying the forms within fixed limits.* (Klaus Bach et al. 1983: 21)

Figure 3 - 2: Examples of pneumatic in living nature.

The principle of formation of all structures in living nature such as plants, animals and man are constructed from pneumatics although each individual has its own form. We can find pneumatics everywhere in our daily lives. For instance air balloons, soft fruit such as grapes and tomatoes or soft eggs of insects. Moreover, every plant or animal cell is a pneumatic consisting of a flexible covering – the membrane and a filling which is the protoplasm. In addition, wood and bones develop from pneumatics as well. Every object in living nature starts as a small cell with a flexible covering and aqueous filling. (Klaus Bach et al. 1983: 17)

3.2. Structural Forms

The structural form depends on the dimension of main directions of expansion and kind of curvature. The pneumatic forms greatly influence the efficiency of its structural system. The form of a pneumatic can be differentiated as follows:

- The first category is air-inflated with one dimensional appearance. For instance, tubes, masts, columns are relatively large in one dimension and small in the other two directions.
- The next is air-inflated with two dimensional appearances. For example, air mattress and cushions. They are widely used in roof and façade construction.
- The last category is air-supported with three dimensional appearances as in air balloons, balls, spheres, etc.

The form of a pneumatic can be further classified in accordance with the types of curvature of the outer surface. The curvature can be singly curved, doubly curved in the same direction or synclastic and doubly curved in opposite directions or anticlastic. (Thomas Herzog et al. 1976: 10)

3.2.1. Basic Geometrical Forms

Basic geometric forms of air-supported structures include a sphere, a spherical cup, an ellipse, and cone and a cylinder. Among these shapes, the sphere is the basic shape for all air supported structures in which membrane stresses are equal at any point under uniform inside pressure. (Heino Engel & Hatze Cantz 1997: 100). Pneumatically-stressed, stiff skins can be used to produce basic geometrical forms.

A sphere can be used in sports ball, satellite balloon, and a high-pressure gas container, etc as shown in Figure 3-3. The other type, conic forms air-supported systems can be constructed by fixing on a plane or joined to a sphere.

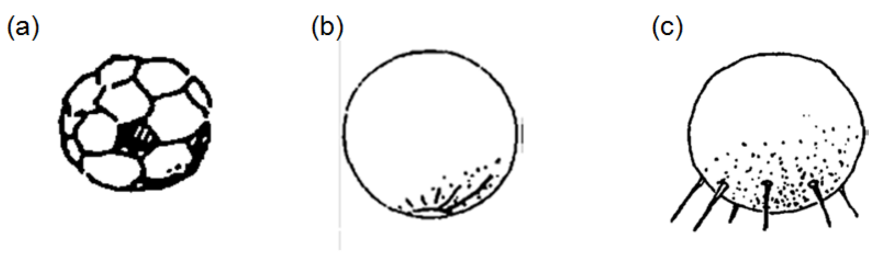

Figure 3 - 3: Basic geometrical forms (a) a sport ball; (b) satellite balloon; (c) a high-pressure gas container.[6]

A cylindrical air-supported structure can be stretched between two surfaces and it can also be terminated with other pneumatic rotating bodies and can be fixed to any

[6] Frei Otto et al. 1976: 27

surface as shown in Figure 3-4. For example, an air-supported hall can be constructed with a semi-cylinder at the center and two quarter spheres in both ends. However, it should be aware that upon transition from one form to another may cause folds or excessive strains due to the case of changing internal pressure which causes sudden changes in the surface stresses.

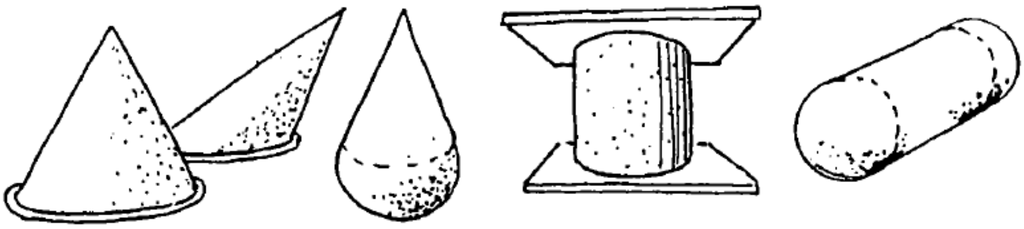

Figure 3 - 4: Basic geometrical forms of pneumatics as conic & cylinder.[7]

An air-inflated cylinder with infinitely long in length is considered as tube. Tubes can be bent into any shape in order to achieve different shapes such as car tires and bicycle tires. Moreover, they can also be used to transport of gases and liquids. However, straight and bent tube systems are not very suitable for the transmission of large uniaxial pressure loads and bending stresses. (Frei Otto et al. 1976: 27-29).

Closed air-inflated tubes are available in very different forms. The determination can be done by the form and extensibility of the envelope, the magnitude and the distribution of the internal pressure and by outside influence. (Frei Otto et al. 1976: 52)

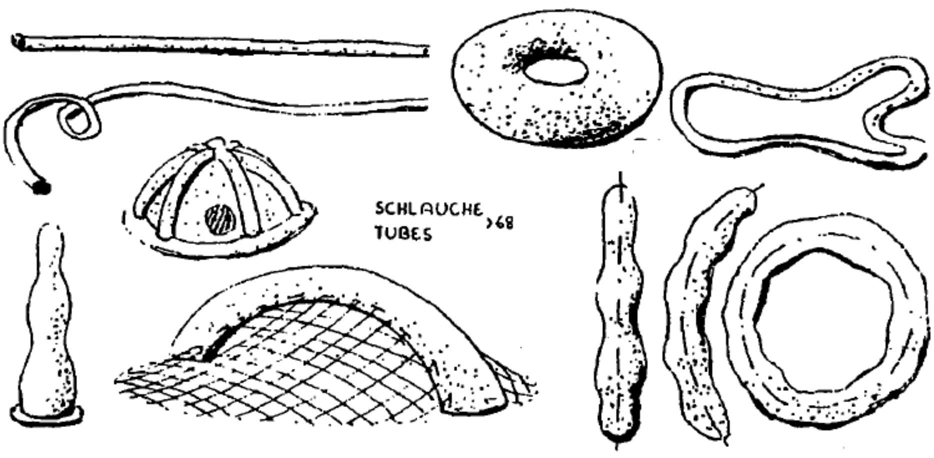

Figure 3 - 5: Air-inflated tubes in different applications.[8]

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[7] Frei Otto et al. 1976: 28
[8] Frei Otto et al. 1976: 29

3.2.2. Compound Forms

Several forms of pneumatic systems may be joined to one another or be fitted within one another. As such, envelopes may touch each other or be tightly connected with each other including single or double walls. It should also be noted that when the envelope touches each other, its form and membrane forces are changed. Double tube is one of the simplest compound forms. The partition may be different form such as perforated or net. It is an essential part of the supporting system when it is strained under a load. (Frei Otto et al. 1976: 31)

Figure 3 - 6: Instant city; an example project of compound form.[9]

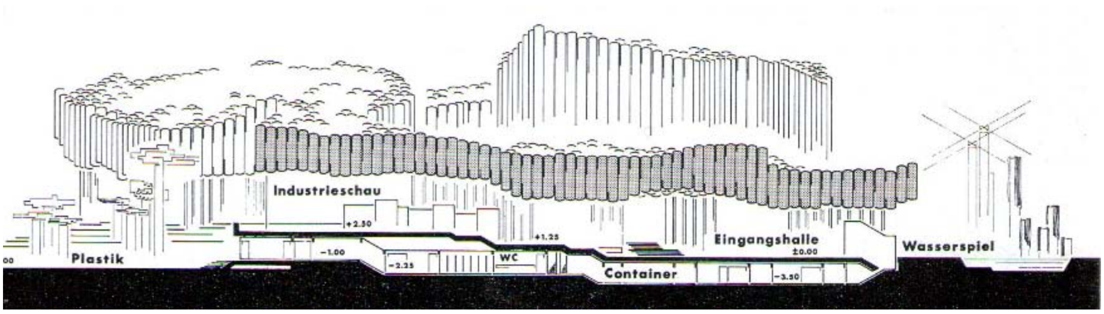
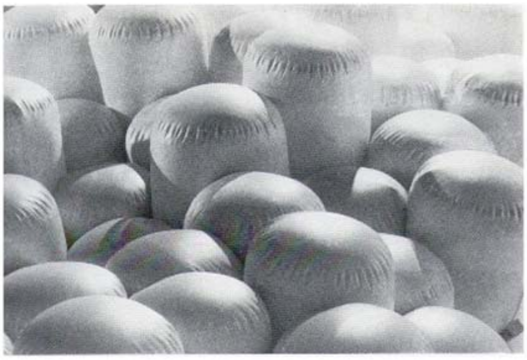


Figure 3 - 7: Elevation of German pavilion for Expo 70, Osaka.[10]

[9] Jacobo Krauel 2013: 42

[10] Thomas Herzog et al.1976: 79



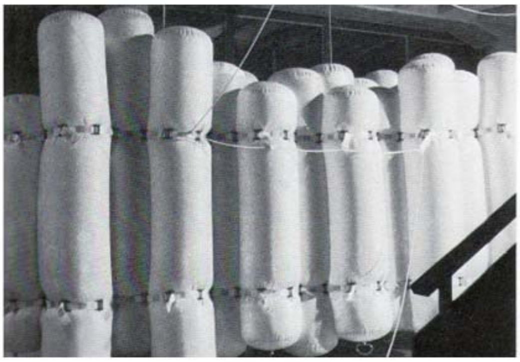


Figure 3 - 8: Details of German pavilion for Expo 70, Osaka.[11]

3.2.3. Complex Systems

A combination of various types of air-inflated / air-supported such as basic forms, tubes, cushions, etc with membrane strutting and bracings formed complex form. In complex form system, positive and negative pressure stabilizations and both stationary and mobile systems are possible. (Frei Otto et al. 1976: 124)

Figure 3 - 9: An example of complex system: Trial structure in Delft.[12]

[11] Thomas Herzog et al.1976: 79

[12] Thomas Herzog et al. 1976: 90

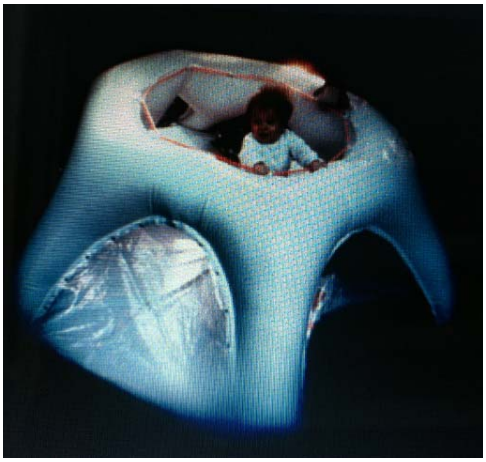


Figure 3 - 10: Inflatable running kennel for children.[13]

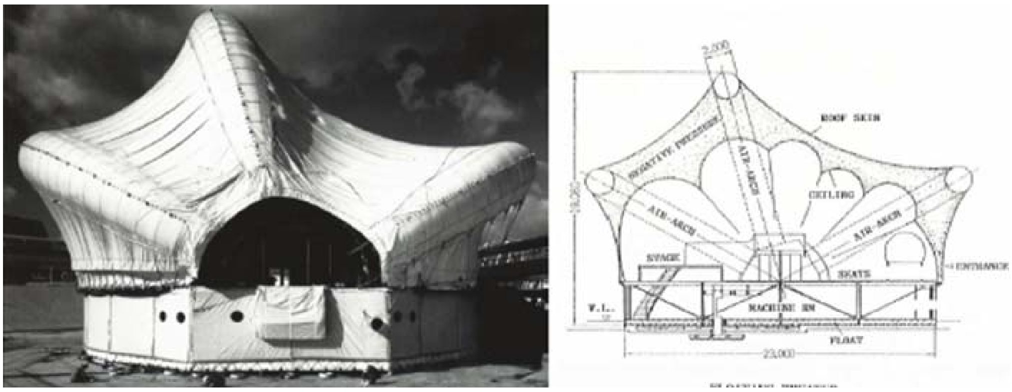


Figure 3 - 11: Floating theatre, Expo 70, Osaka.[14]

Figure 3 - 12: Inflatable barrage balloons.[15]

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[13] Frei Otto et al. 1976: 125

[14] Thomas Herzog et al. 1976: 90

[15] Jacobo Krauel 2013: 25

3.3. Structural Systems & Classifications

Pneumatic structural system can be divided by different features such as: formation of membranes, kind of differential pressure and kind of additional support. For each of the features, there are different characteristics. (Thomas Herzog et al. 1976: 15)

Pneumatic structures can be divided into two main categories; air-stablised structures which will be used extensively in mechanical and aeronautical engineering. Another type is air controlled structures. They are most relevant to architectural applications. Furthermore, air-controlled structures can be divided into air-supported structure and air-inflated structures based on their forms and applications. (C.G. Riches & P.D Gosling)

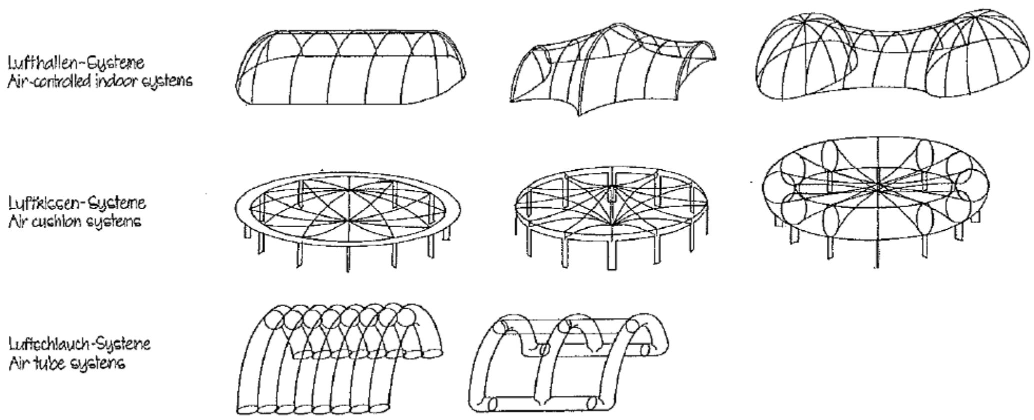


Figure 3 - 13: Classifications of pneumatic structures.[16]

3.4. Pneumatic Pressure Systems

The pneumatic pressure systems can be differentiated by the low pressure system and high pressure system.

3.4.1. Low Pressure Systems

Inflatable structures formed by an assembly of self-supported low pressure membrane elements are ideal to cover large space areas. They also adapt easily to any design shape and have minimal maintenance requirements, other than keeping

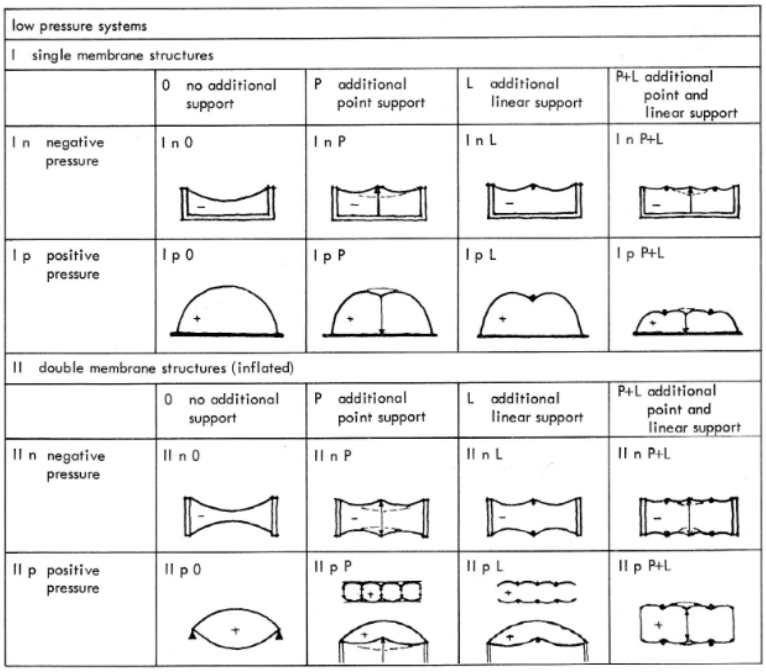
[16] Heino Engel & Hatze Cantz 1997: 61

a constant low internal pressure accounting for the air losses through the material pores and the seams. (Javier Marcipar, Eugenio Oñate et al. 2005: 244)

Figure 3 - 14: Inflatable pavilion formed by an assembly of low pressure tubes.[17]

The low pressure system can be divided into single and double membrane structures. In single membrane structures, a space is enclosed by single membrane under positive or negative pressure. However, in double membrane structures, the parts of the membrane surrounding the support medium are always curved in opposite directions to each other. The membrane is always curved outward in positive pressure systems. But, in negative pressure systems, it is always curved inwards, however, except in the area where secondary supports are introduced. (Thomas Herzog et al. 1976: 17)

[17] Javier Marcipar, Eugenio Oñate et al. 2005: 246



low pressure systems				
I single membrane structures				
	0 no additional support	P additional point support	L additional linear support	P+L additional point and linear support
I n negative pressure	I n 0	I n P	I n L	I n P+L
I p positive pressure	I p 0	I p P	I p L	I p P+L
II double membrane structures (inflated)				
	0 no additional support	P additional point support	L additional linear support	P+L additional point and linear support
II n negative pressure	II n 0	II n P	II n L	II n P+L
II p positive pressure	II p 0	II p P	II p L	II p P+L

Table 3 - 1: Classification of low pressure systems.[18]

Air-Supported Hall (Single Membrane Structure)

In this air hall system, the inner used space volume is generated from fully closed membrane supported by low pressure and stabilizes it against the acting forces. The pressurized volume is also the used space. (Javier Marcipar et. al 2005: 244). The membrane forces are transferring towards the boundaries. (Heino Engel & Hatze Cantz 1997: 102)

Figure 3 - 15: Air-supported hall.

[18] Thomas Herzog et al. 1976: 17

Air Cushion (Double Membrane Structure)

Figure 3 - 16: The Galet project for Swiss expo.[19]

The pressurised air within the cushion serves only to stabilize the bearing membrane and, together with the upper membrane. In this system it is required the membrane to be attached at a rigid frame in order to transfer the forces at the membrane edges. The air cushion system is widely used in building and construction industry such as roof and façade construction. (Heino Engel & Hatze Cantz 1997: 102)

Figure 3 - 17: Bellver castle in Spain.[20]

[19] http://www.tensinet.com/database/viewProject/4183.html - retrieved on August 30, 2015
[20] http://www.tensinet.com/database/viewProject/4474.html - retrieved on August 30, 2015

Figure 3 - 18: The Cloud, World Youth Day, Marienfeld Kerpen, Germay.[21]

Nowadays, ETFE cushions are widely used in building industry not only as roof systems but also as façade systems due to its aesthetic appearance. It is a very transparent material. It transmits across the ultraviolet in the range of (320-380mm) that allows plants and vegetation underneath to thrive. Moreover, ETFE film absorbs large amount of infra red light transmitted; therefore it can improve buildings energy consumption.[22]

Figure 3 - 19: ETFE Cushion as building façade, Allianz arena at night in Munich.[23]

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21 http://www.if-group.de/en/membrane/pneumatic-structures/pope-cloud.html - retrieved on September 01, 2015

22 http://www.architen.com/articles/etfe-foil-a-guide-to-design/ - retrieved on September 02, 2015

23 http://www.thefalsenine.co.uk/2013/01/17/has-englands-bundesliga-romance-gone-too-far/allianz-arena-at-night-munich1/ - retrieved on September 01, 2015

Figure 3 - 20: ETFE Cushion as roof covering for Nottingham high school for boys (Interior View)[24]

Figure 3 - 21: ETFE Cushion as roof covering for Nottingham high school for boys (Exterior View)[25]

Moreover, additional supports within the membrane surface is suitable when the span of the membrane is large so that these supports could help to decrease the radius of curvature of the membrane. As a result, the tension in the membrane can

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[24] http://www.architen.com/projects/nottingham-high-school-boys-etfe-roof/ - retrieved on September 02, 2015

[25] http://www.architen.com/projects/nottingham-high-school-boys-etfe-roof/ - retrieved on September 02, 2015

also be reduced. There are two types of additional supports; point support and linear support. (Thomas Herzog 1976: 18)

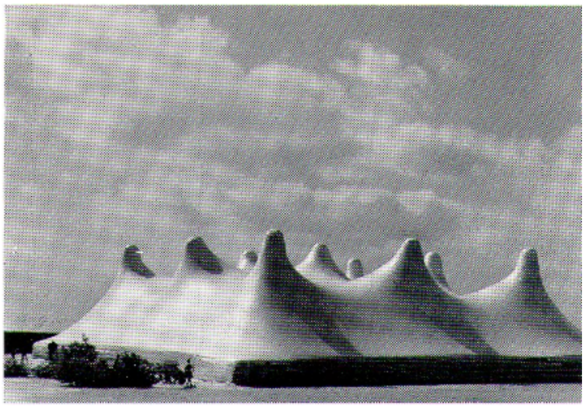

Figure 3 - 22: Multi-purpose hall with additional point supports, study project.[26]

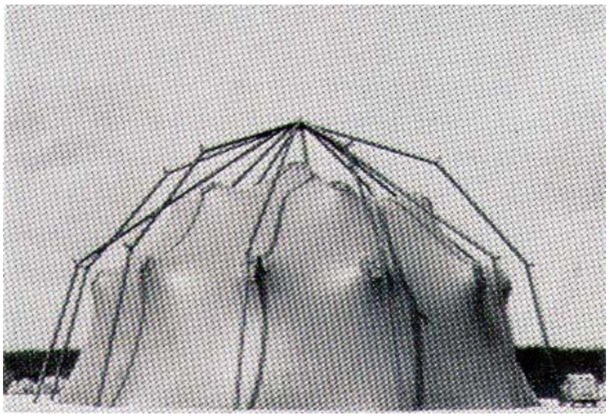

Figure 3 - 23: Demountable exhibition hall with additional point supports, study project.[27]

Additional supports can be placed at an exact location on the membrane surface in order to provide strength to the curvature of the surface as in a balloon made of an elastic rubber membrane by pressing with a pencil point. It could be clearly noted that very high tension occurs at the support point in relation to the rest of the membrane. These individual point supports can be expanded to a circular band or a rounded-off bulged surface. (Thomas Herzog et al. 1976: 18). Nevertheless, it should be noticed that point directed inward need to be fixed otherwise it would turn outward automatically due to its internal pressure. (Frei Otto et al. 1976: 26)

[26] Thomas Herzog et al. 1976: 22

[27] Thomas Herzog et al. 1976: 22

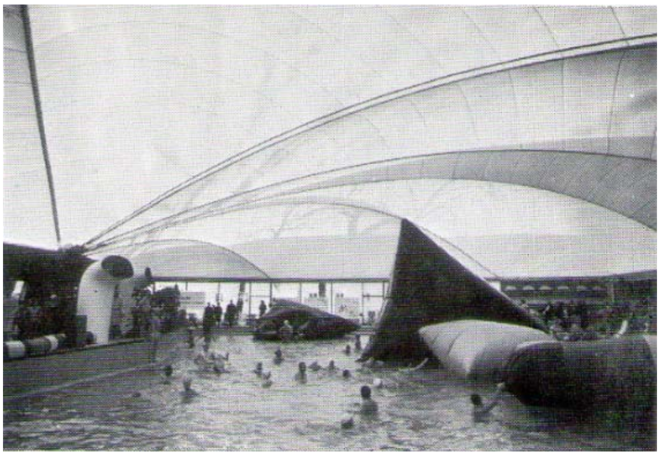

Figure 3 - 24: Roof covering of the swimming pool with additional linear supports.[28]

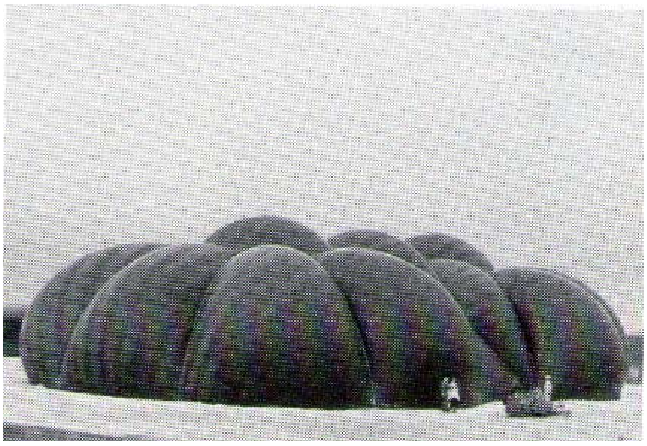

Figure 3 - 25: Exhibition hall with additional linear supports, study project.[29]

Additional linear supports act exactly same as additional point supports. Additional linear supports can maintain a uniform distribution of stress to the membrane. (Thomas Herzog et al. 1976: 21)

[28] Thomas Herzog et al. 1976: 25

[29] Thomas Herzog et al. 1976: 25

3.4.2. High Pressure Systems

The obvious disadvantages of these structures are the design of the joints and their big vulnerability to air losses. In general, high pressure inflated structures are difficult to maintain and repair and have a high cost. (Javier Marcipar, Eugenio Oñate et al. 2005: 243)

Air-Inflatable Structures / Air Tube

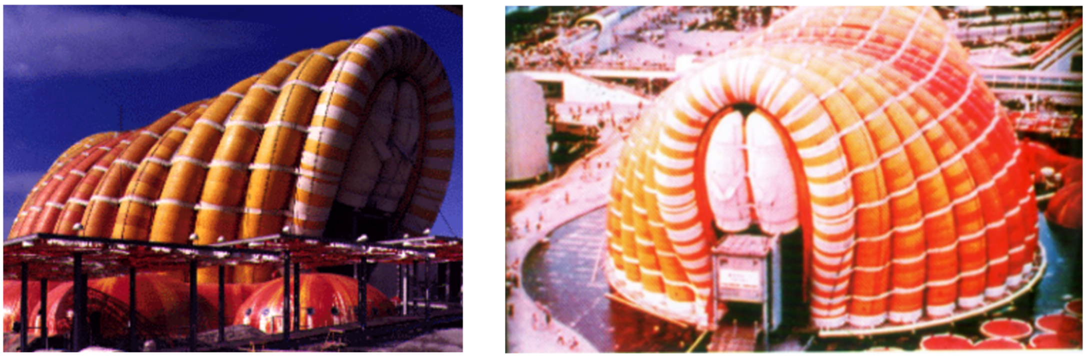

Figure 3 - 26: Inflated pavilion formed by assembly of high pressure tubes[30]

In this system, the pressurized air stabilizes the tube shape, therefore, forms linear structure membranes for diverse frameworks of spanning spaces. As similar in air hall system, the membrane forces will be discharged directly at the edges of the membrane. (Heino Engel & Hatze Cantz 1997: 102)

Figure 3 - 27: (a) Inflated fabric arches used in aircraft shelters; (b) Demonstration of an arch load carrying capability.[31]

[30] Javier Marcipar et. al 2005: 244

[31] Paul V. Cavallaro 2006: 3

The air tube systems require high pressure in order to achieve a very strong curvature in one direction, however, a very small or no curvature in the other direction is also possible. These air tubes are able to transfer transverse forces in low curvature direction. This system can be used as supporting element such as a beam, an arch, a grid or a lattice shell and therefore belong to the frame structure group. (Thomas Herzog et al. 1976: 28)

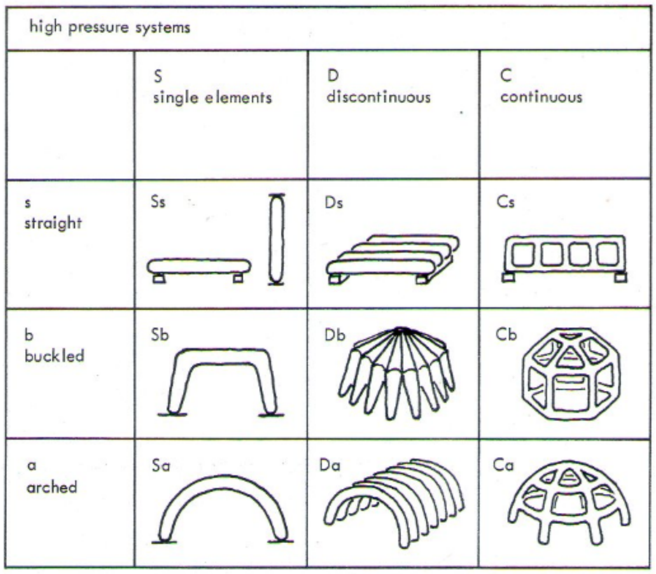

Table 3 - 2: Classification of high pressure systems.[32]

High pressure system can be distinguished by the pattern of the elements and kind of connection of the elements to each other. As shown in the above Table, the pattern of the elements can be based on three characteristics straight, buckled and arched. The kind of connection of the elements to each other can be considered on three characteristics; single elements, discontinuous and continuous. As seen in the table, the terms straight, buckled and arched referred to the axis of each element and they are provided with a mnemo-technically drived code and presented as system diagrams. (Thomas Herzog et al. 1976: 29)

Furthermore, the system “Ss” in Table 3-2, the beam type of structure can be differentiated from the column type. Similarly, the plate type “Ds” can be distinguished from the disc type. *Also, the lattice shell system “Ca” can be divided according to the kind of surface curvature into unilaterally, synclastically or*

[32] Thomas Herzog et al. 1976: 29

anticlastically curved structural type or rotation, translation and ruled surface types and further according to the arrangement of elements as in net, radial, lamella and geodesic dome types. (Thomas Herzog et al. 1976: 29)

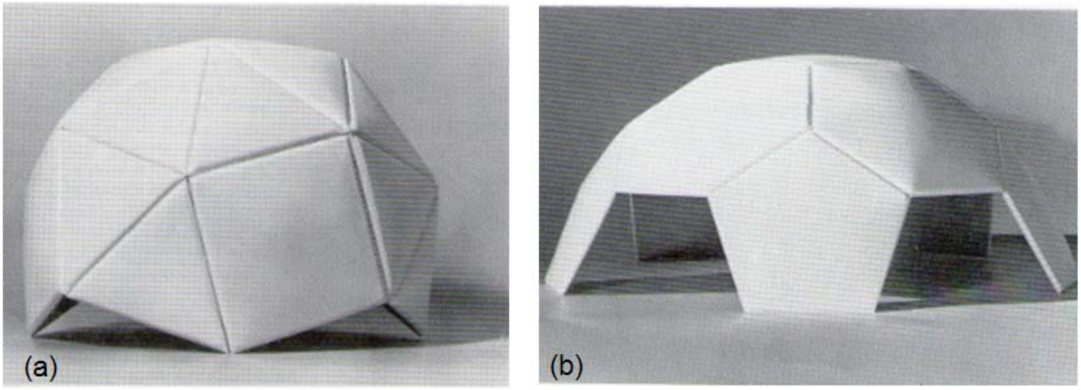

Figure 3 - 28 (a) & (b): Study project: filling element for grid shell.[33]

3.5. Tensairity

Tensairity is a hybrid system. The main idea of this system is to combine the lightness and simplicity of an air beam with the load bearing capacity of a truss structure. The structures are designed to carry their own weight even without pressure. The system simply combines with rigid element; strut on the top side and the flexible element which is able to get tension in this case is a cable in the lower side as shown in Figure 3-29.

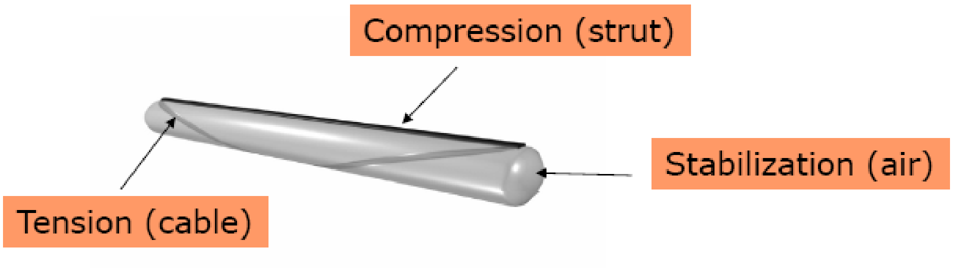

Figure 3 - 29: Synergetic combination of a pneumatic structure with cables and struts.

As soon as the beam is loaded from the top, the compression will occurre at the upper fibers and tension in the lower fibers. The goal of Tensairity is to divide forces into forces of compression and forces of tension. The loads transfer tension in the lower fibers which are taken by the cable and it stabilizes the strut against buckling

[33] Thomas Herzog et al. 1976: 51

the compression will be taken by the strut. In tensairity technology, the role of air is totally not to carry loads. Loads will be carry by the elements, cable and strut. Tensairity technology are mainly used for temporary structures, such as tents and paddocks, permanent and temporary bridges and also use in medium to wide span roof structures.[34]

Figure 3 - 30: Dismantled Tensairity Components.[35]

3.6. Pneumatic Motion Systems

Pneumatics which can be subjected to large deformation without incurring damage are suitable for motion system. But also, several pneumatics with opposite directions of motion can be combined or construction elements can be added. (Frei Otto et al. 1976: 112) *Pneumatically tensioned tubes and cushions for variable structures with mechanical drive are possible on the rolling, folding or displacing principles*. (Frei Otto et al. 1976: 12)

Bellows, diaphragm pumps and air suspension elements, belong to this category. The stiffening of rolled of folded tubes is often used. With an increase in pressure they become larger. This is especially true of rods and surfaces consisting of large

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[34] http://www.tensairitysolutions.com/#concept – retrieved on August 17, 2015

[35] http://www.tensairitysolutions.com/applications/ - retrieved on August 18, 2015

chambers. Furthermore, tubes are used for ring fasteners and for mobile control dams in rivers and locks with one and with more chambers. The systems represented until now are enlarged by increased pressure. However, some systems become smaller with an increase in pressure. Upon inflating a transversely stretched tube, it again becomes cylindrically rounded. (…). For instance, spiral tubes shorten considerably if pressure is increased. Their capacity to transmit forces, however, is low. (Frei Otto et al. 1976: 42)

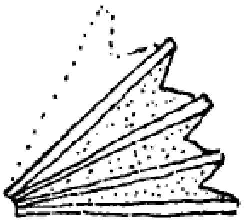
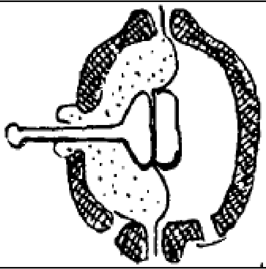
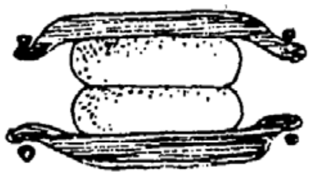
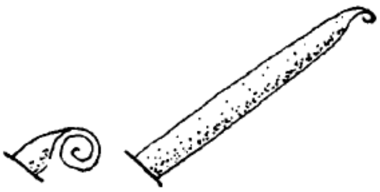
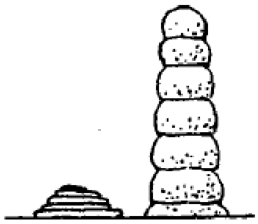
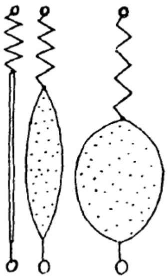
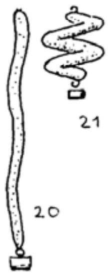
		
Bellow	Diaphragm pump	Air suspension elements
		
Rolled tubes	Pneumatics with separate chambers	Tubes for ring fastener
		
Inflating a tube	Tube shorten – pressure increased	

Figure 3 - 31: Pneumatics with motion system.[36]

[36] Frei Otto et al. 1976: 42

Figure 3 - 32: Mush-balloon at Expo 1970, Osaka.[37]

Figure 3 - 33: Mush-balloon: Opened & Closed.[38]

[37] http://www.tensinet.com/database/viewProject/3839.html - retrieved on August 30, 2015

[38] http://www.tensinet.com/database/viewProject/3839.html - retrieved on August 30, 2015

3.7. Pneumatics Building Workshop

During the last unit of this master's course, the students got a chance to build pneumatic inflatable cushion system practically. This two-day workshop was supervised by Mr. Thomas Herzig of pneumocell GmbH which was held in the country side of Melk, Austria. The main idea of this workshop is to build any type of pneumatic components by students to gain practical experiences about pneumatics.

As such, it was decided to manufacture one side of the wall from a pneumatic Japanese tea house designed by one of the students of this master course. This cushion is similar to a pneumatic mattress made of TPU (thermoplastic polyurethane) fabric. It consists of internal partition to maintain its shape.

Firstly, the cutting patterns were prepared on paper and then a fabric was laid onto it and cut accordingly. Secondly, the pieces were welded together by using the welding machine. The final step was to inflate the whole element.

Figure 3 - 34: Cutting pattern preparation.

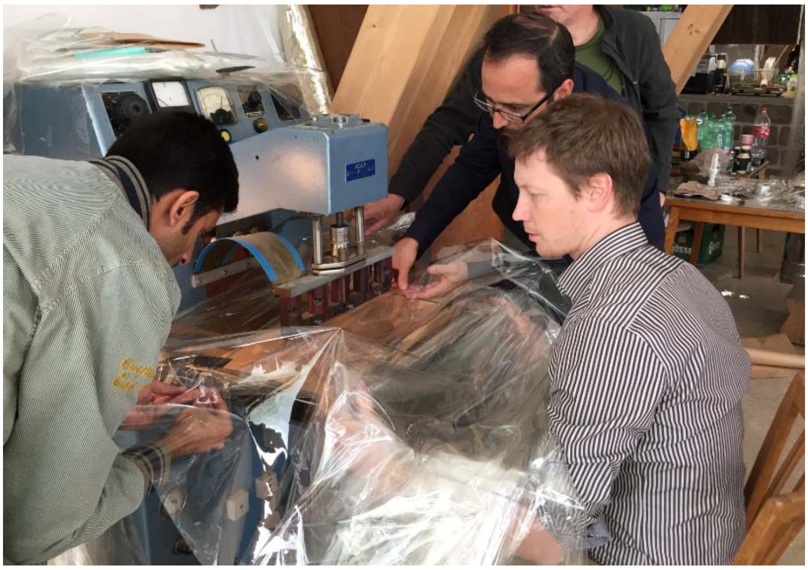


Figure 3 - 35: Welding work of air-inflated wall.

During this interesting two-day workshop, the students learnt and gained behaviours of pneumatic components, hand on experiences on making pattern, welding and inflating the cushion.

Figure 3 - 36: Completed air-inflated wall.

After the inflating of the fabricated air-inflated wall, it was tested whether this element was airtight by placing it in the lake and proved that the whole piece is airtight.

Figure 3 - 37: Testing of air-inflated wall

The knowledge gained from this two-day workshop was very useful in designing this accessible children playground as the same principles and techniques were referred to design the accessible children playground. The design of the playground is presented in the next chapter; Chapter 4.

3.8. Analytical Method

The analysis of a pneumatic membrane structure may be carried out using either mathematical techniques, numerical methods or experimentally. Mathematical and numerical techniques have many similarities in their formulation and method of solution. Numerical procedures must be based upon a mathematical relationship and many closed form solutions rely upon an iterative solution technique. It is in the representation of the structural model where two methods differ. Although a comprehensive understanding of the complex behavior of pneumatics has yet to be achieved, certain particular forms can be modeled using mathematical techniques. Spherical, cylindrical and many axisymmetric pneumatic forms have been analysed mathematically. (C.G. Riches & P.D Gosling)

The fundamental relationship between membrane stress and shape in a pneumatic structure for simple forms can be found by resolving forces normal *to the plane of the membrane this leads to a formula relating the membrane tensions to the principle radii of curvature for a given internal pressure*:

$$P = \frac{M_1}{r_1} + \frac{M_2}{r_2} \qquad (1)^{39}$$

Where $M_1 = M_2$ *= membrane stresses*

$r_1 = r_2$ = the principle of radii of curvature

P = internal pressure

For a sphere, where the principle radii of curvature are equal, the stress at every point on the surface and in every direction is the same and equal to:

$$M_1 = M_2 = \frac{P.r}{2} \qquad (2)^{40}$$

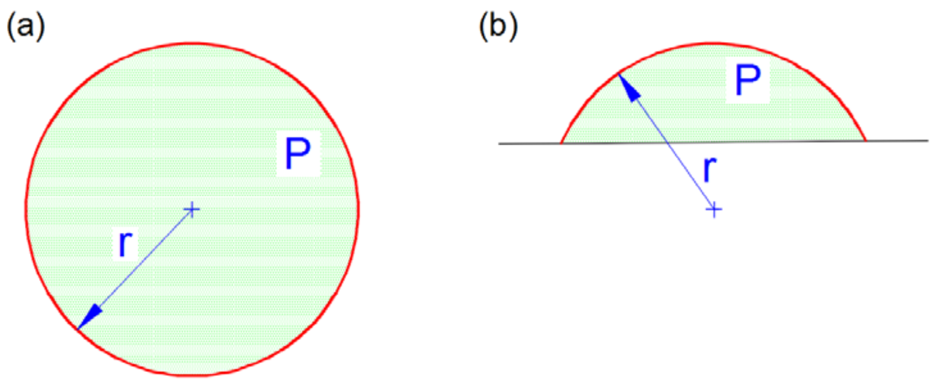


Figure 3 - 38: (a) A complete sphere. (b) A spherical segment

The above equation (2) also applies to spherical segment.

For a cylinder, a cylinder section and a tube, the following relation applies:

$$M_1 = \frac{P.r}{2} \qquad (3)^{41}$$

The radial tensions, M_1, in a cylindrical form can also be found as r1 = r and r2 = ∞. Hence,

$$M_2 = P.r \qquad (4)^{42}$$

The longitudinal tensions, M_2, are indeterminate and depend upon end conditions

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[39] C.G. Riches & P.D Gosling

[40] Frei Otto et.al 1982: 91

[41] Frei Otto et.al 1982: 92

[42] Frei Otto et.al 1982: 92

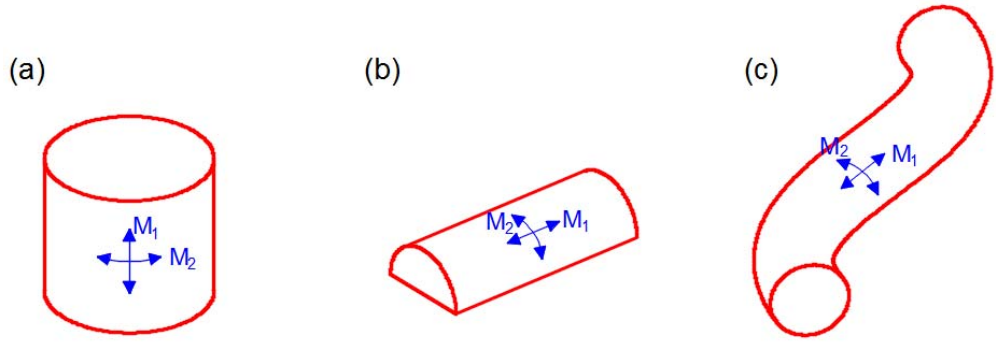

Figure 3 - 39: (a) A cylinder. (b) A cylinder section. (c) A tube

3.9. Load Assumptions

In pneumatic structures very large deformations can occur which affect wind and snow loading through the changed geometry of the envelope. The load is approximately applied to the undeformed and affixed there. Conservative loads, such as deadweight and snow, remain true to direction; internal pressure and wind act always normal to the deformed membrane. (Thomas Herzog et. al 1976: 166)

Internal Pressure

The form of the membrane and the internal pressure determine the tensions in the membrane and in the edges. The internal pressure is a permanent load which can be compared with the self weight or with the pretensioning of a construction. The required minimum and permissible maximum internal pressures dependent on several factors. The most important factors are the form of the structure and loadings, especially from snow and wind. For instance, the general internal pressure in normal air halls should be at least 30 - 50% higher than the maximum wind or snow loading. Air pressures of 300-500 N/m^2 (30 - 50 mm water column) have to date been usual in air halls which are shallow in shapes. (Frei Otto et. al 1982: 90)

For pneumatic low pressure systems, the differential pressure of the media divided by the membrane generally amounts to 10 to 100mm of water pressure. In the case of high pressure systems, the differential pressure generally amounts to 2000 to 70,000mm of water pressure. (Thomas Herzog et. al 1976: 17). For any geometry, the minimum internal pressure can be *determined by restriction of the displacements and by a margin of safety against folding in*. (Thomas Herzog et. al 1976: 166)

Dead Load

The specific gravity (γ) of the envelope material lies between 0.8 and 1.6 kp/m² per mm fabric thickness. The fabric usually used (t ≤ 1mm, g ≤ 1 kp/m²) are very light, so that the dead load can be ignored in structural calculations. Because of the low weight of the envelope material, a pressure difference of 1 to 2 mm water column is sufficient to maintain the envelope in its shape. (Thomas Herzog et. al 1976: 166)

Live Load

Air supported structures and other tensile membrane structures, frequently have to be walked on by man during installation and maintenance. (Frei Otto et. al 1982: 107). However, unlike other structures, this elevated play components are intended to withstand live loads from children while they are playing.

Wind Load

The movement under wind load is highly influenced by the geometric stiffness of the internal pressure in inflated structures. Wind, especially in the form of uplift, is regularly the critical case for membrane and cable stresses in lightweight membrane structures. (Brian Forster & Marijke Mollaert 2004: 194)

The necessary information on wind behaviour such as wind directions, top speeds, etc. has to be obtained from the nearest weather station. (Frei Otto et.al 1982: 95). Wind load is generally considered as a static load case, defined by a dynamic pressure (q) multiplied by a pressure coefficient (C_p).

$$w = C_p \times q \qquad (5)$$ [43]

$$q \approx \frac{1}{16} v^2 \qquad (5)$$ [44]

where, v = wind speed

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[43] Frei Otto et.al 1982: 99

[44] Frei Otto et.al 1982: 99

The local (C_p) values for small and simply-shaped structures can be derived using appropriate codes and papers. However, (C_p) values for complex and irregular forms which are sufficiently different from those described in the codes and long-span structures can be derived by carrying out wind tunnel tests and running Computational Fluid Dynamics (CFD) analysis. (Brian Forster & Marijke Mollaert 2004: 196)

Loading Capacity

> *Compared with other structural systems, the loading capacity of pneumatic structures s is very high for all kinds of stresses, if the internal forces exert a uniform tension on the envelope. The magnitude of the forces, which can be transferred by a pneumatic is determined by the elasticity of the envelope, the shape and the internal pressure of the pneumatic and finally by the type of the application of force (point-like or planer). The changes in the form of the pneumatic because of the effect of external forces depend on the character of the envelope (elasticity and thickness) and on the internal pressure*. (Frei Otto et al. 1976: 128)

Limit of Loading Capacity

> *Any closed (or partly open) envelope acquires another form and a different and generally higher capacity to transmit forces when filled with another medium. The limit of the capacity to transmit forces is reached if the object loses its original form through the intervention of external forces, or if the envelope bursts from the effect of the internal pressure. The bursting pressure is found by increasing the internal pressure to the breaking point.* (Frei Otto et al. 1976: 46)

3.10. Computational Modeling

There are many software tools, plug-ins and programs for modeling pneumatic structures. Among them, the computational modeling of the pneumatic accessible playground is designed by Rhinoceros which is flexible in modeling architecture model. The following Figure 3-40 shows some software tools and plug-ins for modeling.

Figure 3 - 40: Tools and plug-ings for modeling.

4. ARCHITECTURAL DESIGN

Pneumatic structures in building and construction industry are widely used to build air supported structures, façade systems and roof covering systems so as to cover the designed area. However, this pneumatic accessible children playground is designed not only to cover a space but also to serve as the supporting system. Therefore, it is necessary to withstand both its own weight and other loadings such as loadings while children are moving and jumping, rain load and wind load as well. The architectural design of this pneumatic accessible children playground is presented by introducing design inspiration and followed by the chapters describing design requirements, design considerations and design development in consideration for both children with disabilities and able-bodied children.

4.1. Design Inspiration

Pneumatic structures are part of living nature and it can be seen everywhere in this world. This accessible children playground was designed by referring to one of the living substances, flower is taken for the present study. Also, every plant or animal cell is a pneumatic because they consist of a flexible covering, the cell membrane, and a filling, the protoplasm. (Frei Otto et. al 1983: 17)

Figure 4 - 1 (a) & (b): Design study models.

A daisy is comprised of a floral receptacle, bracts and inflorescence as seen in the Figure 4-2. The petals are the major component which make up the form, shape, size, beautiful colour and appearance of the whole inflorescence.

Figure 4 - 2: Flower structure of a typical daisy.[45]

They are long and thin in shape and protruding upwards and leaning outwards making up the whole form and style of the flower. Their bases are attached firmly to the peripheral disc formed by bracts.

These petals can withstand their own weight and also additional live loads from bees, beetles, hoverflies, etc., while pollinating. In addition, it has to withstand under rain load and wind load. As daisies are honey plant and due to its colour, they are very attractive and colourful among meadows and fields[46]. Daisy was chosen to inspire this playground design as it is a symbol of innocence and also children are born innocent. They want only to be loved, to play, to learn, and to contribute.

In fact the petals of a daisy are like cantilever objects that we have been seeing every day as part of a building or a structure. A cantilever object also has the same principle as a petal of a flower at which the support is only at one end and they resist different kind of loadings.

4.1.1. Architectural Form

After understanding the principle clearly, the architectural form of the pneumatic elevated play components at the accessible children playground which is the centre of attraction of the whole play ground is designed by referring to the shape of the daisy. As it is an open structure type, it provides the public with the feeling of comfort, ease, relaxation, freedom, pleasure and attraction.

[45] http://www.invasive.org/weedcd/species/5937.htm - retrieved on September 27, 2015
[46] http://www.botanical-online.com/english/daisy_plant.htm - retrieved on September 27, 2015

The construction of a petal consists of an envelope which is a thin film. Inside the film there are fibers and the rest is filled with fluid. By referring to this principle, the design approach of the pneumatic elevated playground was decided to adapt the daisy's form and its principle. As such, the elevated playground is basically made up of combining the fabric envelopes together as in petals. Inside these envelopes, smaller pneumatic columns are placed together in separate cell of the envelope to take the form of a petal.

4.1.2. Structural Stability

As described above, due to its behaviour, a fabric envelope (which is considered as a petal) itself can withstand certain level of apply load if sufficient foundation is designed. However, for safety reasons, structural stability and the envelope to be able to resist wind loads, concentric pneumatic circular tubes are considered as first approach. The design consideration was tested using the physical models.

The first approach was made by using rubber balloon tubes as pneumatic tubes and connecting these tubes together with adhesive tape as belt connection. The study models are shown in Figure 4-3 and Figure 4-4.

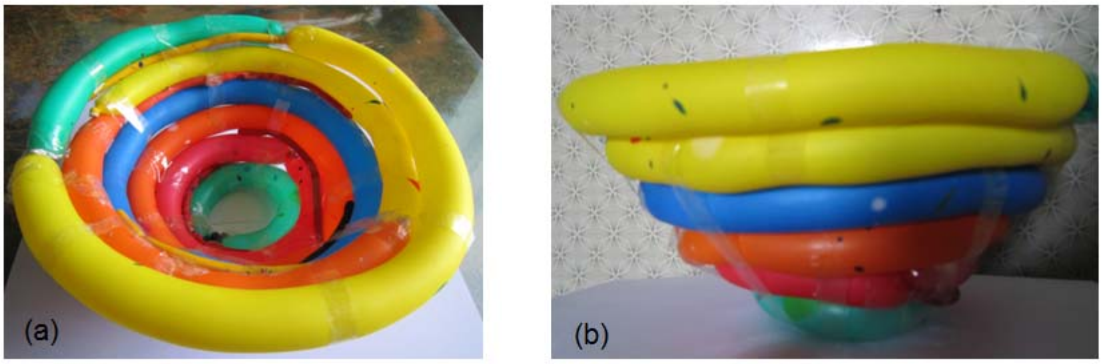


Figure 4 - 3: Design study model for pneumatic tubes. (a) Top view; (b) Side view.

The second approach is by adding the pneumatic tubes vertically to the horizontal pneumatic tubes in order to withstand the downward vertical loads such as rain loads. This inspiration has also been tested with physical models by arranging the vertical tubes in different locations as presented in Figure 4-4 (a) and (b).

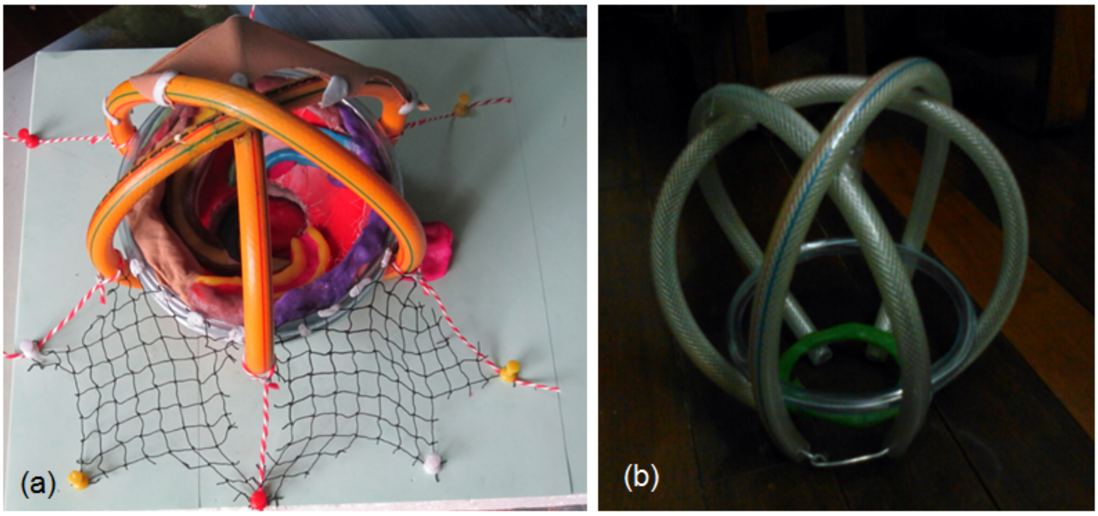


Figure 4 - 4: Design study model. (a) Vertical tubes; (b) Simplified vertical tubes.

However, during the testing it was observed that the vertical pneumatic tubes were difficult to stabilize under the loads due to their lengths, sizes and its structure system became more complex.

As such, the final approach was to stabilise the structure without adding any vertical tubes in order to form a real daisy shape and to prevent the structure from being very tall in height and bulky in shape. Finally, horizontal pneumatic tubes and sufficient numbers of safety cushions were introduced at close intervals as shown in Figure 4-5 below.

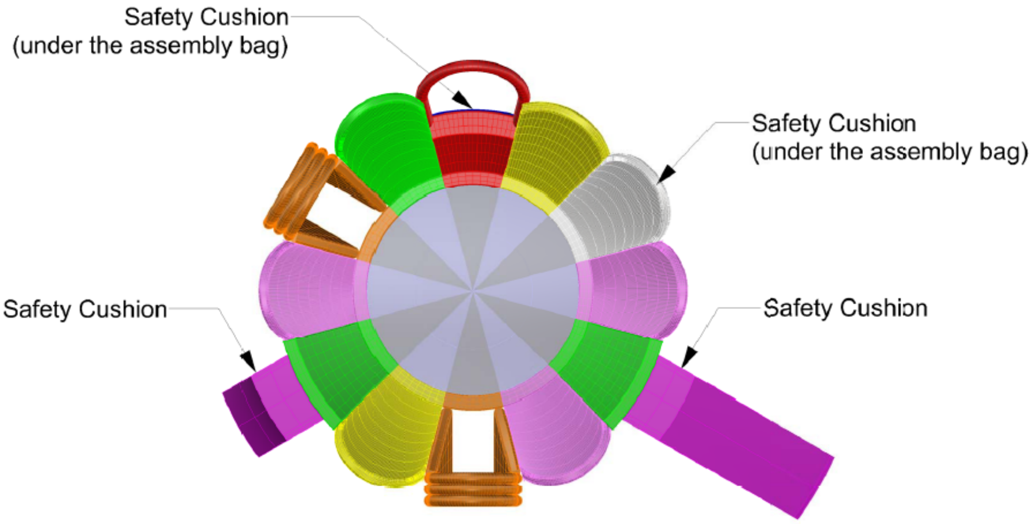


Figure 4 - 5: Safety cushions designed as supporting system.

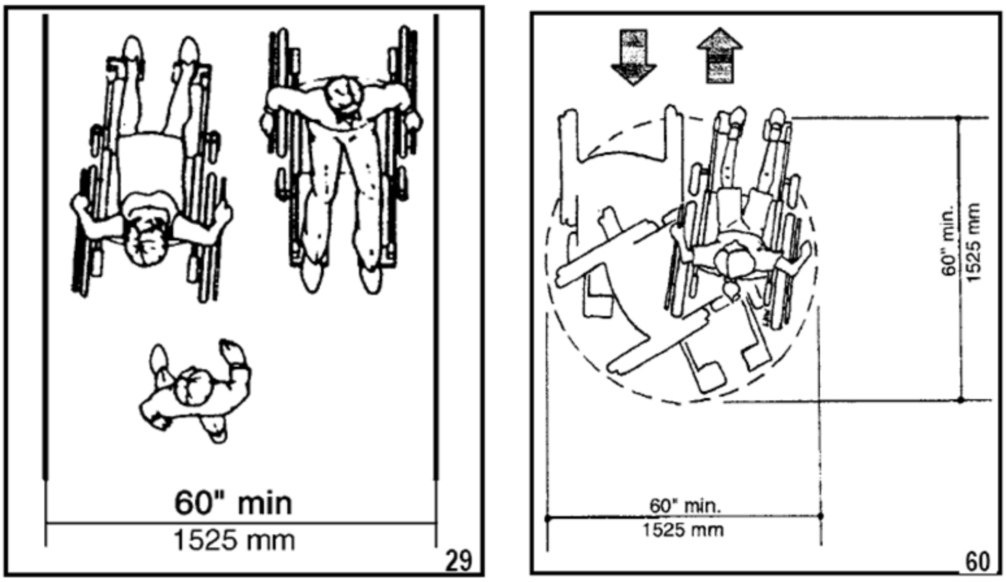
4.2. Design Requirements

As per requirement of the ADA (The Americans with Disabilities Act), a playground should consist of both ground-level play components and elevated play components. Therefore, this accessible children playground has both ground-level play components and elevated play components and all these components are designed by applying pneumatic principles. These components are designed carefully to comply with children safety rules described according to the "Accessibility Guidelines for Play Areas" published by the ADA.

As described, one of the main concerns of this playground is to create a place where normal children and children with disabilities can play together. Also, it is to make sure all the children, especially children with wheelchair can access the whole area of the playground with no difficulties and they are safe while playing. Unlike other playgrounds, the play areas for normal children and children with disabilities are located side by side without placing them apart. Therefore, at this playground the play areas for normal children and children with disabilities are located together so that they can interact with each other, learn and solve each other difficulties and share enjoyment together. Special care and attention has been paid while designing the locations of the play components.

The accessible routes for wheelchairs and mobility devices are designed by referring to the ADA. As shown in the Figure 4-6 below, the minimum width required for two wheelchairs to pass each other or to change direction is 1525 mm and the designed width of the wheelchair ramp has satisfied this requirement.

Moreover, the wheelchair ramp of this pneumatic accessible children playground also complies with the gradient of the route which satisfies the requirements of the ADA. The elevated landing is designed in such a way that enough space is available for a wheelchair to park and to make a 180 degree turn.



(a) (b)

Figure 4 - 6 (a): Minimum requirement for two wheelchairs; (b) Minimum requirement for turning circle.[47]

For safety, the grip of the climbing net has also fulfilled the requirement of public playground safety which is less than 430mm (17 inches) to prevent from entrapment hazard. Moreover, the ropes are soft and made with non-slip covering to protect children from hurting their hands while they are climbing. In addition, the climbing net is protected by pneumatic cushion to provide full safety to the children.

According to ADA, the slide landing platforms and slide chutes also need to meet the requirements. For instance, the slide platforms should meet minimum length and width requirements to help children from changing positions such as standing and sitting. In order to comply with the requirement, the pneumatic cushion is designed as the elevated slide platforms. Similarly, designing the slide chutes also need to meet minimum width and height for the safety of the children. Also, it is required to set up a use zone and slide exit zone with protective surface to eliminate the hazard of falls from elevated heights and to make sure there is no object near this area. The circular shape inflatable cushion is provided in the middle of the pneumatic elevated play components to comply with the requirement.

Another different kind of access to the elevated slide platform in this playground is stairway with steps to improve children physical movement Thus, it is important for

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[47] Play guide ADA 2005: 20

the stairway to meet the slope requirements for both disabled children and able-bodied children to climb up easily without any difficulties.

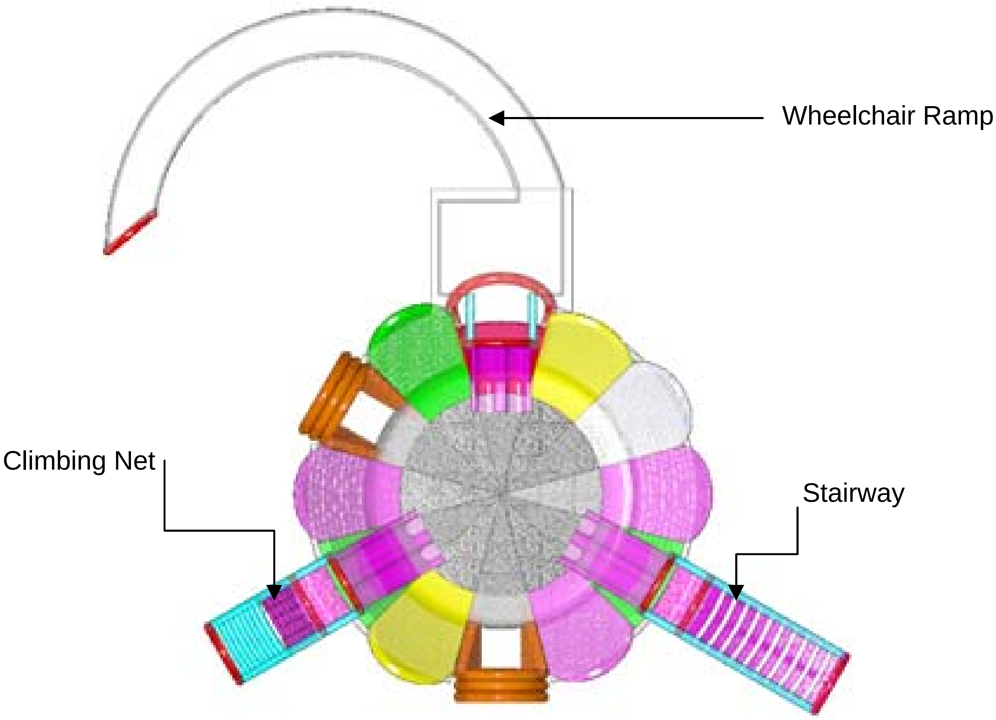

Figure 4 - 7: Different accesses to elevated playground.

As safety is a major concern of the playground, all the play components, stairway and climbing net are well designed with handrail and pneumatic side covers to help children to balance themselves while playing and climbing. The design of these handrails complies with the ADA as well. Surfacing is also an important role to avoid children from being hurt from playground injury. The pneumatic cushion is designed as surface protection at the elevated play component.

4.3. Design Considerations

The main idea of this thesis is to design an accessible children playground for all children by applying pneumatic principles and technology. In addition, it is intended to provide not only enjoyment and fun but also help the children increase their physical activities and develop critical thinking and problem solving skills which are essential to achieve success in their lives.

Literature studies and survey have shown that pneumatic principles could be a good solution to design this type of playground. Unlike some rigid bodies, pneumatic bodies according to its principles, will resist the applied load with small and ease deformation due to the pressure of air inside. Moreover, it will return to its normal shape as soon as the force was released.

At playgrounds, slides are the centre of attraction and children enjoy playing there. When there are lots of children enjoying the slides there surely will be a little bit of waiting. This fosters social skills like taking turns, being patient and tolerating others physical abilities. Three slides are incorporated into the elevated play components and it is very much interesting due to its shape and design.

The elevated play components are in the shape of a daisy formed by using pneumatic cushions and tubes as its structure systems to withstand the loadings and to form an interesting and beautiful structure system. Without these, pneumatic tubes and cushions, it will not be able to withstand the loadings. As the structure system; pneumatic tubes and cushions are lives of this playground and it is very important to design these elements strong and safe to provide each child safety while they are playing. As such, careful attention has been paid to the design of the structure system and designed to satisfy the structural requirements at the same time forming an interesting, beautiful and pleasing architecture shape.

The other consideration is to provide children lots of enjoyments and challenging activity as well. These activities are incorporated into the design by providing varieties of ways to access the elevated platforms areas. They include access by easy ramps for wheelchair users, stairway with steps and net climbing, so that children can choose any appropriate methods based on their abilities to access to the elevated platforms.

Moreover, to provide children with great fun and thrilling moments, one of the access methods to reach a slide platform is by climbing net for those children who love challenging and inspiring adventures. Another different kind of access to the elevated slide platform in this playground is stairway with steps to provide children with physical movement.

Additionally, various kind of ground level play components are designed to provide children with lots of joy and great benefit for them to enjoy long term health.

4.4. Design Development

This aesthetically pleasing pneumatic accessible children playground is a public recreation place that serves both children and parents with enjoyment and leisure. As it is an outdoor playground, it also provides the users with the feeling of comfort, relieve, relaxation and freedom. This playground has been developed by paying special attention to the design considerations, which is based on the knowledge of behaviours and requirements of disable children gained from the visits to the children's rehabilitation center at Yangon Children Hospital Child Neurology department in Myanmar.

As described above in the design requirements and consideration, this accessible children playground has included elevated play components and ground-level play components designed by using pneumatic principles and technology. The elevated level play components is designed to provide children with great fun and thrilling moment and at the same time help them with the development of strength in the upper and lower parts of the body and to provide children with long term health. In order to achieve these benefits, the elevated play components are made up of slides; which are the central attraction in the accessible children playground and the climbing net, the stairway and wheelchair ramp to reach to the elevated platforms for sliding.

The ground-level play components include bouncing station, sticker station, dome climbing, swing ball, walking aid, crawling tubes and play station as shown in the Figure 4-8 below. These ground level play components are purposely designed to introduce the essential handicapped equipment for exercise, to develop children's motor planning, to strengthen up the muscles and to help them improve their balance coordination and timing.

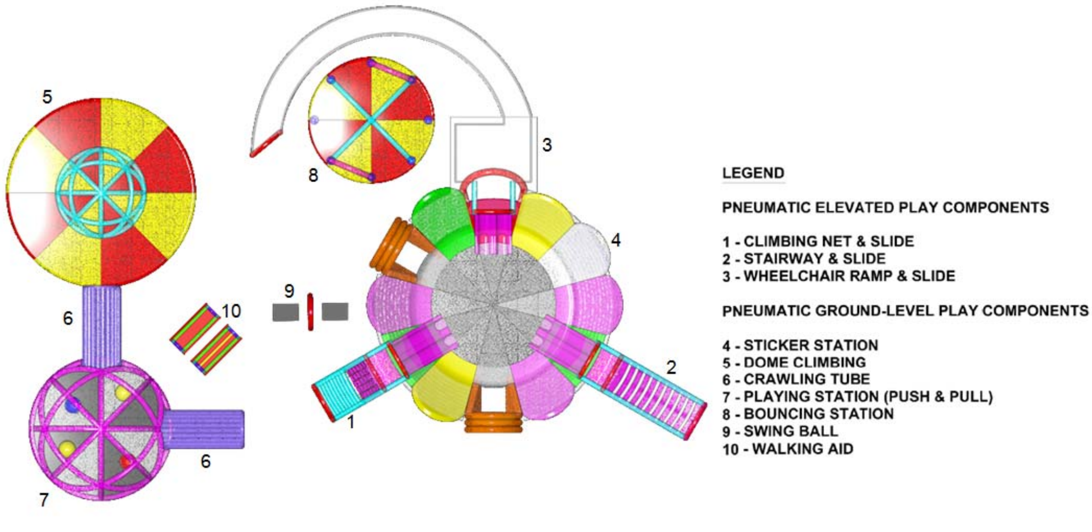

Figure 4 - 8: Plan view of the pneumatic accessible children playground.

Elevated Play Components

First of all, the pneumatic elevated play components which are the main component in the accessible children playground comprise fabric envelopes, pneumatic tubes, and safety cushions.

Inside the elevated play component, three slides are designed for the needs of children with different abilities. Their heights differ from 1000mm and 1900mm, respectively. The slides are designed with pneumatic technology to provide safety to the children. These slides are purposely constructed as double lane for the convenience of disable children to slide together with the help of their parents and care takers.

The children can choose the desire access based on their abilities such as climbing net, stairway and wheelchair ramp. Climbing nets provide children with great fun and thrilling moments. This type of play encourages children to reach the top. Climbing definitely helps to *strengthen the muscles* to achieve better ability for the movement of a part of the body.[48]

In addition, if a child is physically unfit to do pulling and climbing activities, she / he will not be left behind. She / he can reach to the top of elevated landing by pushing the wheelchair. From the elevated slide, she / he can slide on a pneumatic air cushion slide joyfully. As safety is one of the major concerns for the playground, its base is covered fully with pneumatic cushion to receive all the children from the slides. The base diameter of the elevated play components is 9000mm and the top is 13500mm and the highest petal is 2750mm high.

The stairways improve children physical movement. This climbing exercise especially helps the development of *strength in the upper and lower body equally well* since children used both their legs and arms to pull themselves up the stairs.[49]

Due to its beautiful shape, attractive colours and behavior of pneumatic structures, children will definitely willingly go inside the daisy to play. There are altogether two entrances to enter the playground if one does not want to do any climbing and sliding activities.

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[48] www.climbnet.com/playgrounds - retrieved on 20 September, 2015

[49] http://www.aaastateofplay.com/different-types-and-benefits-of-playground-slides/ - retrieved on September 20, 2015

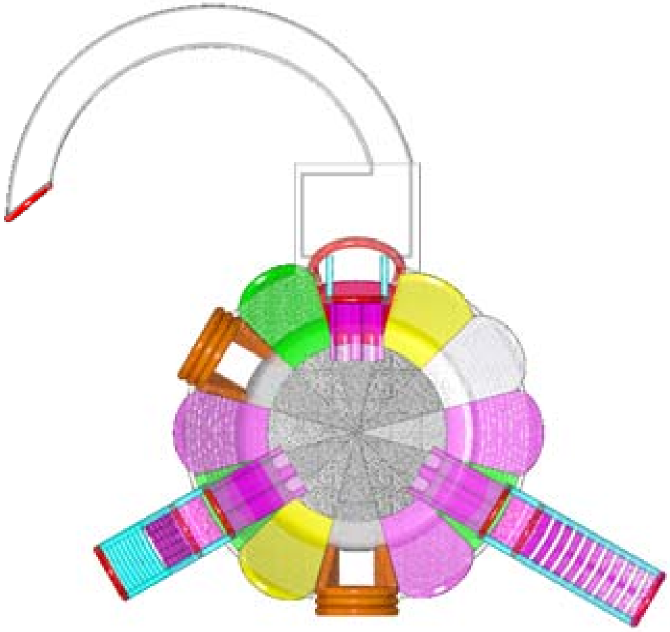

Figure 4 - 9: Plan view of pneumatic elevated playground.

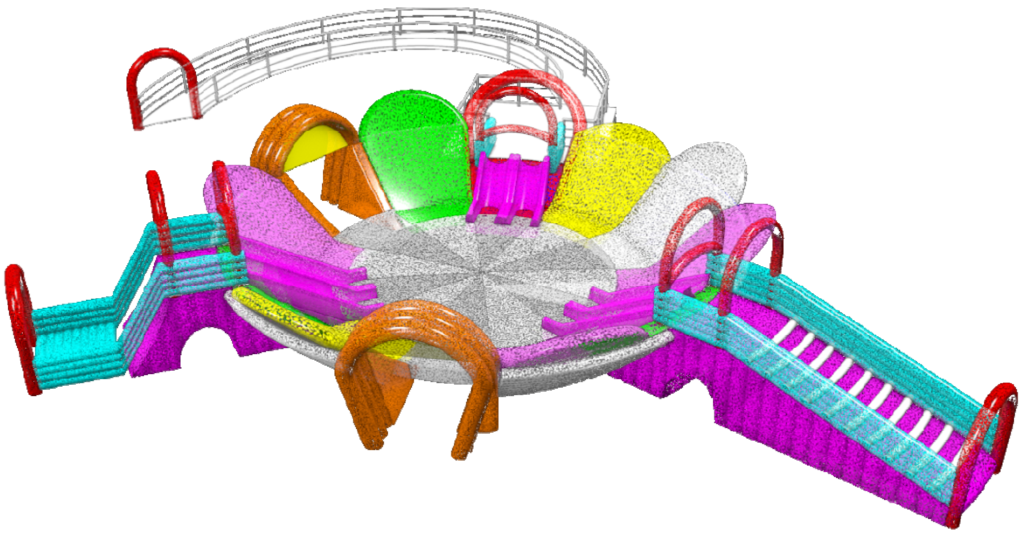

Figure 4 - 10: Isometric view of pneumatic elevated playground.

Ground-Level Play Components

Sticker Station

There is a sticker station provided on the surface of one of the petals where numbers of Velcro are attached. Children can pick any shape and colours of readymade fabric and simply stick on the petal's surface. Allowing children to stick or paint on vertical or inclined surface like wall or easel is very good because they have to put their arms over and up at shoulder height and try and keep that arm elevated which means *strengthening of shoulder blade muscles*.[50] As such, the petals shape fabric envelopes are the best place for children to enjoy such kind of activity.

Dome Climbing

If one comes out from the elevated playground, there are some attractive colourful play stations waiting. The dome which is 5000mm in diameter, 1800mm in height and comprises of inflated tubes. It allows children to climb over and crawl under the inflated tubes. For safety, there is also an inflatable cushion provided underneath the dome. While climbing these tubes up, down and sideways children will learn that they need to work on *balance coordination*. Also, research on health play has shown that playground climbing is of great benefit for children to enjoy *long term health*.[51]

Crawling Tubes

From this exciting dome, children can craw along the circular shape crawling tube which comprises inflated tubes and to get access to the play station. Crawling tubes provide fun and excitement in playgrounds. They are used to develop motor planning. In a crawling tube physically and neurologically disabled children can crawl as well as perform balance activity. By crawling, muscles of the neck, shoulders, wrists and back are strengthened. A crawling tube helps children practice large movement of their arms and legs.[52]

Play Station

The play station is designed for those children who can do their therapy exercise. It is made up of triangular shape air-inflated tubes which comprise the 8000mm diameter half sphere shape. There are some toys provided for children to participate in pushing and pulling activities. Pushing and pulling activities are very important for children who suffer from *Brachial Plexus Palsy*. This is an injury that occurs to the nerves and muscles that occur in the shoulder, shoulder blades and down to the finger tips. This activity contributes to *strengthening up shoulder blades and shoulder* for the arms to be able to move better.[53]

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[50] https://www.youtube.com/watch?v=U7umR9sPUqs - retrieved on 15 September, 2015
[51] www.climbnet.com/playgrounds - retrieved on 20 September, 2015
[52] http://www.myspecialneedsnetwork.com/profiles/blog/show?id=5940659%3ABlogPost%3A29429&commentId=5940659%3AComment%3A29388 - retrieved on 20 September, 2015
[53] https://www.youtube.com/watch?v=U7umR9sPUqs - retrieved on 15 September, 2015

Bouncing Station

Outside the play station, there is a thrilling, colourful bouncing station. The bouncing station provides inflatable arches as support for children who need to grab a handrail while they are jumping. This pneumatic bouncing station with diameter 7300mm is designed by using pneumatic tubes as hand supports and the base support which is the pneumatic cushion is for bouncing. Bouncing is great for children because it helps them improve their *balance, coordination and timing*. It helps children to be more confident in their movement skills and gain more control of their bodies.[54]

Walking Aids

The pneumatic walking aid is located outside the play station. There are some children who suffer from several physical disabilities and are not able to walk on their own. The walking aid is designed to help the children *practice walking*. Both sides of the walking aid have protective pneumatic walls so as to protect children from falling down. Moreover, there is also a walking aid with knee separator to help the children to keep their *knees separated*.

Swing Ball

There is also another play equipment for those children who are not able to leave their wheelchair. The swing ball will provide children to stay on their wheelchairs and swing the ball. It will help *children to strengthen up their shoulder blades and shoulder* for the arms to be able to move better.

[54] http://blog.childorganics.com/2011/11/benefits-of-bounce.html - retrieved on September 20, 2015

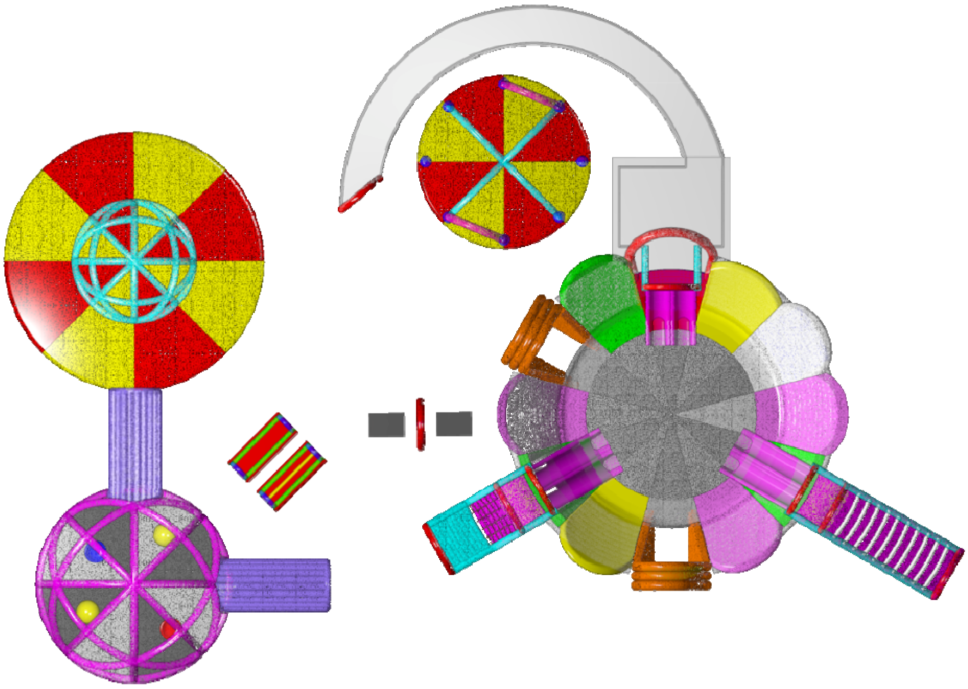


Figure 4 - 11: Plan view of pneumatic ground-level & elevated playground.

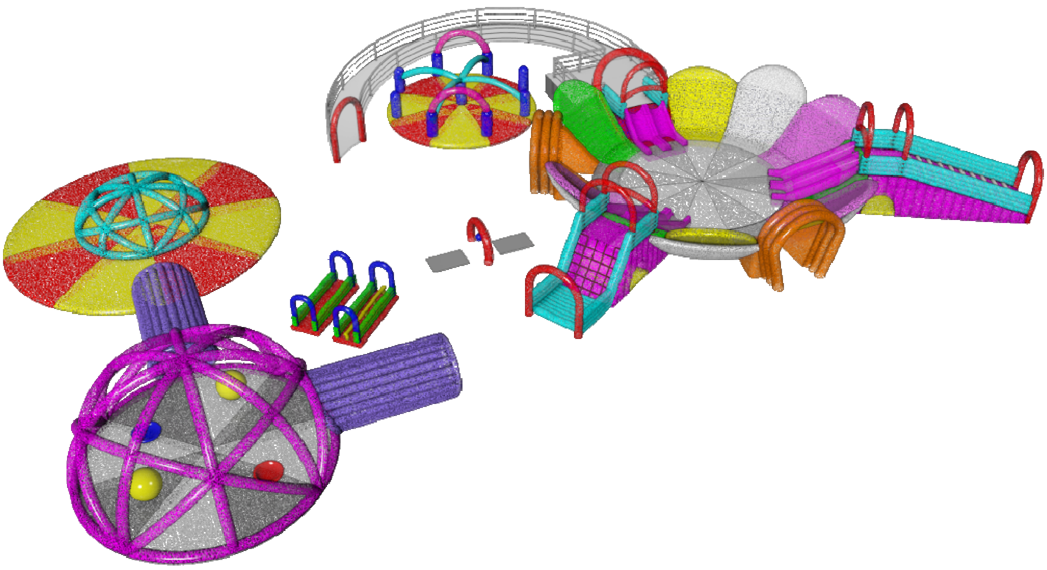


Figure 4 - 12: Perspective view of pneumatic ground-level & elevated playground.

5. STRUCTURE SYSTEMS & CONSTRUCTION DETAILS

This chapter presents the structure systems and construction details of the pneumatic elevated play components. The shape of the play components is designed from a segment cut from a parabola to satisfy the mathematical formula for stability. The overall dimensions of the pneumatic elevated playground are 10000mm base diameter, top diameter is 13500mm and the vertical height is 1900mm, respectively. The entire elevated play components are divided into two main structure systems namely primary structure and secondary structure.

5.1. Primary Structure

The primary structure system comprises of air-inflated tubes, entrances which are made up of combining the bended air-inflated tubes in the form of arches and supporting cushions.

Firstly, the air-inflated tubes were designed by using printed transparent TPU fabric and they enclose the parameter of the playground. The main function of these tubes is to resist outward deflection by transferring lateral forces to the entrances and cushions and to prevent the secondary structure from buckling due to dead loads and live loads from children and other loadings such as wind load and rain load. In addition, air-inflated entrances and supporting cushions resist the downward loads and provide extra stability and strength to the secondary structure.

The air-inflated tubes are 300mm in diameter and the bases of these tubes connect directly to the footings at every 2000mm interval. In order to prevent these tubes from buckling, to shorten their slenderness ratio and to stabilize themselves to withstand the downward vertical forces, they are divided into 5 separate sections as can be seen from the Figure 5-1, the two ends of the section 1 of primary structure have been connected to one side of entrance 1 and one side of supporting cushion 1, respectively. Similarly, section 2 of primary structure has been connected to the other side of the supporting cushion 1 and on one side of entrance 2 and the rest of the primary structures are also connected likewise.

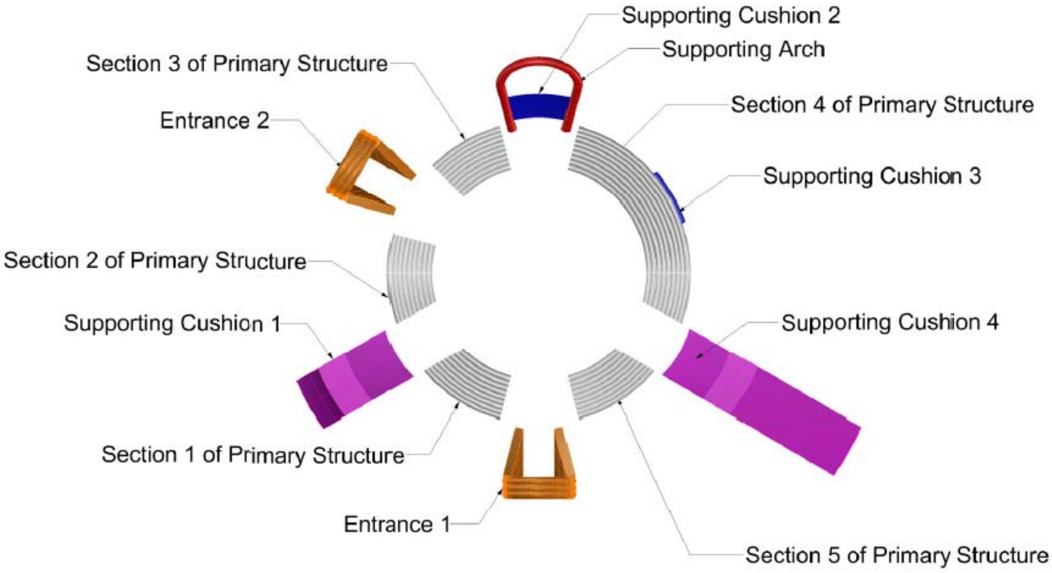


Figure 5 - 1: Plan view of the primary structure before assembling.

There are altogether 2 entrances at the elevated children playground. A variety of colourful printed transparent TPU fabrics are used to attract children's attention. The entrance 1 is located near the 2 slides to provide convenience for the children to slide and once again go back to climb the net and stair way very quickly. The entrance 2 is located near the wheelchair ramp so that children can access their wheelchairs easily and quickly once they have done sliding activity. Both entrances are designed with 3 pieces of 400mm diameter inflated tubes and supporting cushion joining together to withstand the forces from the perimeter tubes. These 3000mm high entrance tubes are joined together by means of belts and their bases connected directly to the foundation in order to transmit forces.

This elevated play component includes 4 supporting cushions. They support the downward loads and lateral forces from the secondary structure as well as the primary structure. In addition, the supporting cushions 1 and 4 as shown in Figure 5-2 and 5-3 are designed to resist the loading from children while they are climbing on the stairway, crawling and climbing on the net and during sliding. They are to reach to the pneumatic elevated platform which is 1900mm high. As such, these cushions are designed by paying special consideration and care has been taken.

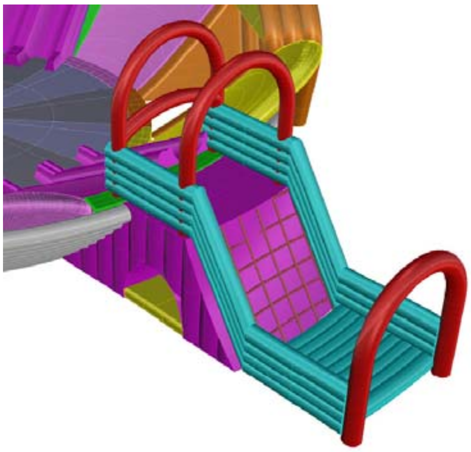


Figure 5 - 2: Close-up view of the pneumatic supporting cushion 1 which is designed for climbing net and sliding.

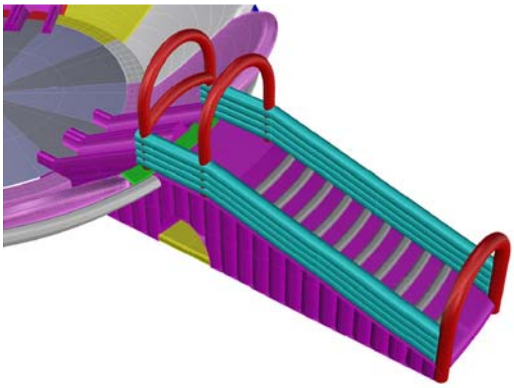


Figure 5 - 3: Close-up view of the pneumatic supporting cushion 4 which is designed for climbing stairway and sliding.

The supporting cushion 2 is supporting the slide of 1000mm in height designed for those children who are not able to reach to the 1900mm height. The remaining supporting cushion 3 and entrance arch are designed to shorten the slenderness ratio of the primary tubes.

All these components are joined together in the factory by welding and the inflation will be done on site after installation.

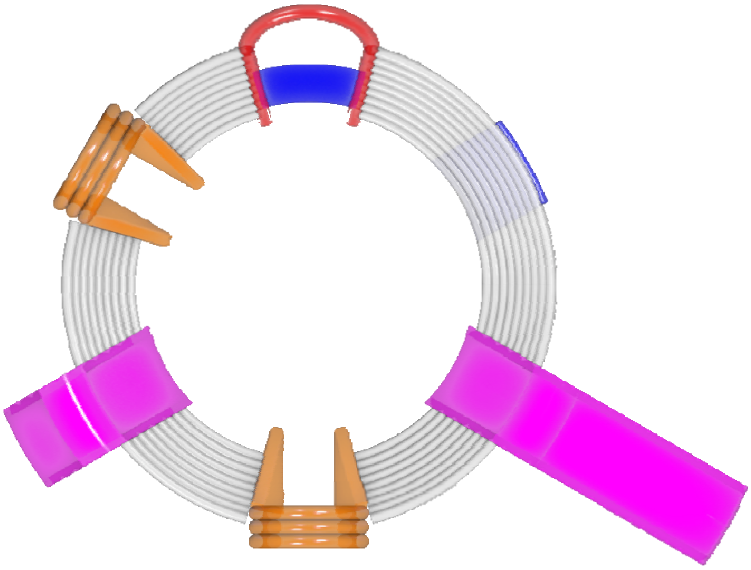


Figure 5 - 4: Plan view of the primary structure after assembling.

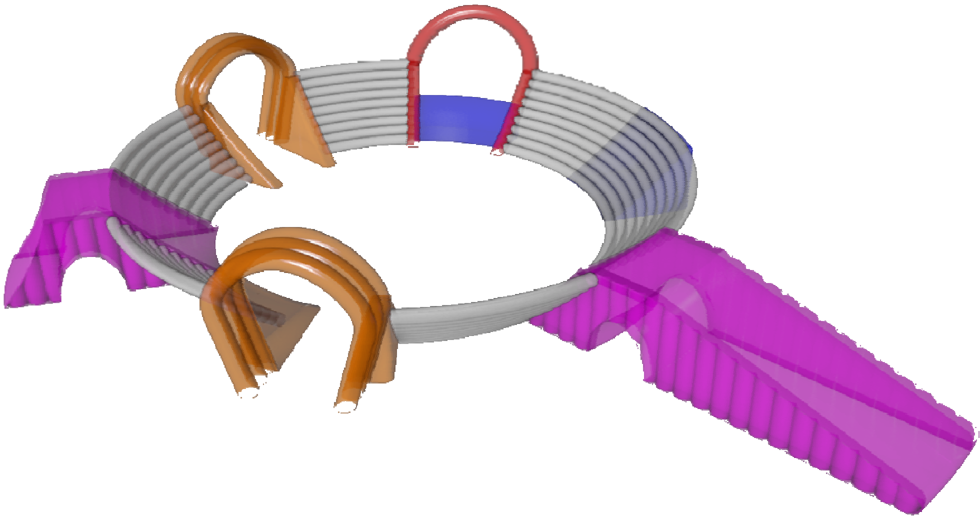


Figure 5 - 5: Isometric view of the primary structure after assembling.

5.2. Secondary Structure

The secondary structure of the elevated play component is developed by referring to a segment of a shell in parabola form in order to get a smooth curvature. They are connected to the primary structure at the top and connected to the foundation at the bottom in order to withstand its own weight, dead loads, live loads and other external loads such as wind and rain.

The secondary structure of the playground consists of two layers; the inner layer is made of column type pneumatic bags and the outer layer is the fabric envelopes with partitions to install the pneumatic columns, as shown in Figure 5-6. Each envelope consists of four partitions and they are made up of printed transparent TPU fabric. The envelopes are designed with separated partitions so as to maintain the required shape and prevent it from bulging out. Without these partitions, the cushion will behave like a pillow when it is being inflated.

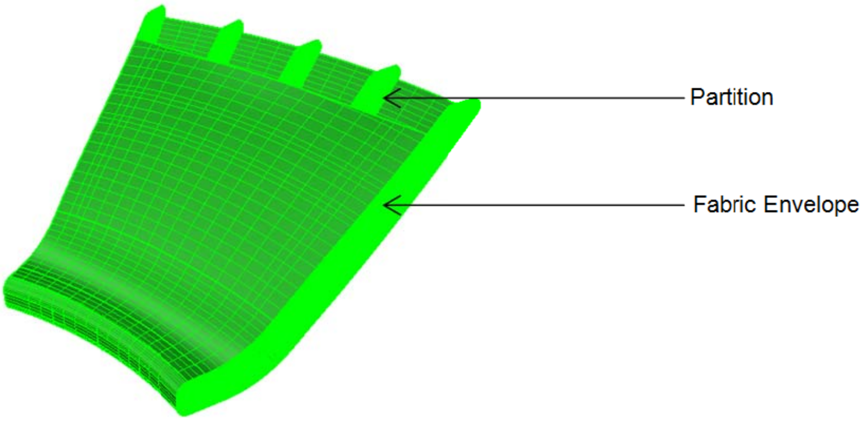


Figure 5 - 6: A fabric envelope with partitions.

There are altogether 10 pieces of fabric envelopes to form the secondary structure as shown in Figure 5-7. They are divided into 2 sections; section 1 and section 2 of the secondary structure. The first group consists of three fabric envelopes welded together to each side of the entrance 1 and entrance 2. Similarly, the second group contains seven envelopes and welded together to the other sides of the entrances.

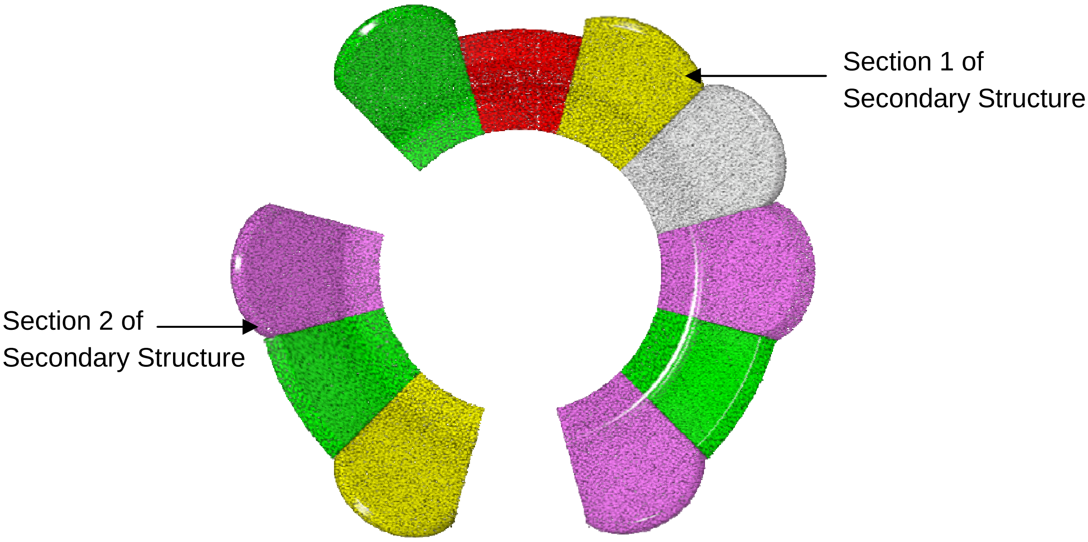


Figure 5 - 7: Plan view of secondary structure.

The base dimension of each fabric envelope is 2200mm length and the top is about 3300mm and its width is 300mm. Their heights vary from 1000mm, 1900mm, 3000mm, 3300mm and 3500mm, respectively. The variable heights help the structure to form daisy's petals and it enhances the architectural design.

The inner components to put into the partitions of the fabric envelopes are made of replaceable pneumatic columns. Their shapes are designed to withstand the downward and bending load as shown in Figure 5-8. They are to be installed into the fabric envelopes. Another advantage of using separated pneumatic column is that it can provide better safety for the users than the conventional single pneumatic component. If in case a pneumatic column fails, it is replaceable with a new column immediately on site without any difficulties.

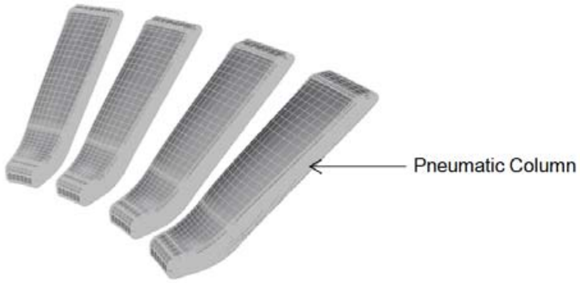


Figure 5 - 8: Standardised pneumatic columns.

Form like compound forms are very sensitive to concentrated outer forces if they are designed without a firm skin or an envelope as shown in Figure 5-9. As such by putting these pneumatic columns into the fabric envelope provided relatively firmer than using the pneumatic columns themselves, sensitivity is considerably reduced. (Frei Otto et. al 1976: 33).

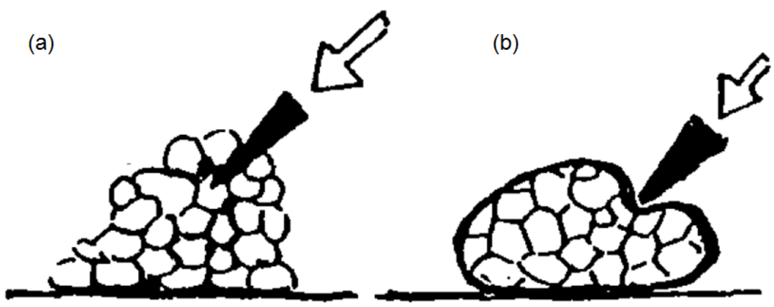


Figure 5 - 9: Pneumatic compound form. (a) without an envelope; (b) surrounded by an envelope.[55]

[55] Frei Otto et. al 1976: 33

After these secondary structures; fabric envelopes are welded together, the pneumatic columns will be installed one by one into the partitions of envelopes, Figure 5-10. Some of the fabric envelopes need to install an additional air bag to form a complete part of the petal. The pneumatic air bags will be put inside the fabric envelopes and will be inflated to form complete structure. In order to help the installation easier and maintenance simple, these pneumatic air bags are designed not only of the same dimensions and size but also can be accessed from the top part of the fabric envelope.

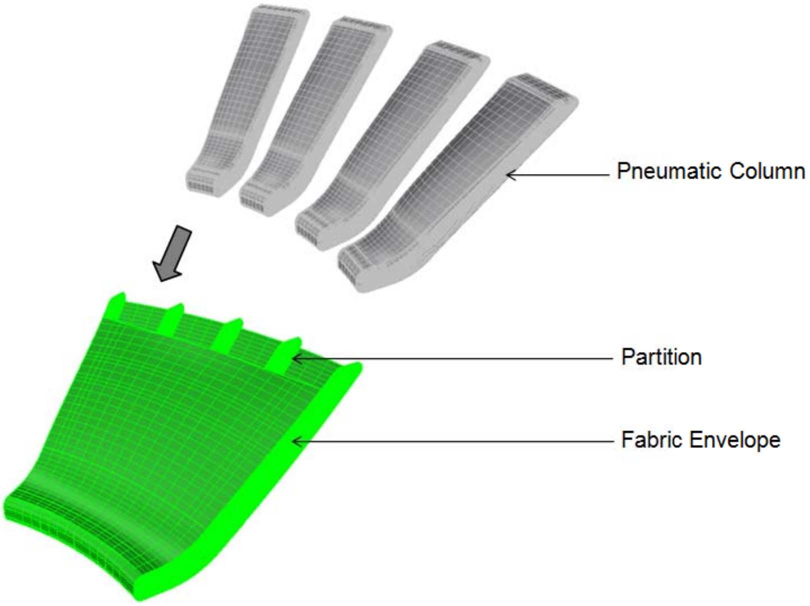


Figure 5 - 10: Overall view of an envelope and pneumatic column.

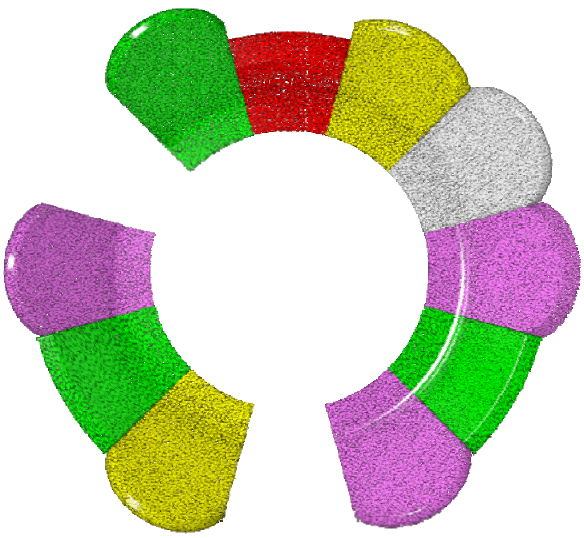


Figure 5 - 11: Plan view of secondary structure after assembling.

In order to keep these fabric envelopes in place firmly, they are connected with the primary structure by means of membrane pockets. Their bases are connected to the foundation by using membrane strips, galvanized mild steel clamping bar and bolt and nut connections.

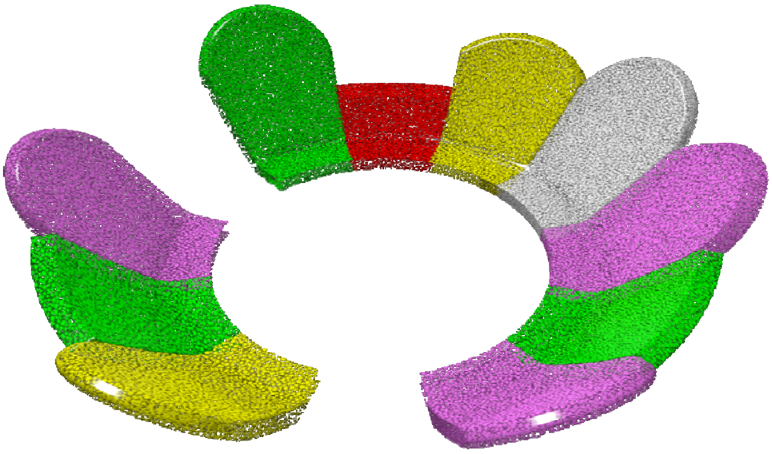
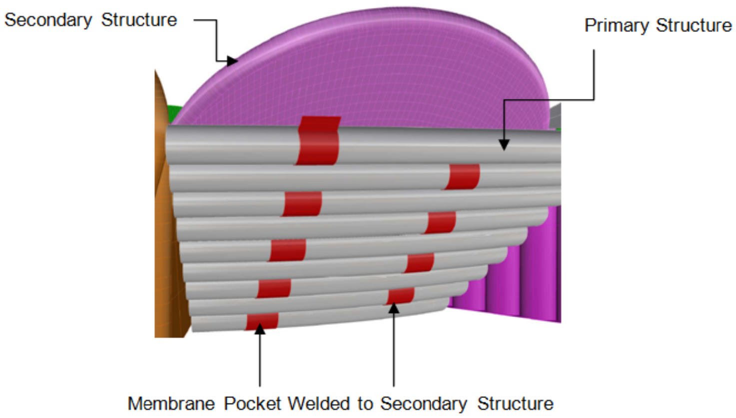


Figure 5 - 12: Perspective view of secondary structure after assembling.

(a)



(b)

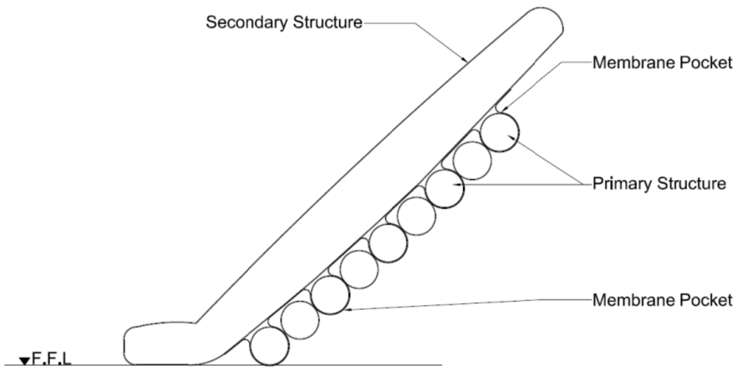


Figure 5 - 13: Primary and secondary structures connection detail. (a) 3D View; (b) Section.

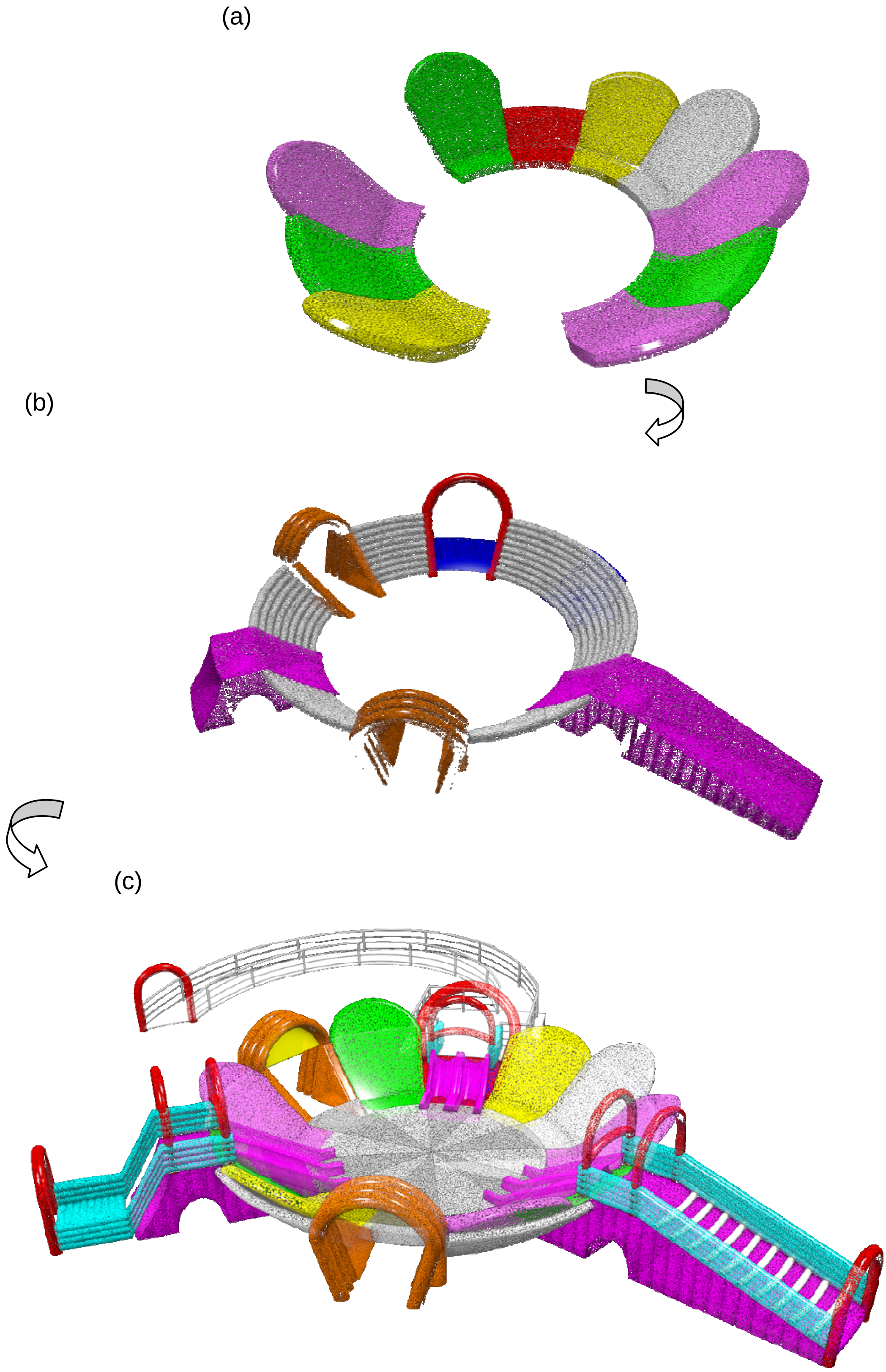


Figure 5 - 14: Elevated play components perspective views. (a) Secondary structure; (b) Primary structure; (c) Complete structure.

5.3. Anchorage Details

Pneumatics playground can be very interesting and attractive to children and at the same time it can also be a dangerous playground if necessary safety measures are not taken into account. Since inflatable structures have a particular low self-weight, generally insufficient to compensate the potential uplift generated by wind loads, they must be securely anchored to the ground. (Jacobo Krauel 2013: 45). The anchorage design of the elevated play component consists of 300mm length membrane strips welded to the primary and secondary structures. The other ends of these strips are welded with keder. Then, these keder ends are being clamped to the foundation by means of clamping bars and casted anchor bolts.

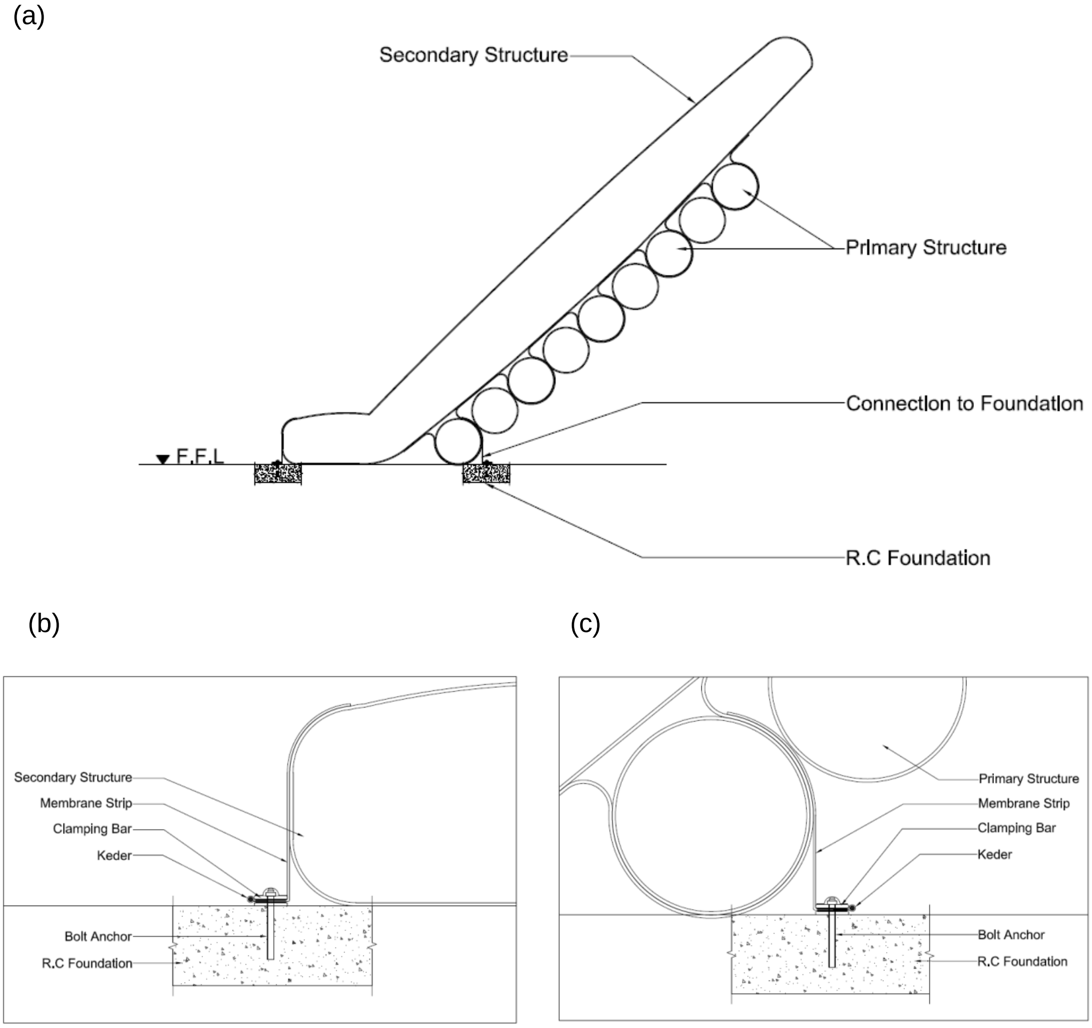


Figure 5 - 15: Fixing of the membrane to foundation (a) Section view. (b) Fixing at secondary structure; (c) Fixing at primary structure.

Render Pictures

Figure 5 - 16: Render Picture View 1.

Figure 5 - 17: Render Picture View 2.

6. CONCLUSION

This master's thesis has presented the design of accessible children playground by referring to pneumatic principles and technology. In order to design an attractive and functional pneumatic accessible children playground, this master's thesis started with literature study about pneumatic structures, their principles and applications. Additionally, the literature review was extended to types and treatment of disabilities and disabled children behaviours to understand the knowledge and incorporate in designing the accessible playground.

Moreover, site visits were made to some handicapped children playground in order to study the types of play components there and how these components are arranged for the convenience of the children. Furthermore, number of visits were made to the child rehabilitation center at Yangon Children Hospital Child Neurology department situated in Myanmar, to observe how physiotherapists and occupational therapists are using equipment to help the children to be able to perform their daily activities by their own, to improve their health physically and mentally and which type of equipment can be designed by using pneumatic principles and technology and what are the benefits children can gain by using these pneumatic tools and equipment.

This playground is achieved by combining several basic pneumatic forms together. These forms include air-inflated cushion with internal partitions, pneumatic cylinder, bending the air-inflated tubes into different shapes in order to achieve the desired forms to help children build up their strength physically and mentally. Compared to other materials such as steel or timber, technical fabrics provide different feeling and also allow multifaceted range of applications due to its flexibility, availability of different fabric colours and significant product properties. Moreover, by using inflatable cushions as floors and side covers help a lot for disabled children as it is very hard for some of them to walk on their own and also they can fall down any moment and unlike other materials using inflatable cushions help and protect the children from getting hurt and keep them safe.

After incorporating all the knowledge, this pneumatic playground is designed in such a way that disabled and able-bodied children can play side by side. Able-bodied children can be of great help when they learn and know about the nature of their friends' weaknesses and disabilities. They thus become helpful play partners.

According to ADA regulations, playgrounds should include both elevated play components and ground-level play components. As such, elevated play components are designed using pneumatic principles. Slides, climbing nets, stair case and wheelchair ramp comprise elevated play components. Pneumatic walking aid, jumper, play station for pushing and pulling, swing ball, dome climbing, rotating cushion, crawling tubes and sticker station make up the ground-level play components.

By playing with the play equipment designed in this playground, each child will gain physical improvement such as improve their balance, coordination and timing, practice large movement of their arms and legs, strengthening up shoulder blades and shoulder for the arms to be able to move better, development of strength in the upper and lower body equally well and so on. Moreover, they will also learn social skills, being patient and tolerating others physical abilities and problem solving skills which are essential to achieve success in their lives.

As the saying goes, "*All work and no play makes Jack a dull boy*", playing is of vital importance in the physical and mental development of children. With an aim to provide enjoyment and fun, challenges and safety in this accessible playground, the structure is designed and constructed using pneumatic principles and abiding to ADA rules and regulations. Various types of pneumatic ground-level and elevated level play components are used each with its own purposes as mentioned in above paragraph. As colour and space play vital role in child development, a variety of striking colours and ample space is provided. The author is confident that everyone will enjoy themselves with fun and thrilling moments while playing in this playground regardless of their abilities.

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Written by David Werner

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http://blackoaknaturalist.blogspot.com/2013_05_01_archive.html - retrieved on September 07, 2015

http://www.edencentre.org/about-us/social-model-of-disability - retrieved on September 24, 2015

LIST OF ABBREVIATIONS

ADA	the Americans with disabilities act
CFD	computational fluid dynamic
ETFE	ethylene tetrafluoroethylene
TPU	thermoplastic polyurethane

LIST OF FIGURES

Figure 3 - 1 Envelope – Filling – Medium. 7
Figure 3 - 2: Examples of pneumatic in living nature. 8
Figure 3 - 3: Basic geometrical forms (a) a sport ball; (b) satellite balloon; (c) a high-pressure gas container. 9
Figure 3 - 4: Basic geometrical forms of pneumatics as conic & cylinder. 10
Figure 3 - 5: Air-inflated tubes in different applications. 10
Figure 3 - 6: Instant city; an example project of compound form. 11
Figure 3 - 7: Elevation of German pavilion for Expo 70, Osaka. 11
Figure 3 - 8: Details of German pavilion for Expo 70, Osaka. 12
Figure 3 - 9: An example of complex system: Trial structure in Delft. 12
Figure 3 - 10: Inflatable running kennel for children. 13
Figure 3 - 11: Floating theatre, Expo 70, Osaka. 13
Figure 3 - 12: Inflatable barrage balloons. 13
Figure 3 - 13: Classifications of pneumatic structures. 14
Figure 3 - 14: Inflatable pavilion formed by an assembly of low pressure tubes. 15
Figure 3 - 15: Air-supported hall. 16
Figure 3 - 16: The Galet project for Swiss expo. 17
Figure 3 - 17: Bellver castle in Spain. 17
Figure 3 - 18: The Cloud, World Youth Day, Marienfeld Kerpen, Germay. 18
Figure 3 - 19: ETFE Cushion as building façade, Allianz arena at night in Munich. 18
Figure 3 - 20: ETFE Cushion as roof covering for Nottingham high school for boys (Interior View) 19
Figure 3 - 21: ETFE Cushion as roof covering for Nottingham high school for boys (Exterior View) 19
Figure 3 - 22: Multi-purpose hall with additional point supports, study project. 20
Figure 3 - 23: Demountable exhibition hall with additional point supports, study project. 20
Figure 3 - 24: Roof covering of the swimming pool with additional linear supports. 21
Figure 3 - 25: Exhibition hall with additional linear supports, study project. 21
Figure 3 - 26: Inflated pavilion formed by assembly of high pressure tubes 22
Figure 3 - 27: (a) Inflated fabric arches used in aircraft shelters; (b) Demonstration of an arch load carrying capability. 22
Figure 3 - 28 (a) & (b): Study project: filling element for grid shell. 24
Figure 3 - 29: Synergetic combination of a pneumatic structure with cables and struts. 24

Figure 3 - 30: Dismantled Tensairity Components. 25
Figure 3 - 31: Pneumatics with motion system...26
Figure 3 - 32: Mush-balloon at Expo 1970, Osaka. 27
Figure 3 - 33: Mush-balloon: Opened & Closed. 27
Figure 3 - 34: Cutting pattern preparation. 28
Figure 3 - 35: Welding work of air-inflated wall..29
Figure 3 - 36: Completed air-inflated wall..29
Figure 3 - 37: Testing of air-inflated wall 30
Figure 3 - 38: (a) A complete sphere. (b) A spherical segment...............................31
Figure 3 - 39: (a) A cylinder. (b) A cylinder section. (c) A tube................................32
Figure 3 - 40: Tools and plug-ings for modeling. 35

Figure 4 - 1 (a) & (b): Design study models..36
Figure 4 - 2: Flower structure of a typical daisy. 37
Figure 4 - 3: Design study model for pneumatic tubes. (a) Top view; (b) Side view.38
Figure 4 - 4: Design study model. (a) Vertical tubes; (b) Simplified vertical tubes. ..39
Figure 4 - 5: Safety cushions designed as supporting system. 39
Figure 4 - 6 (a): Minimum requirement for two wheelchairs; (b) Minimum requirement for turning circle...41
Figure 4 - 7: Different accesses to elevated playground. 42
Figure 4 - 8: Plan view of the pneumatic accessible children playground. 44
Figure 4 - 9: Plan view of pneumatic elevated playground.......................................46
Figure 4 - 10: Isometric view of pneumatic elevated playground. 46
Figure 4 - 11: Plan view of pneumatic ground-level & elevated playground............49
Figure 4 - 12: Perspective view of pneumatic ground-level & elevated playground. 49

Figure 5 - 1: Plan view of the primary structure before assembling. 51
Figure 5 - 2: Close-up view of the pneumatic supporting cushion 1 which is designed for climbing net and sliding. 52
Figure 5 - 3: Close-up view of the pneumatic supporting cushion 4 which is designed for climbing stairway and sliding..52
Figure 5 - 4: Plan view of the primary structure after assembling. 53
Figure 5 - 5: Isometric view of the primary structure after assembling. 53
Figure 5 - 6: A fabric envelope with partitions. 54
Figure 5 - 7: Plan view of secondary structure. 54
Figure 5 - 8: Standardised pneumatic columns. 55

Figure 5 - 9: Pneumatic compound form. (a) without an envelope; (b) surrounded by an envelope. 55
Figure 5 - 10: Overall view of an envelope and pneumatic column. 56
Figure 5 - 11: Plan view of secondary structure after assembling. 56
Figure 5 - 12: Perspective view of secondary structure after assembling. 57
Figure 5 - 13: Primary and secondary structures connection detail. (a) 3D View; (b) Section. 57
Figure 5 - 14: Elevated play components perspective views. (a) Secondary structure; (b) Primary structure; (c) Complete structure. 58
Figure 5 - 15: Fixing of the membrane to foundation (a) Section view. (b) Fixing at secondary structure; (c) Fixing at primary structure. 59
Figure 5 - 16: Render Picture View 1. 60
Figure 5 - 17: Render Picture View 2. 61

LIST OF TABLES

Table 3 - 1: Classification of low pressure systems..16
Table 3 - 2: Classification of high pressure systems. 23